Part B Report
A Screening Study
of
Oil Sand Tailings Technologies and Practices

Prepared for
Alberta Energy Research Institute
AERI Contract 2008 0326

REVISION I.
March 2010

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The Rock Doctor
March 2010
Part B: Overview of Oil Sand Tailings

Executive Summary – Part B Report.

The Part B Report is an overview of oil sands tailings practices and related topics.

The report starts with an overview of regulatory matters and the governing fiscal regime. These have a significant impact on the project direction, economics and decision making.

The Evolution of Oil Sand Tailings reviews the history of tailings practice and how it resulted in today’s unfortunate inventory of stranded fluid tailings. It also recognizes the effect of world opinion on oil sands. Finally it describes ERCB Directive 074 that seeks a new direction in tailings management.

The next section provides a step by step description of tailings technology and practices. It reviews why fluid tailings are created, containment requirements, dewatering requirements required to create solid tailings, and technologies that are available to densify fluid tailings. Overviews of oil sand geology, material properties and behaviour, provide background knowledge.

A brief section on world tailings practice notes that some mines prefer to take short term profits, accumulate fluid tailings, and defer reclamation. Stockpiling tailings often creates unnecessary risk, and may be more expensive. Deferring reclamation transfers reclamation costs to future generations. The main reason for this section is to profile the poor image of industries that engage in deferral practices.

Chapter 13 reviews procedures used to screen options for tailings. Traditional economic analysis offers poor guidance for oil sand projects. Discounting, over the long time spans associated with oil sands projects, reduces future obligations to a fraction of their real value. Distortion does not occur if reclamation obligations are booked as they are created, instead of when funds are spent to correct them. Recognition can be accomplished by depositing funds of equivalent value in an environmental trust when the obligation is created. Added benefits of the environmental trust approach – deposits are recognized operating costs. That causes governments to share in the expense. In addition trust deposits offset an automatic reduction in asset value. Finally, the approach encourages management that is more compatible with public expectations.

Information on oil sands project plans, technologies, and performance is limited. Greater transparency is needed.

The review closes with an overview of oil sand research practices, and recommends topics that should be explored.

Appendices support the main text. Appendix 1 provides electronic models. The first summarizes all life cycle work and the associated cost differences for different tailings technologies. The second offers an economic model to appraise the full life cycle of an integrated oil sand plant. The third is a tailings forecast model. All models allow users to input their own values – so the impact of different input can be observed. Appendix 4 focuses on material properties and behaviour – an essential part of understanding tailings.
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B.1 Oil Sands Background

B.1 Introduction

This section provides background information about Alberta’s oil sands. All information is from public sources.

The oil sands are a world class source of oil. Figure B.1 shows how the resource compares with other world supplies. Some facts about the resource

- **Resource base**: 1.7 trillion barrels
- **Proven reserves**: 170 billion barrels recoverable using today’s technology
- **Shallow mineable**: 35 billion barrels
- **Production (2008)**: 1.3 million barrels per day
- **Outlook**: 3 million barrels per day by 2018

Figure B.1 How Alberta’s oil sands rank with world deposits. (Alberta Energy, 2008).

![Proven World Reserves](chart.png)

Half of the oil sand production comes from shallow deposits that are mined, the bitumen extracted using a hot water process and upgraded to a pipelineable product.

Characteristics of three oil sand projects are summarised on Table 1. The projects all started big and are getting bigger. All have plans to expand to produce half a million barrels per day in the next few years. Syncrude, now 30 years old, expects to last for 100 years.
B.1 Oil Sands Background

Table B.1 Characteristics of three mineable oil sands projects.

<table>
<thead>
<tr>
<th>Project/Component</th>
<th>Suncor</th>
<th>Syncrude</th>
<th>Albian Sands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-up date</td>
<td>1967</td>
<td>1978</td>
<td>2002</td>
</tr>
<tr>
<td>Years in operation</td>
<td>43</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>Configuration</td>
<td>Integrated facility Mine Mine Waste disposal Extraction Upgrading Upgrader Tank farm Utilities Tailings ponds</td>
<td>Integrated facility Mine Mine Waste disposal Extraction Upgrading Upgrader Tank farm Utilities Tailings ponds</td>
<td>Separate facilities At site Mine Extraction Waste disposal 455 km 24” diluted bitumen and 12” diluent return line. Upgrader at Scotford (near Edmonton)</td>
</tr>
<tr>
<td>Satellite</td>
<td>Mine and extraction satellites nearby Remote In-situ</td>
<td>Large satellite contains mine, extraction, tailings</td>
<td>Expanding on site</td>
</tr>
<tr>
<td>Start-up production</td>
<td>45,000 bbl SCO/day</td>
<td>105,000 bbl SCO/day</td>
<td>150,000 bbl SCO/day</td>
</tr>
<tr>
<td>Current production</td>
<td>260,000 bbl SCO/day</td>
<td>300,000 bbl SCO/day</td>
<td>150,000 bbl SCO/day</td>
</tr>
<tr>
<td>Planned production</td>
<td>500,000 bbl SCO/day</td>
<td>500,000 bbl/day</td>
<td>500,000 bbl/day</td>
</tr>
<tr>
<td>Extraction efficiency %</td>
<td>92%</td>
<td>90.7%</td>
<td>80% (after asphaltene loss)</td>
</tr>
<tr>
<td>Upgrading yield</td>
<td>84%</td>
<td>87.5%</td>
<td>100%</td>
</tr>
<tr>
<td>Coke production</td>
<td>2 million tonnes/year</td>
<td>2.5 million tones/year</td>
<td>Asphaltenes are rejected and added to tailings</td>
</tr>
<tr>
<td>Tailings</td>
<td>Conventional MFT followed by CT</td>
<td>Conventional MFT followed by CT</td>
<td>Produce thickened tails. Less MFT because not using dispersant.</td>
</tr>
<tr>
<td>Green house Gas</td>
<td>0.6</td>
<td>0.85</td>
<td>NA</td>
</tr>
<tr>
<td>Tonnes / m3 SCO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC emission (kg/m3)</td>
<td>1.73</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Naphtha loss</td>
<td>NA</td>
<td>.0043 bbl/bbl</td>
<td>NA</td>
</tr>
<tr>
<td>Energy use GJ/m3 SCO</td>
<td>7.4</td>
<td>8.1</td>
<td>NA</td>
</tr>
<tr>
<td>Water import m3/m3</td>
<td>2.4</td>
<td>2.03</td>
<td>NA</td>
</tr>
<tr>
<td>Water recycle %</td>
<td>N/A</td>
<td>88%</td>
<td>NA</td>
</tr>
<tr>
<td>Cumulative disturbance ha</td>
<td>13,093</td>
<td>21,282</td>
<td>NA</td>
</tr>
<tr>
<td>Cumulative area reclaimed</td>
<td>949</td>
<td>4,668</td>
<td>NA</td>
</tr>
<tr>
<td>Reclamation Certificate - ha</td>
<td>0</td>
<td>104</td>
<td>0</td>
</tr>
</tbody>
</table>
B.1 Oil Sands Background

Figure B.1 is an aerial view of the base plants for Syncrude and Suncor. Table B.2 summarises land use at the Syncrude base plant. Open pit mines, waste dumps and tailings facilities dominate the landscape. The footprint is just under two townships.

Table B.2  Land use at the Syncrude Mildred Lake Facility (Base Plant)

<table>
<thead>
<tr>
<th>Land use/area</th>
<th>Ha</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant site related</td>
<td>550</td>
<td>3%</td>
</tr>
<tr>
<td>Mining</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open pit space</td>
<td>4,250</td>
<td>25%</td>
</tr>
<tr>
<td>Overburden waste dumps</td>
<td>1,100</td>
<td>6%</td>
</tr>
<tr>
<td>Tailings ponds and related areas</td>
<td>6,400</td>
<td>38%</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>4,700</td>
<td>28%</td>
</tr>
<tr>
<td>Total</td>
<td>17,000</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure  B.2 Satellite view of Syncrude and Suncor base plants
B.2 Regulating Oil Sands

B.2. Regulating oil sands

B.2.1 Background

Oil Sand development is regulated in Alberta by Alberta Environment (AENV), the Energy Resources Conservation Board (ERCB) and Alberta Sustainable Resource Development (SRD). The Federal government manages its role through Environment Canada and the Department of Fisheries and Oceans.

AENV and SRD have primary responsibility for managing the environment. That includes, pollution prevention and control, water allocation, use and protection of potable water, conservation and reclamation planning, and the evaluation of air, water, and land for environmental performance reporting. AENV also manages the financial assurance program that encompasses many types of development including oil sands.

The ERCB regulates oil sands mining and processing operations, as well as discard from those operations, including tailings.

A Memorandum of Understanding (MOU) between AENV, SRD and the ERCB outlines each agency’s responsibilities and how they work together. The MOU addresses tailings ponds and other aspects of mineable oil sands management, including water use and reclamation.

B.2.2 Alberta Environmental Protection and Enhancement Act

The Alberta Environmental Protection and Enhancement Act provides the mandate for AENV. (Alberta, 1993). The writer’s interpretation of some underlying principles contained of the Act, that have a direct bearing on oil sands management, include:

- The party that disturbs land is responsible for restoring it. The disturber is obliged to qualify for a “Reclamation Certificate” that signifies the land has been satisfactorily reclaimed.
- The public is invited to review and input to decisions on the environment.
- Regulators may require developers to provide financial assurance that funds will be available to reclaim sites. The form and amount of financial assurance is at the regulator’s discretion.
- There is to be no intergenerational transfer of environmental liabilities.

B.2.3 ERCB Mandate

The ERCB mandate is governed by The Alberta Oil Sands Conservation Act. Approvals for mines and plants are required by Sections 10 and 11 of the Act. Approval to commence, suspend, or abandon an oil sands site is required by Section 3. Approval for storage of discard generated by a mine or a plant is required by Sections 24 and 48.
B.2 Regulating Oil Sands

In 2004 the ERCB and the Canadian Environmental Assessment Agency identified several long-term objectives respecting tailings management:

- to minimize and eventually eliminate long-term storage of fluid tailings in the reclamation landscape;
- to create a trafficable landscape at the earliest opportunity to facilitate progressive reclamation;
- to eliminate or reduce containment of fluid tailings in an external tailings disposal area during operations;
- to reduce stored process-affected waste water volumes on site;
- to maximize intermediate process water recycling to increase energy efficiency and reduce fresh water import;
- to minimize resource sterilization associated with tailings ponds; and
- to ensure that the liability for tailings is managed through reclamation of tailings ponds.

In February 2009 the ERCB issued Directive 074. It requires oil sand operators to solidify increasing amounts of fluid tailings each year, report on “fines” management, and report on the performance of each tailings facility annually.
B.3 Fiscal Terms for Oil Sands

**B. 3. Fiscal Terms**

Oil sand projects are highly taxed so the fiscal regime is very important.

Individual components of the fiscal regime include Alberta royalty, capital investment incentives, and federal and provincial income tax.

Alberta Royalty varies with the stage of a project and the price of oil. Before payout, Alberta Royalty is a percentage of Gross income. After payout, Alberta Royalty is the greater of: a specified percentage of net profit, or a percentage of gross income.

Payout occurs when cumulative income exceeds cumulative expenditures.

After payout, a dollar of profit is shared according to fiscal terms, as graphed on Figure B.3. Depending on the price of oil, fiscal sharing leaves the developer with $0.45 to $0.56 from each dollar of profit. Governments receive the rest.

If money is spent, the same fiscal sharing occurs. Then the cost to the developer of spending one dollar is $0.45 to $0.56. Through foregone profits, the governments pay the rest.

Fiscal sharing is an important part of oil sand economics and must be part of any economic assessment.

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**Figure B.3 Fiscal sharing vs price of oil**

![Diagram showing fiscal sharing vs price of oil](image)
B.4 Evolution of tailings and reclamation practices

B.4.1 Early History

Tailings practice has evolved. There were few environmental guidelines when Suncor started operations in 1967. That was 5 years before Alberta Environment existed.

Tailings were a surprise when Suncor started operations in 1967. A temporary dyke was constructed to Tar Island in the Athabasca River to hold the tailings until a solution could be found. Today the dykes of that facility are 100 m high and it is being reclaimed after 42 years of service.

Today applications for oil sands development are obliged to study the lease, identify all potential adverse impacts and show how they will manage them. They are also obliged to submit a long term closure plan. At the end of the project operators are expected to reclaim the site and qualify for a reclamation certificate. The Reclamation Certificate is issued by the government and means that reclaimed lands are acceptable to the regulators and that the developer is no longer responsible.

B.4.2 The 1990’s

Initially all of Syncrude’s tailings were stored in the Mildred Lake facility.

After 10 years of operation, Syncrude introduced a pump-around-system to prevent the Mildred Lake facility from filling. (List et al, 1995). It is illustrated by Figure B.3. The system works as follows:

- Plant waste is pumped to the South West Sand Storage facility where sand is deposited. Thin tails runoff is pumped to the Mildred Lake Settling Basin.
- At the Mildred Lake facility, fines settle and form MFT.
- Mature MFT is pumped from the Mildred Lake Settling Basin to the Base Mine Lake storage.
- MFT for making CT is recovered from the Mildred Lake facility or from the Base Mine Lake.
- CT is stored in the active CT tailings repository.

In the same period Suncor developed new facilities to hold fluid tailings in mined out areas. Figure B.2 shows how tailings ponds dominate the Suncor base plant site.
In Syncrude’s 1992 application for project expansion Syncrude proposed to:
- Decrease MFT production through a number of in-house initiatives.
- Solidify MFT using the CT process.
- Permanently store MFT that remains at the end of operations below a water cap in an end-pit-lake. They proposed a full scale demonstration test in the Base Mine Lake commencing in 2012. The demonstration would last for 10 to 15 years.

The ERCB agreed to the demonstration test provided the facility would be reclaimed if the test was not successful. The ERCB noted that they preferred that fluid tailings be reclaimed as a trafficable solid. They also noted that the proposal to permanently store MFT under a water cap was not approved. (Houlihan et al, 2008).

Since Syncrude proposed it in 1992, most oil sand applications have proposed to start with a surface tailings pond, and then switch to CT or equivalent when the project moves in-pit. At the end of the project, fluid tailings left over would be stored permanently under a water cap. The list of look alike applications include:
- Syncrude applications (Syncrude 1992, 2002)
- Suncor applications (ERCB 2003, 2004)
- Kearl Lake application (Kearl, 2005).
B4 Evolution of tailings and reclamation processes

Syncrude’s in-house initiatives program was implemented and was largely successful. The main program involved reducing the water content in the extraction plant and in the tailings discharge so fines capture in the sand deposits would be maximized. Fines that are captured in the beach are not available to make MFT.

Syncrude successfully operated small scale demonstration tests with water over MFT. However, the tests were small and did not evaluate the effect of gas emissions that started at a later date. Syncrude evaluated CT in a 5 million cubic metre demonstration pilot in the mid 1990’s. They started using CT in commercial operations in 1999. That deposit is being prepared for reclamation – the first tailings pond to be reclaimed at Syncrude.(Fair, 2008).

Suncor have been using CT in commercial operations since the 1995.(Shaw, 2008). Suncor are reclaiming their start-up pond that had been in use for over 40 years.

B.4.3 Recent events

Industry appears to focus on:

- Traditional plants to make fluid tailings until operations can move in-pit;
- Then solidify fluid tailings using CT or an equivalent technology;
- Permanently store residual amounts of fluid tailings under a water capped end-pit-lake.

That is a strong contrast to the goals set out by the ERCB (Houlihan et. Al. 2008):

- Minimize and eventually eliminate long-term storage of fluid tailings.
- Create a trafficable landscape at the earliest opportunity.
- Eliminate or reduce fluid tailings in an external tailings disposal area.
- Ensure that the liability for tailings is managed through reclamation.

Pilot research is apparently evaluating other technologies such as sand stacking, thickener evaluations, cyclone treatment, drying, freeze thaw treatment and centrifuge treatment. (Fair, 2008). Suncor are many of the above as well as self contained mobile mine/extraction units. General information about the Syncrude or Suncor research has been released but little if any specifics have been made public.

Shell are researching thickened tailings options (Matthews, (2008)). They started their operation without the use of dispersing agents to reduce tailings produced. However, they have subsequently been adding sodium citrate, a dispersant. Shell are still producing thickened tailings and storing it in their out-of-pit starter pond.

In the past decade Syncrude produced about 200 million cubic metres of MFT. Ten percent of that was solidified with CT treatment. (Fair, 2008).
B4 Evolution of tailings and reclamation processes

MFT storage interferes with land reclamation. Syncrude have disturbed over two townships of land area. 20% has been reclaimed. Suncor have only reclaimed 4% of their disturbed lands. To date 104 hectares in the oil sand region have received formal reclamation certificates.

The Total application (Total, 2006a, 2006b) propose to store weak CT at depth, cover it with stronger CT all of which will be covered with a strong sand cap. (Total 2006b). Figure B.5 illustrates the Total proposal.

Figure B.6 shows the growth of MFT for the whole industry. Today the volume totals 750 million cubic metres. If there is no change in processes used the volume is forecast to reach 1 billion cubic metres in 2014 and two billion in 2034. (Houlihan et. al. 2008).
B.4.4 500 Ducks

Oil sands developments are located on a major fly-way that birds use as they migrate to nesting sites in the Arctic. Millions of birds fly over the oil sands developments each spring, and return with their young each fall. Tailings ponds are incompatible with this natural migration because birds that land on the ponds are apt to become oil covered and die. Figure B.7 shows oil on the surface of a Syncrude tailings pond.

Deterrents such as man sized statues standing on floats spaced at regular intervals on the pond surface are used to keep the birds from landing. The statues are supplemented by propane "cannons" that fire at regular intervals and mimic shot gun blasts. Albian Sands use a radar scanner to detect incoming birds and activate an artificial hawk to scare birds away.

In April 2008, late winter storms delayed installation of the seasonal duck deterrents. A flock of Mallard ducks landed on a Syncrude tailings pond before the deterrents were installed. 500+ ducks perished.

Adverse world wide publicity followed. Internet searches reveal a plethora of anti-oil sand, anti- Canada, and anti-U.S.A. web sites, books (Nikiforuk, 2008), and magazines (Kuneig, R., (2009),National Geographic). The publicity may exaggerate and support other agendas on energy use and climate change. However, some of the concerns are justified and reveal an oil sand industry outlook that, if Syncrude’s 2006 C&R Plan is a model (Syncrude, 2006), was sadly out of date. The impact is damaging the marketability of oil sands products, and Canada’s image in world trade.
B.4.5 ERCB Directive 074

In 2008 the ERCB held meetings with oil sand operators to share concerns about the growing inventory of fluid tailings and to discuss new reporting requirements.

In February, 2009 the ERCB issued Directive 074. It requires operators to report on all fines processed and to solidify increasing percentages of the fines processed each year. (20%, 30%, and 50% in the next three years). The Directive specifies strength criteria for the solidified fines (a minimum undrained shear strength of 5kPa in the first year and a minimum of 10 RPa after 5 years). In addition, Directive 074 requires that operators inventory their tailings ponds and report performance annually.

Houlihan presented a summary of the public and regulatory concerns about tailings that were behind Directive 074 (Houlihan et al, 2008).

Public concerns:
- Seepage and potential water contamination,
- Fugitive emissions,
- Risk of a tailings dam failure,
- Return of the land to traditional use,
- Progressive reclamation (lack of it),
- Intergenerational transfer of liability.

Regulator’s concerns:
- Applications underestimate the fluid tailings volumes,
- CT performance targets and commitments not met,
- Fluid volumes growing steadily,
- No fluid tailings pond reclaimed,
- Neither the public nor the government is prepared to accept commitments that are not met and increasing liabilities.

Historically the government has encouraged industry to show leadership in oil sands management. Directive 074 represents a new direction.
B.5 Oil Sand Geology

B.5.1 Resource Base - mineable area

The ERCB estimates that 35 billion barrels of bitumen is recoverable from the surface mineable area (ERCB, (2009b)).

For mineable developments the minimum resource base is enough to support a project for 25 years. That amounts to over 1 billion barrels of reserves per 100,000 barrels of production per day.

B.5.2 Bedrock Geology

The mineable oil sand area is defined as oil sand that has up to 50 metres of overburden over the ore zone. It is located north of Fort McMurray. Figure B.8 shows the distribution of bedrock formations in the Fort McMurray area. (Alberta, 2009)

Granite of the Canadian Shield lies under the oil sand area a few hundred metres below surface. The granite is covered by Paleozoic formations of sandstone, salt, shale, limestone and dolomite that dip gently to the west.

The McMurray Formation is the host rock for bitumen. It was deposited unconformably on top of the Paleozoic formations. It is of Cretaceous age, (120 million years old). Depositional environments, created when a shallow sea invaded the area, left complexly inter-layered deposits of sand, silt and clay.

The Clearwater formation was deposited on top of the McMurray. It contains marine deposits that formed in the deepened sea. Some layers of the Clearwater are sandy but most are clay-shale that contains considerable amounts of bentonite. Other formations followed so at one time the McMurray was covered by one to two kilometres of sediment.

B.5.3 Local structure

Solution of the salt beds was occurring in during Cretaceous time, especially east of the Athabasca River. Solution activity disrupts the continuity of overlying beds. Thickened sections of the McMurray developed in areas that were subsiding in Cretaceous time.

Karst features, evident on surface today, indicate that solution activity is continuing. (Fraser, 1975).
Figure B.8 Bedrock of the Mineable Oil Sands Area
The Bitumont basin developed north of Suncor and Syncrude. It is indicated on Figure B.8 by the circular area occupied by Clearwater clay/shale. There the entire profile, including the granite surface subsided, indicating that the origin is more deep seated than solution of salt beds. Subsidence during McMurray time resulted in thicker and coarser beds of sand. Subsidence after oil entered the area depressed parts of the bitumen saturated zone 30 metres below the Athabasca River. (Isherwood, 2009).

B.5.4 Origin of the bitumen

At an unknown time, conventional oil from the Alberta Basin migrated eastward into the area. It floated on a water layer, and filled the top of the McMurray formation. Bacterial action stripped light components from the oil, leaving heavy bitumen. (McNeely, 1973). The bitumen / water interface tends to be horizontal in the Suncor area, coinciding with the present level of the Athabasca River. In the Bitumont Basin the bitumen saturated zone is depressed about 30 metres below the Athabasca River.

B.5.5 Surficial Geology

Surficial deposits include Pleistocene glacial till – both dense basal till and weaker ablation till. Outwash deposits, wind blown sands and lacustrine deposits followed at the close of the Pleistocene glaciation.

Surface deposits include local alluvium and muskeg deposits.

Continental glaciations melted from south to north. The northern sections blocked drainage so large lakes formed south of the ice sheet. Glacial Lake Agassiz covered much of Manitoba and Saskatchewan. About 10,000 years ago it discharged down the Clearwater River and carved the present valley of the Athabasca River north of Fort McMurray. (Smith et.al., 1993).

Upstream from Fort McMurray the Athabasca River flows on bedrock. Downstream from Fort McMurray there is a buried valley below the Athabasca River. The buried valley North of North of Fort McMurray probably represents a pre Cretaceous river valley (Devenny, 2000).

Continuing salt solution is indicated by salt springs that enter the Athabasca River – especially near the Bitumont Basin (Bauman, 2008).

Upstream from Fort McMurray the Athabasca River flows on the surface of Paleozoic bedrock. Downstream from Fort McMurray there is a buried valley below the Athabasca River. The buried valley North of North of Fort McMurray probably represents a pre Cretaceous river valley (Devenny, 2000).

Continuing salt solution is indicated by natural salt springs that enter the Athabasca River –especially near the Bitumont Basin. (Bauman, 2008).

B.2.6 Ore body character
B.5 Oil Sand Geology

In the mineable oil sands area, overburden tends to be about 50 metres thick. The ore zone also tends to be about 50 metres thick. Ore grades are highest in sandy zones (as high as 15% by weight bitumen) and lowest where fine grained material is present. Table 3. characterizes “average” ore at Syncrude.

Table B.3 Average ore used in the study reported in Report A

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight %</th>
<th>Weight per cubic metre (tonnes)</th>
<th>Volume in one cubic metre</th>
<th>Density/ specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen</td>
<td>11%</td>
<td>0.231</td>
<td>0.229</td>
<td>1.01</td>
</tr>
<tr>
<td>Water</td>
<td>5%</td>
<td>0.105</td>
<td>0.105</td>
<td>1.00</td>
</tr>
<tr>
<td>Fines</td>
<td>16%</td>
<td>0.336</td>
<td>0.127</td>
<td>2.65</td>
</tr>
<tr>
<td>Sand</td>
<td>68%</td>
<td>1.428</td>
<td>0.539</td>
<td>2.65</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>2.100</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>

The following discussion deals with facts about average ore that we can interpret from Table B.3.

1. The Bitumen density is very close to the density of water. That challenges separation in extraction and is the reason that air bubble assistance is used to float bitumen. It is also the reason that solvent is used to change the density of bitumen in froth treatment.
2. Bitumen represents 22% of the total volume of oil sand ore. That suggests a clean porous sand.
3. The clay/water ratio is low indicating that in-situ the clay is not dispersed.

Other facts about oil sand ore:

4. Oil sand ore is highly variable, a result of the variable depositional environments of the host reservoir. It contains complexly interlayered ore and waste deposits of sand, silt, and clay. All processes, from the mine face through extraction and tailings, must be robust and able to accommodate variations in the ore.
5. Quartz and clay minerals ilmenite and kaolin are the dominant minerals in oil sand.
6. A quartz surface has a greater affinity for water than bitumen. As a result each sand grain is surrounded by a thin film of water – that allows easy separation via agitation in hot water. Oil sand deposits elsewhere in the world are often composed of other minerals that attract bitumen to the sand grain surface. They require solvent to extract the bitumen.
7. Bitumen particles released in extraction reflect the size of the void space that they are released from. In sand the void space is quite large. In fine grained soil the void space is quite fine.
8. Bitumen associated with fine grained deposits can be difficult to extract because:
   - The surface may be oil wet,
   - Bitumen droplets are too fine for air bubbles to contact and float them to surface.
9. There are minor quantities of heavy minerals – ilmenite, rutile and zircon. Centrifuge action in extraction concentrates the heavy minerals many fold – so they are potential ores for titanium and zirconium.
B.6 Mining

All projects mine overburden and ore using large shovels and 400 ton trucks. Ore is hauled to a dump facility where it is crushed, screened, slurried with warm process water and pumped to the extraction plant. Turbulence during hydrotransport breaks the ore into individual particles – needed for separation in extraction. Process aids, dispersing agents and small air bubbles, are added before the ore reaches extraction.

Mine waste (overburden and interburden) is hauled to waste dumps. Suitable waste is also used to construct facilities such as tailings dykes. It is usually compacted by driving 400 ton trucks over it. Some wastes are unsuitable for construction, because they are too wet, or contain undesirable material (e.g. swelling and erodible clays of the Clearwater Formation.)

Care is required to ensure that materials that are deleterious to extraction are kept out of the ore supply. Deleterious materials include active clay from the Clearwater Formation.

Figure B.8 shows a 400 ton truck that is used in oil sand mining. Figure B.9 shows a shovel loading ore onto a 400 ton truck. Shovels are sized so they can fill the trucks with three scoops.

Figure B.9 400 ton mine truck

ERCB Interim Directive ID 2001-7 stipulates cut-off criteria for mining. Projects are expected to mine to a minimum TV/BIP of 12 where TV is the total volume of ore, interburden and overburden, and BIP is the volume of bitumen in-place. The minimum waste layer is 3 metres thick. The cut off grade is 7%.
Mine openings must depressurize aquifers encountered in and below the ore body. At the Suncor and Syncrude base plants groundwater aquifers are limited and the ore seldom dips below the level of the Athabasca River. At Albian Sands the basal aquifer is more extensive but mining activity tends to be above the level of the Athabasca River. Projects in and near the Bitumont Basin could be mining ore 30 metres below the surface of the Athabasca River. Groundwater control in those mines could encounter large quantities of very saline water.

Figure B.10 Loading a 400 ton haul truck

Mined out areas are backfilled with overburden and tailings. Figure B.11 shows how tailings and mining activity exist side by side at Syncrude. It can take 50 years to accommodate mining, tailings storage, tailings reclamation and finally surface reclamation.

There are waste products that must be accommodated in mined out areas:
- Overburden and interburden waste,
- Material rejected at the screen before Hydrotransport (cemented layers and clay lumps),
- Coke produced in upgrading (approximately 2 million tonnes per year at both Syncrude and Suncor). The ERCB requires that coke be placed so it will be accessible to future generations.
- Sulphur (usually stored on site because shipping cost exceeds the market value). Sulphur is also stored so it will be accessible in the future.
Figure B.11 How mining and tailings work in-pit at Syncrude

Legend

EIP       East in Pit Mine
SWIP      South West in Pit mine
North Mine Active North Mine
B.7 Extraction

The first step in extraction is to add water to the incoming ore slurry. The first vessel in the extraction plant contains relatively still water. In that environment sand drops out of suspension and is sent to tailings. Bitumen, aided by small attached air bubbles floats to the surface where it is removed as froth. The remaining mixture is called middlings. It contains water, silt, clay, and small droplets of bitumen, is sent to the next stage of the extraction plant for further processing.

After bitumen has been removed from the middlings circuit residual waste is blended with the sand tailings stream and sent to tailings.

In froth treatment, solvent is added to dilute bitumen and to change its specific gravity. Then the slurry is centrifuged to separate the bitumen from water and solids. Residual waste containing water, solids, unrecovered bitumen and solvent losses is discharged as froth treatment tailings.
B.7 Extraction

Froth treatment tailings contain the most bitumen and solvent as well as concentrations of heavy minerals such as ilmenite, rutile and monazite. There is some interest in ilmenite and rutile as potential sources of titanium. Monazite contains radioactive elements that are detectable with geophysical logging tools. Blending froth treatment tailings with regular tailings degrades the quality of regular tailings. It also wastes concentrated ilmenite and rutile, and adds concentrations of radioactivity that interfere with using geophysical tools to determine the clay content of MFT. Perhaps waste from froth treatment should be stored separately.

The extraction systems described are illustrative. Other configurations are also used.

ERCB Interim Directive ID 2001-7 specifies the minimum bitumen recovery. For ore that contains more than 11% by weight bitumen, extraction is expected to recover 90% or more of the bitumen. For ore grades between 7% and 11% the minimum bitumen recovery curve is indicated by Figure B.13.

![Figure 6 ERCB Bitumen Extraction Recovery Curve](image)

ERCB Recovery Criteria:
- Maximum ore/reject thickness 3m
- Cut off grade 7%
- TV/BIP Cut off 12
- Minimum recovery in extraction

\[ \text{Recovery} = 54.1 \times -2.5X^2 - 202.7 \]
where \( X \) = feed grade

Suncor and Syncrude operate integrated plants. They produce bitumen that is suitable for their on-site upgrader but does not meet specifications for pipeline transport. Table 1 indicates that Suncor and Syncrude recover 92% and 90.7% of the bitumen in extraction. The difference probably reflects slightly lower grade ore at Syncrude.
The Albian Sands Project produces bitumen and then ships it 455 km to the Shell upgrader in Scotford Alberta. Pipeline specifications require cleaner bitumen than Syncrude and Suncor produce. The new froth treatment used to produce clean bitumen causes asphaltenes to precipitate. They are added to tailings from froth treatment. As a result the overall hydrocarbon recovery at Albian Sands is probably 80% or less.

Suncor and Syncrude add caustic soda in extraction to facilitate bitumen removal. Caustic soda also disperses clay. That adds to the volume of fluid tailings created.

Originally, Albian Sands proposed to operate extraction without adding dispersing agents. The reason: anticipated superior performance in tailings — denser, rapidly settling tailings, and faster water clarification. However, the project now adds sodium citrate, a dispersing agent, to aid bitumen extraction.

Process water discharged in the waste streams from extraction contains heat. Heat loss is reduced if the amount of water discharged with plant waste is reduced.

Water discharge can be reduced by concentrating the solid content of the discharge streams. The fines stream can be concentrated to about 30% solids in a thickener. The sand waste stream can be densified by cyclones to over 70% solids. Process water recovered in the plant, with its contained heat, is immediately recycled and reused.

Traditional extraction produces waste that can be pumped. The upper limit for the strength of pumpable waste is 100 kPa. That is 1% of the strength desired for reclamation.
B.8 Basic Tailings – from Extraction to MFT

B.8.1 Introduction to Tailings

Tailings are the waste product of oil sand processing.

The assignment for tailings management is:

1. Receive all solid and fluid waste produced by extraction,
2. Store it in a safe, cost effective manner,
3. Return clarified process water to the plant for reuse,
4. Reclaim waste deposits to meet reclamation requirements for closure in a timely manner.

The assignment is a difficult one because:

- Tailings waste is received as a liquid slurry.
- A zero discharge policy requires that all process affected water be retained on site.
- For closure, some of the waste must be transformed into a strong, self-supporting solid.
- Extraction do not know the clay content of their tailings discharge.

B.8.2 The tailings cycle

Figure B.14 shows the steps in the path that transforms ore to tailings. Figure B.15 shows the relative volume of the components of tailings along that path. Steps in tailings management are described below:

- Ore is mined, slurried and pumped to extraction. In transit the ore separates into individual particles, in preparation for bitumen extraction. The volume of solids remain constant from stage to stage. Volume changes are due to bitumen removal, water addition and water removal.

- In extraction the ore components are separated into three streams (coarse, fines and froth) because each requires different treatment. After bitumen has been extracted, the sand and fines waste streams are combined and pumped to the tailings disposal site. Froth treatment waste may be pumped directly to the tailings pond. Waste slurries sent to tailings contain process water, sand, fines, unrecovered bitumen, and minor impurities from natural and man-made sources. When tailings exit the plant the volume of the slurry is more than twice the original volume of the ore. Heat loss is associated with the large volume of water in the tailings slurry.
Figure B.14 The Oil Sands Tailings Cycle

1. Make-up Water
2. Hydrotransport
3. Extraction Plant
4. Sand Dyke
5. Water Clarification Zone
6. Recycle Water
7. Solid Fine Tails

Figure B.15 Volume change on the path from ore to waste
B.8 Basic Tailings – from Extraction to MFT

- At the waste storage site, the slurry is discharged onto a sand deposit. Seventy-five percent of the waste accumulates as a solid sand deposit. Void space in the sand is filled with water and suspended components. The void space in the sand is almost equal to the volume of fluid tailings. Surplus material overflows to the pond.

- Material entering the tailings pond consists of a dilute suspension of water, fines, unrecovered bitumen and solvent, and impurities. Section B.A4.3 in Appendix B.4 describes how solids settle to become MFT.

- Most tailings material balances in Applications for a commercial development stop at the MFT stage. Figures B.14 and B.15 assume that closure requires that MFT should be reclaimed as solid fine tailings or SFT. The final step changes MFT to SFT with a fines density of 70% solids by weight.

- Surplus water in the pond is available for reuse. When the fines are stored as MFT the volume available for recycle is 1.15 cubic metres per cubic metre of average ore processed. Converting MFT to SFT adds an additional 0.18 cubic metres of water to recycle.

- Dissolved salts accumulate with each time water is reused. The salts come from connate water in the ore, mine depressurization water, and process aids.

Lord (Lord et al, 1997) reports MFT densities of 35% and even 40% at Syncrude. The densities noted indicate that some consolidation is taking place. There are subtle differences in MFT at Syncrude and Suncor (McKinnon et al, 1993). The preceding facts do not change the thrust of discussions in this report.

Tailings water becomes saltier with reuse. Implications:
- At some point the water chemistry will cause clay to flocculate in extraction – halting bitumen extraction.
- Salty process water suppresses vegetation so adversely affects reclamation.
- It will be difficult to assimilate tailings water in the surroundings if it is too salty.

B.8.3 Transporting tailings

Process waste is blended and pumped to the tailings disposal site for several reasons:

- Fine grained components assist fluid transport of sand.
- Blended waste means that only one transport system is needed.
- Waste is pumped because it is believed to be the lowest cost transport system.
- Discharged waste automatically flows to its final resting place.
B.8 Basic Tailings – from Extraction to MFT

Tailings is pumped at a speed of 3 to 5 metres per second to keep all solids in suspension.

The upper limit on “strength” for pumped slurries is about 100 kPa. The strength of the pumped material will have to increase by a factor of 100 to equal 10 kPa, the lower limit of strength desired for solid reclaimable tailings.

To save heat, operators try to keep the density of the waste slurry high (between 50% and 60% solids). It is not practical to pump at higher densities.

B.8.4 Tailings Sand deposits

Three types of sand deposits form at the end of the tailings line.

Sand construction cell

Large cells are created to collect sand for construction. When the tailings slurry enters the broad cell, flow velocity decreases and sand drops out of suspension. Dozers maintain small perimeter dykes around the cell and compact the newly deposited sand by tracking back and forth across it. Void space in the sand is filled with process water and suspended material.

Figure B.16 is a photo of a tailings sand cell in preparation. Figure B.17 is a photo of a dozer compacting sand in the construction cell. (Matthews, 2008).
Sand that is not used for construction is directed to the beach.

Beach deposits are indicated on Figure A.17.
B.8 Basic Tailings – from Extraction to MFT

Beach above water

The tailings discharge is spread over the beach to prevent concentrated flow. Small streams flow over the beach. They deposit, erode and re-deposit sand and material captured in the voids. That makes the deposit in the beach above water highly variable, ranging from clean sand to sand with voids filled with captured material.

Beach below water

Conditions in the beach below water are quieter than they are above water.

In the underwater environment gentle placement creates loose deposits form that can trap a lot of fine grained material. The loose deposits are prone to liquefaction. Submarine landslides and turbidity flows are part of the system that delivers material down the slope and into adjacent deposits of MFT.

The volume and character of sand deposits is relatively predictable and is summarized by Table B. 4. The volume and character of the fine tailings component is much more complicated, partly because information on clay and its activity is not collected.

Table B.4 Forecast properties of tailings sand deposits:

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Porosity N</th>
<th>Void Ratio</th>
<th>Weight % Solids</th>
<th>Dry Density t/m³</th>
<th>Beach Slope %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand compacted in a cell</td>
<td>0.37</td>
<td>0.6</td>
<td>82%</td>
<td>1.67</td>
<td>-</td>
</tr>
<tr>
<td>Sand deposited in a beach above water</td>
<td>0.40</td>
<td>0.68</td>
<td>80%</td>
<td>1.59</td>
<td>2%</td>
</tr>
<tr>
<td>Sand deposited in a beach below water</td>
<td>0.43</td>
<td>0.75</td>
<td>78%</td>
<td>1.51</td>
<td>4%</td>
</tr>
<tr>
<td>Fines forming MFT in the pond</td>
<td>0.86</td>
<td>6.2</td>
<td>30%</td>
<td>0.37</td>
<td></td>
</tr>
</tbody>
</table>

B.8.5 Behaviour in the tailings pond

The tailings pond is a large vessel that clarifies water and provides storage for fine grained deposits.

Material that enters the tailings pond consists of water, unrecovered bitumen, silt, clay, dissolved chemicals, solvent losses, and process aids.

The waste slurry entering the tailings pond is quite dilute, with a typical solid content of 5 to 10%. Suspended solids slowly settle leaving clear water behind. As the solids settle, the suspension becomes denser and particles interfere with each other. This transition zone extends to a depth of a few metres. Finally, when the density reaches about 30% solids, repulsive forces between clay particles prevent further densification. The deposit at that stage is known as “mature fine tails” or MFT.
B.8 Basic Tailings – from Extraction to MFT

A weak soil structure forms in MFT and represents the start of soil strength. Initially the deposit is extremely weak. The low strength in early MFT is indicated by the fact that individual sand grains break through it and accumulate at the base of the deposit – 10’s of metres below.

When surface water reaches a solid content of 0.1% it can be recycled to the plant.(Fine Tails Fundamentals Consortium (1995) page IV-74.)

Mats of bitumen also accumulate in the pond deposits.

B.8.6 Predicting the volume of tailings

Tailings personnel are responsible for forecasting the volume of tailings so storage facilities can be constructed and ready to store expected tailings.

The volumes of sand deposits are predictable, but the volume of fine tailings is not. The volume of MFT is a largely a result of clay, and the way it interacts with water and the chemicals present in the water. Extraction operators do not measure the clay content. They measure ‘fines’ that can contain from 0% to 100% clay sized material.

The accuracy of tailings forecast models, that do not consider the amount of clay present, or the extent of clay dispersion, is highly suspect.

Other indicators of the MFT volume can be derived from historical data. At Syncrude the average volume of MFT produced per cubic metre of average ore is 0.266 cubic metres.

A tailings forecast model was developed to explore trends affecting tailings volumes. Findings are summarized in Table B.5 below. An electronic copy of the tailings forecast model is in Appendix B.1.

Table B.5 Highlights of information obtained from the tailings forecast model:

1. Oil sand extraction creates two types of waste deposits: sand deposits that are solid, and fluid tailings deposits that must be contained. Waste derived from “average” ore is 75% sand and 25% fluid tailings (MFT).
2. For average ore the void space in the sand is almost equal to the volume of fluid tailings.
3. Fines capture in the void space of sand is important:
   a. Fines captured in the sand displace water and thereby reduce water loss.
   b. Fines captured in the sand are not available to make MFT in the pond.
4. Low grade (high fines) ore yields less bitumen, creates considerably more MFT, consumes more water, and results in higher heat loss than high grade ore.
5. Methods of reducing the amount of MFT include:
   a. Reduce clay dispersion in the extraction process.
b. Increase the density of the waste slurry discharged from the plant.

c. Increase the density of MFT.

6. Heat loss is proportional to the amount of hot water discharged from the plant. It can be reduced by densifying the waste discharge stream (capture and recycle process water with the contained heat).

7. Water loss equals the amount of water trapped in sand voids and in MFT. Water surplus to those needs is available for recycle to the plant. Water loss can be reduced by densifying the discharge stream (noted in 6 above) and by reducing the creation of MFT (Item 5 above).

8. The model forecasts that most of the unrecovered bitumen will concentrate in the pond. Bitumen follows water to the pond, and the water is then recycled.

9. If MFT is densified to a solid state, the % bitumen by weight could rise to 11% and the volume to 17%. If tailings also includes asphaltenes, the above numbers could double. That suggests that serious consideration should be given to recovering bitumen if MFT is reprocessed.
B.9 Tailings Dams

B.9 Tailings Dams

B.9.1 Introduction to tailings dams

Building containment structures to hold fluid waste is an important part of tailings management.

Tailings dykes are massive structures. Typical dimensions of the tailings facilities are shown in Table B.6

Table B.6 Typical dimensions of tailings dykes.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>50 to 100 metres</td>
</tr>
<tr>
<td>Crest width</td>
<td>50 + metres</td>
</tr>
<tr>
<td>Side slope</td>
<td>1:4 with good foundations</td>
</tr>
<tr>
<td></td>
<td>1:15 over poor foundations such as the Clearwater Formation</td>
</tr>
<tr>
<td>Footprint</td>
<td>1,500 hectares and above</td>
</tr>
</tbody>
</table>

The dykes provide space to store sand, so dimensions can be quite generous.

At the start of a project waste is placed on surface until there is room to place it in-pit. Table B.7 shows highlights of the surface pond proposed in the Shell Jackpine application (Albian Sands, 2003).

Table B.7 Highlights of the Jackpine surface tailings pond.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Design life of active phase</td>
<td>6 years</td>
</tr>
<tr>
<td>Footprint</td>
<td>1,600 hectares</td>
</tr>
<tr>
<td>Dyke height</td>
<td>50 m</td>
</tr>
<tr>
<td>Holding capacity</td>
<td></td>
</tr>
<tr>
<td>Fluid tailings</td>
<td>278 million m³</td>
</tr>
<tr>
<td>Beached sand</td>
<td>171 million m³</td>
</tr>
<tr>
<td>Compacted dykes</td>
<td>115 million m³</td>
</tr>
<tr>
<td>Total</td>
<td>565 million m³</td>
</tr>
</tbody>
</table>

Dykes are often constructed of sand using the construction cells described earlier. Sand accumulates in the construction cell and is compacted by dozers. Fine grained material remains in suspension and flows to the tailings pond.

Figure B.19 shows a tailings dyke constructed using the centreline method. Figure B.20 shows the upstream method of dyke construction.
With centreline construction all material downstream of the centreline is accumulated in construction cells and compacted. Material placed on the pond side of the centreline is pumped onto a beach, but is not compacted. Material that is not used in cell construction is discharged onto beaches.

With upstream construction the external face of the dyke is constructed of compacted cell sand. Sand placed on the pond side is beached but not compacted. As the dyke grows higher the compacted face shifts upstream. Eventually that places it above uncompacted beach sands. The advantage of the upstream method is a lower cost and a permanent external face that is ready to be reclaimed. The disadvantage is a potentially poor foundation. There is a risk that sand deposited under water will...
experience liquefaction. In addition, the poor foundation may prevent raising the dyke above the design level in the future. Dyke raising is common with oil sand tailings ponds.

### B.9.2 Constructing with overburden instead of sand

Sometimes overburden or mine waste, instead of sand, is used to build dykes.

Figure B.21 Indicates changes in design that are required when overburden is substituted for sand.

Construction with overburden is more expensive than building with sand. Activities that add to the cost of constructing earth structures with overburden vs. sand are summarised in Table B.8.

Table B.8 Additional costs incurred when overburden is used to build dykes instead of sand

- Earth dykes are more complicated than those built of sand (Fig. B.21).
- Must inspect and identify suitable material for construction at the borrow source.
- Must selectively load construction material for transport.
- Transporting the select material to the construction site involves:
  - extra haul distance and
  - transport by truck instead of by pipeline
Place material where needed.
Compact material (probably by driving 400 ton trucks over it).
With no beach there will not be any fines capture. That could increase the MFT by 30%.

The added cost of the preceding steps could be a few dollars per cubic metre of construction material.

**B.9.3 Constructing retention facilities in-pit.**

Dykes are needed to separate waste storage from mine operations in-pit. Figure B.11. showed how tailings and mining work together at Syncrude (Fair, 2008).

Not all waste is fluid. Figure B.22 illustrates the difference in approach used to store fluid waste vs. material that is strong enough to be self supporting.
B.10 Processes to densify MFT

Appendix B.4 describes Soil Properties and Behaviour. It supplements information provided in this chapter and is recommended reading. The novice may wish to read it before reading this chapter.

B.10.1 Direct treatment processes

MFT is a liquid that will require confinement and support until it becomes a self supporting solid.

Figure B.23 summarizes the behaviour of a suspended solid as the solid content changes.

Data plotted on Figure B.23 Include

1. The solid content increases from low values with liquid like properties at the top of the page to solid material with strength at the bottom of the page.
2. Horizontal bars across the page represent the relative amount of water and solid corresponding to the solid or water content indicated.
B.10 Processes to densify MFT

3. The middle column describes behaviour of a settling solid as it progresses from a liquid to a solid.
4. The column on the right describes mechanical processes that can be used to densify materials like MFT and indicates the range of effectiveness of each.
5. The column on the left shows natural processes that densify suspensions. It also indicates the water content of MFT and the target for solid MFT.

**Horizontal bars** represent the void ratio of corresponding material. The void ratio is defined as the volume of voids per unit volume of solid material. The top bar corresponds to suspended solids entering the tailings pond. It has a solid content of 5% to 10% and a void ratio of 24. That means 24 volumes of water per unit volume of soil.

MFT is shown, with a solid content of 30% and a void ratio of 6.

The target material for reclamation as a solid material has a solid content of about 30% and a void ratio of about 1.5.

**B.10.2 Behaviour as MFT densifies**

**Middle column - behaviour**

The middle column describes the behaviour as a material changes from a dilute slurry to a solid strong material. At the top of the chart particles experience free settling in water. The next state is hindered settling as particles become more numerous and interfere with each other. Finally at about 30% solids settling stops because repulsive forces between particles prevent a denser packing.

30 % solids corresponds to MFT where a soil skeleton and the beginnings of strength develop.

With increasing density, strength develops and the behaviour progresses from liquid, to plastic, to solid behaviour. The liquid limit and plastic limits define the water content between those zones.

**B.10.3 Mechanical processes**

The column on the right of Figure B.23 progresses from gravity settling to mechanical processes that are listed in order of capability.
B.10 Processes to densify MFT

Thickener operations
Thickener operation usually involves dilution to about 10% solid to separate suspended particles in a large diameter tank. A flocculent is added to draw the particles into agglomerates that behave as larger particles. Gentle stirring by rakes at the base of the thickener, sometimes aided by sand addition, and by the weight of overlying material forcing flocked material to the outlet in a conical base aid densification. The normal processing yields a density of about 30% solids. Higher densities are reported but may be due to the addition of sand. As noted in Section 4.1 of Appendix B.4, adding sand adds to mass and to volume but not to strength at low sand to fines ratios.

The typical residence time in a thickener is half an hour. It takes a few years to achieve the same density in a tailings pond. The advantage of the thickener is that it recovers process water, with its contained heat, that can then be recycled and reused. Another advantage of the thickener is that it densifies the plant’s tailings outlet stream. That enhances fines capture in sand deposits. The captured fines are not available to make MFT.

Super flocculating agents may achieve higher densities – but are approached with caution in case the presence of the super floc in return water adversely affects extraction. (Gu, 2009).

Filter belt
A filter belt is a porous belt. In operation a sand blanket is placed on the belt. Then fines are treated with a coagulant and placed on top of the sand blanket. The coagulant releases water from the fines. Suction applied to the bottom of the belt removes water from the material being treated. The suction force is not great but it only has to act on a narrow thickness of material.

Filter belts have been proposed (Fine Tails Consortium 1995e) but have not been used in commercial oil sand processing. Concerns: very large areas of belt are required to process large tonnages of fines. In addition, bitumen from extraction could easily clog the belt.

Filter press
A filter press exerts a high mechanical force on a small area to compress solids and force fluid from them. They are relatively small units so have not been used in oil sand processing.

Centrifuge treatment
Centrifuges apply thousands of times the force of gravity to extract fluid from material. The outlet streams yields solids at a density of about 60%. The other stream yields water, bitumen, and a minor amount of fines.
B.10 Processes to densify MFT

Centrifuges are used extensively in oil sand froth treatment. They have not been used commercially to process MFT. Centrifuges have been successfully piloted in demonstration plants (Fair, 2008)(Logan et.al. 1984). However, testing at full scale is needed to properly evaluate the potential of this technology.

Brute force heating
The highest level of man-made densification involves brute force heating. It is too energy intensive and expensive to consider.

The preceding technologies offer a progressive approach to dewatering fines. Two cautions:
- Sand addition can add to density without affecting strength and needs to be understood.
- Chemical aids can lower the liquid limit, and in turn change solid content at the target strength.

B.10.4 Natural processes.

The left column of Figure B.23 shows natural processes that densify fines.

Sedimentation
Dilute suspensions are densified by natural settlement and sedimentation. A settling particle passes from a dilute suspension where it is unaffected by neighbours, to a transition zone where other particles hinder settlement. When the density reaches 30% solids interference and repulsive forces between particles halt further sedimentation. That material is known as mature fine tails or MFT.

Consolidation
Consolidation processes are described in Section 6 of Appendix B.4. Current methods of placing MFT do not aid consolidation. It is not likely to work in time unless supplemented by wick drains.

Suction processes
Natural processes are capable of exerting suction to densify a deposit of MFT. Under ideal conditions, suction as high as -10 atmospheres can be exerted through drying, hydroponics, freeze-thaw, or by adding “dry” swelling clay. Application of such large forces is enough to compress a fine grained soil to a dense, strong state.

Drying treatment involves removing surface water and letting the exposed solid dry out. The treatment is a surface phenomenon so only thin layers (e.g. 20 cm thick) can be treated and repeated through the
B.10 Processes to densify MFT

summer. The site is sloped to facilitate surface drainage. Large areas are required to treat large quantities.

Hydroponics involve using plants to exert suction on a deposit of fines. The plants can process a deeper profile of material – but are still limited by thin surface effects and the very limited growing season in Fort McMurray.

When a soil freezes water is attracted to the freezing front where pure ice forms. The suction exerted overloads and collapses soil structure. When the material thaws, ice melts and the water is drained off before it can be reassimilated in the soil. A significant thickness of material can be treated by freeze/thaw if the processes is repeated on top of a previously frozen layer. The limit of how much can be treated per year is probably related to how much can be thawed the following summer – several metres.

‘Dry’ swelling clay would like to absorb more moisture. If blended with MFT it will extract water until the water content of the two materials reaches a state of equilibrium. The drying capability of this technique is quite high, and ‘dry’ swelling clays are abundant in overburden in the mineable oil sands area. This process is not a surface phenomenon so can be applied to any thickness of material.

The main application for densification by blending with swelling clay may be removing the last bit of water required to meet strength targets.

The preceding list shows mechanical and natural processes that can densify fines. It is unlikely that mechanical processes alone will be able to achieve the density desired for solid waste. Natural processes will have to be used as the finishing process.

The sodium adsorption ration of material proposed for treatment by suction based processes that rely on natural water runoff. (see Appendix B.4). Soils with a high sodium adsorption ratio are highly erosive so will tend to be removed by runoff water.

It is unlikely that there will be one “Silver Bullet” to meet all densification needs. It is more likely that a progression of processes should be used – with each working in the zone in which they are most effective.

B.10.5 Mixtures – Paste and CT
B.10 Processes to densify MFT

This section described combined processes that are used to densify MFT

Paste is a blend of coarse and fine grained tailings material. Paste is non segregating over a range of mixes and that property is used to advantage in transportation, deposition and consolidation of tailings.

The use of non segregating mixes is changing tailings practice. CT is a non segregating mix and is described below.

The CT process was developed at the University of Alberta in the late 1980’s (Caughill et al., 1993). It meets the miner’s dream – of creating a product that can be pumped to the disposal site. At the disposal site CT releases surplus water and consolidates to a solid state suitable for reclamation. At least that’s what operators hope will happen.

Some operators use variations of CT and call it Non Segregating Tails or NST. The processes are similar.

CT is created and used as follows:

- MFT is treated with a coagulant (gypsum) and then blended with sand.
- The blend creates a non segregating mix for sand to fines ratios over the range of 3 to 6.
- The resulting slurry is a non segregating blend that can be pumped to its disposal site,
- At the disposal site it flows to its final resting place, again without segregating,
- In-place the deposit slowly releases excess water. Initially it releases excess water, and then water released by consolidation.
- A five meter surcharge of sand is applied at surface to accelerate consolidation and to provide desired strength in the upper layers.
- In time, the deposit consolidates to a strong, self supporting solid.

Table B.9 shows the relative volumes associated with CT manufacture.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Volume m(^3)</th>
<th>Solid Content</th>
<th>Sand/fines ratio</th>
<th>Time to consolidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFT</td>
<td>1.00</td>
<td>30%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>1.27</td>
<td>72%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CT slurry</td>
<td>2.27</td>
<td>57%</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>CT deposit</td>
<td>1.27</td>
<td>80%</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Water release</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated time to consolidate</td>
<td></td>
<td></td>
<td>4.0</td>
<td>10 years</td>
</tr>
</tbody>
</table>
B.10 Processes to densify MFT

| Estimated time to consolidate | 5.0 | 5 years |

CT deposits are fluid so require containment for several years - until they consolidate to become solid self supporting deposits.

Despite many years of commercial use that has produced tens of million cubic metres of CT the process is still under review. Apparently operators have experienced difficulty making, transporting and placing on-spec CT. According to Houlihan et. al. (2008), after 10 years of commercial use, Suncor only achieved 20% of planned production in 2005.

The CT process is an important part of many commercial applications. However, there is a severe lack of public information about the research behind the concept, how it is supposed to work, the target strength for processed material, operating performance, what success indicators are being used, and the probability of success.

Azam and Scott, (2005), developed a Ternary Diagram to map the behaviour boundaries of a non segregating mix. It is a three dimensional plot of sand, fines and water components illustrated on Figure B.24.

![Figure B.24 Ternary diagram for characterizing behaviour of soil slurries](image)
B.10 Processes to densify MFT

Boundaries that can be mapped on the Ternary diagram include:

- The sand matrix,
- The fines matrix,
- Where sedimentation occurs,
- D=segregating vs. non segregating mixes,
- Pumpable vs. non pumpable mixes,
- Saturated vs. non saturated mixes.

For CT manufacture the boundary of greatest interest is the boundary between segregating and non segregating mixes. That defines as mix of materials that can be pumped, deposited and allowed to consolidate.

The Ternary Diagram may be an oversimplification of material properties. A new chart is needed whenever the clay content or clay activity changes in the fines represented.

Table B.10 summarizes concerns with the CT processing option.

Table B.10 Concerns with the CT processing option

- Demand exceeds sand supply
  - The desired sand to fines mix is 4 and 5.
  - The sand to fines mix of ore averages between 4 and 5.
  - An operating efficiency of 100% would be required to process all MFT.
  - A supplemental source of sand will be needed to treat the stranded MFT inventory or
- Require another process to finish the job.
- CT requires containment until it consolidates. Containment is expensive.
- Attempts to assign all sand to CT production are counter productive
  - Requires dyke construction with overburden – much more expensive
  - Lose benefit of fines capture in sand – that may increase MFT make by 30%
  - Lose safety features that beaches add to retaining structures.
- CT performance after 10 years of commercial operation has not been disclosed.
- Sulphate addition may be food for bacterial action – undesirable.
- Concerns that the treatment is reversible have not been answered in public.
B.11 Storing MFT under a water cap

B.11.1 Permanent storage under a water cap

In 1992 Syncrude proposed to solidify MFT using CT technology and to permanently store surplus fluid tailings under a water cap.

Several early papers describe the concept and studies undertaken to confirm its suitability. (Nix et al, 1988), (Boerger et al, 1990), (MacKinnon et al, 1991), (Boerger et al, 1992), (Gully et al, 1993), (MacKinnon et al., 1995), The papers are found in diverse publications. Most of the authors are closely related to projects that stand to benefit from the practice.

A key requirement noted in the early papers is that there should be no mixing between the MFT and the overlying water cap. The papers explored possible mixing by the action of surface waves, and the design depth of the water cap was set to at 9 metres to prevent such mixing. The researchers concluded that gas evolution from biological activity was unlikely!

In the mid 1990’s methane producing bacteria became active in Syncrude’s Mildred Lake Basin and vigorous bubbling has been ongoing since. Limited research recognize the bacterial activity and note that it could affect the viability of the permanent storage scheme. (Holowenko, 2000), (Li, 2008). Different bacteria are active, consuming different food (naphtha (solvent loss), sulphate (used in CT), and sodium citrate (added at Albian Sands to aid extraction). The author was unable to locate publications that show why gas release from bacterial action should not be a concern.

Syncrude showed the viability of storing MFT under a water cap in small pits. The demonstration pits preceded biological activity. A full scale test is planned in the Syncrude base mine lake starting in 2012. The experiment will involve placing process affected water on top of MFT and observing behaviour over the next decade. Further details have not been disclosed.

The most recent publication on the end-pit-lake concept provides an update on the concept and research (Clearwater Consultants, 2007). The paper quoted Syncrude references extensively. It notes that it may be decades or longer before the end-pit-lake will qualify for a reclamation certificate. It did not even mention biological activity – or standards that govern safe locations for perpetual storage of fluid waste. Those factors really need to be addressed. One aspect of a suggested guideline for safe sites for permanent storage of fluid tailings is provided in Figure B.25.
B.11 Storing MFT under a water cap

Sethi suggests that that ongoing bubbling represents a state of flux. He suggests that bacteria should be put into a dormant state. (Sethi, 2009).

Fig B.25 Suggested offset to protect against long term gully exposure

Challenges:

1. There is no public documentation on criteria for a safe surface storage site to hold contaminated fluid in perpetuity. Two suggestions for site selection:
   a. Must not be located on a site where groundwater could discharge at surface. Most locations near the Athabasca River are potential groundwater discharge sites.
2. The site should be safe from future exposure by eroding gullies. A suggested safe geometry Indicated on Figure B.25. Fluid should not be stored above a line sloping upward from an adjacent stream or from the Athabasca River base level. The inclination of the sloping line should be set be qualified professionals (geographers, engineering geologists) and their view of the potential for long term gulley erosion. The author suggests that in sandy soil the expected slope should be 1% or less.
3. There is limited public peer reviewed documentation discussing the concept, of recent verification programs, or of contingency plans.
B.11 Storing MFT under a water cap

4. Biological activity in the fluid tailings emits considerable gas capable of mixing fluid tailings with overlying water. Little if any public disclosure of field performance and why developers consider this to not be a problem. Can we even predict future performance as long as gas emissions are ongoing?

5. Water release from consolidation has been taking place for 40 years. It has apparently increased by orders of magnitude since the biological release of gases shortened the drainage path for release of consolidation water. There is little if any public information on the rate of fluid emissions from fluid tailings.

6. In 1992 Syncrude proposed to solidify MFT using CT. Since then they have only treated 10% of the MFT created. What happened to the original promise?

7. Regulators have not approved permanent storage of MFT under a water cap. Instead they have advocated a solid trafficable landscape instead (Houlihan et al, 2008)

8. There is no public information on how financial assurance is being provided to ensure that stranded fluid tailings will be satisfactorily dealt with. The topic requires disclosure because the largest owner of Syncrude is a Trust with no other source of income to fund reclamation obligations.

B.11.2 End-pit-lake

At the end of operations the last mine opening will be used as an end-pit-lake. Runoff from site surface and groundwater will be directed to the end-pit-lake. Accumulated water will be monitored for quality, prior to discharge. Operators also plan to permanently store MFT in the base of the end-pit-lake.

It could be several decades before the water in the end-pit-lake will be ready for release. (Clearwater Consultants, 2007).

There is little public information about the end-pit-lakes. Key concerns:

- When will the concept be shared with public stakeholders.
- What is the expected quantity and quality of water that will enter the lakes.
- What storage capacity will be required to hold runoff until water can be discharged? Creating storage to handle decades of runoff a forecast by Clearwater Consultants could be a serious challenge.
- Are there plans to treat water if the end-pit lakes do not self cleanse?
- What are the contingency plans?
- How do we fund closure operations and contingency plans that will take place decades after the Operations and income are over.

The end-pit-lake proposal appears to be a high risk option. Adding MFT storage to the base of the lake adds an unnecessary complication.
B.12 World wide tailings management practices.

It is instructive to explore how the world wide mining manages tailings.

The keynote address at Paste 08, an annual international mine tailings conference, presents an unflattering summary of current international tailings management. (Boger et.al., 2008). Highlights of the keynote address follow:

- The minerals industry is the world’s largest producer of waste.
- There have been significant improvements in thickening and dewatering tailings that offer and potential savings in reclamation and environmental management costs.
- However, an emphasis on expenditure deferral promotes low capital tailings disposal solutions.
- Tailings storage facilities allow waste storage for a long period of time while deferring expenditure on reclamation until the end of mining.
- A large part of the industry still continues to pump low density material to very large disposal dams. The dams get bigger and bigger and represent a significant risk. They also represent a significant cost when the time comes to reclaim them.
- Concerns with tailings dams include a tendency to leak and a potential for catastrophic failure.
- Two standards govern financial reporting requirements: “US based Financial Accounting Standard 143: Accounting for Asset retirement Obligations (SFAS 143) and the International Accounting Standard 37: Provisions, Contingent liabilities and Contingent Assets (IAS 37). Both standards require that reclamation liabilities be recognized on the balance sheet as soon as the liability is incurred, and for the amount to be discounted. In addition SFAS ‘43 requires the estimate be increased by the theoretical cost of settling the liability with a third party in order to establish a market value for the liability.
  - Generally future reclamation liabilities are computed as follows:
    - The future cost of reclamation is determined by inflating current costs to the future date when reclamation might occur.
    - The future cost is then discounted back to today by applying a significant discount rate each year.
    - Discounting, over the long time frame typical of mining ventures, reduces the reclamation liability to a negligible amount.
  - Discounting is a systematic bias toward short term profitability.
  - Historically, industry-wide environmental improvements have been achieved through mandating requirements via regulation.”

Table B.11 summarizes some side effects of discounting over long periods of time.
Table B.11 Effect of discounting over long periods of time.

- Discounting severely reduces the apparent cost of future reclamation liabilities;
- Discounting justifies deferring reclamation and maximizing short term profits;
- Reducing the cost of future reclamation liabilities:
  - Reduces the need to set funds aside to meet future obligations,
  - Reduces the need to verify the feasibility of reclamation and closure plans,
  - Reduces the incentive for research to find a better approach,
  - Creates false short term profits that reward those who manage the discount deception.
- Building large inventories of fluid tailings creates risk of:
  - Accumulating larger and larger liabilities that will have to be dealt with in future,
  - Increases risk of seepage or catastrophic failure,
  - The developer being unable to pay for the reclamation,
  - Accumulated liabilities cause a premature halt to operations if they exceed future value,
  - Untested reclamation plans may not be feasible.
- The current approach is contrary to two underlying principles of the APEA Act (Alberta, 1993):
  - Failure to disclose reclamation technology and plans prevents Albertans from providing input to reclamation decisions.
  - Deferred reclamation transfers reclamation liabilities to future generations.
- The preceding actions are not what the public expects of responsible management.

Table B.12 summarizes side effects of booking reclamation as they occur.

Table B.12 Effect of booking reclamation liabilities they occur by funding a QET.

- Placing funds of equivalent value in a Qualifying Environmental Trust:
  - Recognizes reclamation liabilities as they occur
  - Discounting cannot reduce the value of the liability
  - The procedure sets funds aside to pay for future reclamation activities. It does not transfer liabilities to future generations.
  - Reduces the developer’s cost of reclamation. QET funding is an operating expense that triggers fiscal sharing. In the highly taxed oil sands industry that averages 50%.
  - Creates an incentive for progressive reclamation – as it has been paid for.
  - Progressive reclamation reduces stockpiled tailings with the associated risks.
  - Progressive reclamation reduces the need for financial assurance.
- With the value of the liability retained:
  - There is a strong incentive to verify reclamation and closure plans and their costs.
  - There is an incentive to invest in research to improve reclamation and closure plans.
- The preceding actions are compatible with the intentions of the AEPEA Act.
- The preceding actions are compatible with public expectations of responsible management.

Oil sand industry operators could improve their image by adopting the concepts behind Table B.12.


B.13 Screening technology options

B.13.1 Introduction

This section explores what is involved in screening tailings technologies. Topics include:

- Characteristics of mineable oil sand projects
- Typical steps involved in screening technology options
- Typical approaches to economic analysis and the implications to the screening process
- Examples
- Conclusions and recommendations
- About Qualifying Environmental Trusts
- Assigning costs to future reclamation obligations

B.13.2 Characteristics of oil sand projects

Mineable oil sand projects have unique characteristics that affect the appropriate approach to economic screening. Table B.13 summarizes some important characteristics of oil sand projects. Table B.14 shows the timeline for site use.

Table B.13 Characteristics of mineable Oil Sand Projects

- Large size,
- Long project life (up to 100 years),
- Large reclamation liabilities linked to production:
  - Land disturbance,
  - Fluid tailings,
  - Closure costs.
- Long time between when a reclamation liability is created and when it is dealt with:
  - Fluid tailings – currently 25 to 40+ years,
  - Land reclamation – currently 30 to 40+ years,
  - Closure activities - 50 to 100 years.
- Complex fiscal terms that involve capital cost allowances, Alberta royalty, Alberta and Federal income tax, and fiscal sharing of profits and expenditures. After pay-out, between 45% and 56% of profit and expenses is directed to governments,
- A high project rate of return is needed to justify the initial investment and to support the fiscal terms.

Table B.14 Typical time line for site use

<table>
<thead>
<tr>
<th>Year</th>
<th>Land use</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 2</td>
<td>Site preparation</td>
</tr>
<tr>
<td>2-20</td>
<td>Open pit mine</td>
</tr>
<tr>
<td>20-30</td>
<td>Site occupied by tailings pond</td>
</tr>
</tbody>
</table>
B.13 Screening technology options

| 30-40 | Solidify tailings |
| 40-50 | Reclaim surface |
| 100   | Site closure |

Information in Tables 1 and 2 was derived from Fair, (2008); Syncrude, (2006); and Syncrude, (2007). It shows that reclamation of tailings and disturbed lands can be delayed by 20 to 50 years. It also shows that closure activities can be delayed by up to 100 years.

B.13.3. Steps used to screen technology options

Steps in screening tailings technologies are outlined in Table B.15.

Table B.15 Typical steps to screen technology options.

1. Establish goals for the project e.g.
   - Reclaim tailings as a solid landscape.
   - Qualify for a reclamation certificate within a few decades after operations cease.
2. Identify candidate options that will achieve those goals.
3. For each option:
   a. Identify plans to use the option through development, operations and closure.
   b. Identify full life-cycle capital and operating costs associated with the above. (If we are comparing options we only need to identify cost differences.)
   c. Conduct an economic assessment.
   d. Appraise the probability of success.
4. Choose the option that will most economically meet project goals.

Projects spend considerable effort exploring the viability of different technologies and the probable cost vs. time. Equivalent effort should be spent evaluating the economic evaluation process because it can have a major effect on the outcome of screening studies.

B.13.4 Characteristics of economic analysis

Economic evaluations appraise the cash flow over the life of a project. They convert future expenditures to today by applying discounts. All economic evaluations apply some form of discounting to future income or expenditures to convert them to present value.

Figure B.26 shows the effect of discounting to determine the present value of future obligations. The plot shows a rapid drop in value with time. Loss is greatest when high discount rates such as 20% or 30% are applied over long periods of time. They reduce the value of future obligations to near zero in 20 to 30 years.

Traditional economic evaluation of tailings options would combine the trends of Figure B.26 (effect of high discount rates) with the trends of Table B.13 (long time spans). The combination significantly
B.13 Screening technology options

reduces or eliminates future expenditure obligations. That means that decisions about the suitability of tailings options are made without consideration of future expenditure obligations.

![Figure B.26 Effect of Discount Factor and Time](image)

Table B.16 lists three approaches to economic screening that were used to evaluate tailings options in Part A of this report.

Table B.16 Three economic screening methods used to evaluate oil sand tailings options.

1. Compare the undiscounted cost differences vs. time for each option.
2. Compare the undiscounted cost differences vs. time considering:
   a. Cost vs. time as in method 1 above.
   b. Recognize the value of reclamation obligations as they are created.
   c. Deposit an amount equivalent to the reclamation liability as it is created in a Qualifying Environmental Trust as reclamation liabilities are incurred. Funds can be withdrawn as reclamation is undertaken.
3. Finally, compare leading contenders in a project economic model that duplicates the project financial environment. The model considers all applicable fiscal terms such as Alberta royalty, capital cost allowances, and income tax.

Net present value comparisons is often used instead of undiscounted costs. Net present value analysis applies discounting. As Figure B.26 shows discounting over long periods of time distorts and diminishes the value of the parameter under study. Discounting does not reduce future obligations if method 2.c above is used. Placing funds in a Qualifying environmental Trust retains the value of the reclamation.
B.13 Screening technology options

Method three is required to verify that the conclusions of simple screening test still apply to the complex fiscal environment that applies to oil sands projects.

Appendix B.1 contains electronic models that allow user input to evaluate technology and operating options. Models and spread sheets include:

- A spread sheet for each tailings technology studied in Report A. Information includes material balances, site activity, work, capital and operating costs vs time for each technology. Capital and operating costs are suggested but the user can input their own value for capital and operating costs if desired. Technologies are ranked by comparing the unit cost of processing one cubic metre of ore.
- A full project economic model is provided. It addresses royalty, capital allowances, provincial and federal income tax to represent the complex fiscal environment that oil sand projects operate in. Tailings technologies are compared by entering technology specific capital and operating costs vs time in the model while other aspects of the business are held constant. Comparison of the overall project rate of return for each technology indicates economic performance. Input parameters are suggested but the model allows users to input their own data if desired.
- A tailings forecast model is provided. It allows user defined input to evaluate the effect of different material or operating parameters on tailings output.

The models and spread sheets show trends. They are provided to help the user understand the rationale used to appraise the different tailings technologies. The models should also help the user understand the many interactions involved in evaluating tailings performance.

1.

B.13.5 Results of screening studies

Screening tailings technologies

Figures A.19 and A.20 from Section A of this report are repeated below. They show the effect of screening cost differences using undiscounted unit costs. Net present value comparison yields the same trends if method 2.C of Table B.16 is used (fund a qualifying environmental trust)
Figure A.19 compares undiscounted unit cost for the different tailings technologies. Environmental costs are not included because traditional economic analysis discounts them the trivial amounts. This method favours options on the left – that postpone spending, stockpile fluid tailings, and in so doing, transfer environmental obligations to future generations. The favoured technologies do not prepare the project for closure.
B.13 Screening technology options

Figure A.20 compares undiscounted average unit costs that recognize reclamation obligations as they are incurred. That is accomplished by depositing funds equal in value to the reclamation obligation to a qualified environmental trust. This method favours the option on the right, takes care of reclamation obligations on an ongoing basis, and avoids transfer of environmental obligations to future generations. The favoured technology advances the project toward closure.

**Screening options of when to process MFT**

Many oil sand developments plan to stockpile MFT at the start of operations. They plan to add facilities to treat the inventory of MFT after waste storage operations move in-pit.

Section A.4.4.3 of Report A dealt with the topic of adding MFT treatment facilities. It suggests that a plant is barely able to process fines generated inside the plant. The ability to process stockpiled MFT depends on the size of the stockpile and on CT processing efficiency in the plant.

The CT process has been used to treat MFT in commercial oil sand plants for over 10 years. Despite the long period of use public information on the CT performance, and on CT processing efficiency is not available. However, there are indications that industry has had significant difficulty meeting production targets. (Houlihan et. Al. 2008).

Public disclosure about historic CT performance is needed before developers can expect public acceptance of plans accumulate fluid tailings. The plans should be justified by economic assessment that recognizes reclamation obligations as they are created.

**B.13.6 Conclusion on screening options.**

Traditional screening of project options involves discounting cash flows over long periods of time. The combined effect of those factors seriously reduces future reclamation obligations. The results favours:

- deferring reclamation expenditures,
- approaches and technologies that involve high risk and are not preparing the project for closure,
- transfer of liabilities to future generations.

The traditional approach creates false short term profits, and rewards those who use this approach.

Screening methods that recognize environmental obligations as they are incurred favour different project options. They favour:

- ongoing reclamation,
- options that involve lower risk,
- technologies that prepare the project for closure,
- approaches that avoid transferring liabilities to future generations.

Projects should use screening methods that recognize reclamation obligations as they are incurred.
B.13 Screening technology options

B.13.7 Qualifying Environmental Trusts

Qualifying Environmental Trusts (QET) are formal trusts allowed under federal law. The Trusts are created to accept deposits to cover future reclamation obligations.

Deposits to qualifying environmental trusts are recognized as operating expenses. With the fiscal terms that apply to oil sands projects, that means that governments and the developer will share in the cost of making the deposit to the QET.

Funds used for legitimate reclamation activities can be withdrawn from the Trust tax free.

Interest earned by the Trust is taxed as income to the developer. That is an incentive for the developer to accelerate reclamation, and reclaim the deposits at an early date.

B.13.8 Assigning a value to future reclamation costs.

Table B.17 suggests how the cost of reclamation obligations should be determined.

Table B.17 Assigning a cost to reclamation obligations

1. Reclamation obligations start when the liability is created – not when reclamation funds are spent;
2. Reclamation plans should use technology that is proven today:
   - Information about how the technology works, and how it was proven should be available in public peer reviewed technical journals – preferably Canadian;
   - The person advocating the technology must be professionally qualified to do so.
3. Cost – assume today’s cost for work performed by an independent third party:
   - Verified by public disclosure of operating experience,
   - Verified by an independent third party audit if requested.
4. Uncertainty – costs should increased to account for uncertainty
   - Add a factor to account for uncertainty over:
     i. Viability of technology,
     ii. Accuracy of costs,
     iii. Viability of reclamation and closure plans,
     iv. Work after operations cease – no income, no fiscal offset so the cost to the operator doubles.
B.14 Oil Sand Tailings R&D

B.14.1 Introduction to tailings R&D

A thorough review of research needs for oil sand tailings is not part of the current assignment. Documentation on recommended activities is available in the Oil Sands Technology Roadmap (Alberta Chamber of Resources, 2004) Flint, (2005), and the web site for the Oil Sands Tailings Research Facility in Devon.

The intent here is to review how research takes place, who does it, at what scale, how it is funded, and the overall effectiveness.

A list of suggested R&D topics is provided in Appendix 5.

A specific program for centrifuge testing is also provided in Appendix 5.

B.14.2 Incentive for R&D

The following types of R&D are needed for tailings management and planning:

- Fundamental understanding of how processes work so the optimum system can be developed.
- Tests to verify understanding of processes and to provide data for scale-up.
- Demonstrate tests to verify performance and costs at commercial scale.

New tailings technology requires thorough screening before it can be used. Processes must be screened to ensure that they do not have an adverse effect on bitumen extraction. If there is an adverse effect on extraction, the cost of lost production could be immense.

A second area requiring extensive research involves reclamation and closure plans and the technologies involved. Projects need clear goals for closure so effective research can find the optimum path to reach those goals. Otherwise, they could accumulate stranded fluid tailings that will be expensive to correct.

Projects that last 100 years must not be guided by flawed economic procedures that discount future obligations. As the previous chapter showed, discounting over long periods of time can cause future obligations to diminish and disappear. Projects are unlikely to find the right path to closure if the business model trivializes closure costs.

Reclamation and closure of a system that moves one million tonnes of material per day is very expensive. It is essential that the path forward be well understood and lead to timely closure. It will be very expensive to change the path at a later date.
14.3 Suggested project goals for tailings R&D

The writer is unaware of published project goals for oil sand research. *If you don’t know where you are going, you will probably end up somewhere else.* Suggested goals, that reflect today’s expectations, are noted in Table B.18.

Table B.18 Suggested project goals for tailings R&D.

1. Qualify for a timely reclamation certificate. - within 20 years after operations cease.
2. Reclaim fluid tailings as a self supporting solid; or, justify an alternative approach.
3. At an early date, confirm, and continually reconfirm, that current reclamation and closure plans are viable and represent the most effective path forward.
4. At an early date, confirm the viability of key technologies that the plans rely on.
5. Conduct large scale tests to demonstrate that plans work and at what cost.
6. Use progressive reclamation to limit accumulated liabilities.
7. Research lower cost alternatives.
8. Comply with the intent of the Alberta Environmental Protection and Enhancement Act:
   a. Accept responsibility for all disturbances and reclaim them responsibly.
   b. Qualify for a timely reclamation certificate.
   c. Allow Albertans to input on matters affecting the environment.
   d. No intergenerational transfer of liabilities.
   e. Provide financial assurance that funds will be available to meet requirements for a reclamation certificate.
9. Gain public support for plans by:
   a. Clear public disclosure of reclamation and closure plans, contingency plans, the technologies involved and indicate how reclamation will be paid for.
   b. Public disclosure of key technologies in peer reviewed technical journals - preferably Canadian.
10. When unexpected behaviour is encountered that challenges the feasibility of current plans, promptly research the behaviour and publish conclusions that verify continuation of current plans, (e.g. effect of biogenic gas emissions from MFT). Alternatively, outline contingencies.

Finally we should look at suggestions from external sources. Suggestions from A. Sethi (Sethi, 2009) are presented here because they do not appear to be considered in current efforts on fluid tailings research:

1. Processes must meet performance standards under anaerobic as well as aerobic conditions. (It is difficult to appraise anaerobic conditions in laboratory experiments and small pilot facilities).
2. Create an environment that promotes attraction between solid particles, so strength can develop in a short period of time.
3. Restore bacterial action to a dormant state.
4. MFT treatment must not be reversible.

The preceding guidance is long winded but, in the author's view, is needed.

14.4 Characteristics of tailings R&D

The following Tables characterize tailings R&D.

Table B.19 lists the types of research needed for oil sands tailings. The scope progresses from small to
very large.

Table B.20 lists the players, the role of each and their source of funding.

Table B.21 describes the cost of tailings research. After fiscal sharing, SR&ED income tax credits, shared costs through cooperative programs and possible grants, the public pays most of the cost of research, even on large commercial demonstration tests.

University research related to oil sands is guided by industry advisors. Oil sand related research programs listed on the Oil Sand Tailings Research Facility web site is impressive. Much of the university research is funded by the government - i.e. the public.

Table B.19 Types of oil sand tailings research

<table>
<thead>
<tr>
<th>Type</th>
<th>Scale</th>
<th>Purpose</th>
</tr>
</thead>
</table>
| Desk studies                              | Small to large | • Develop understanding  
|                                           |             | • Screen options  
|                                           |             | • Scope research programs                                 |
| Bench scale                               | Small       | Verify predictions                                        |
| Pilot                                     | Intermediate | Verify predictions  
|                                           |             | Measure performance  
|                                           |             | Information for demo design                              |
| Field pilot/demonstration                 | Large       | Verify performance  
|                                           |             | Information for commercial design                         |
| Commercial demonstration                  | Very large  | Verify prediction and performance  
|                                           | E.g. Syncrude 5 million m³ CT demonstration  
|                                           | Proposed test to evaluate the feasibility of permanently storing MFT under a water cap.  
|                                           | 20 years after first proposed  
|                                           | Will last for over 10 years and involve 200 million m³ of MFT  

Table B.20 Research players, their role, source of funding

<table>
<thead>
<tr>
<th>Who</th>
<th>Role</th>
<th>Source of funding</th>
</tr>
</thead>
</table>
| Project staff - research   | • Research to facilitate understanding  
|                           | • Design, execution, and interpretation of verification tests  
|                           | • Trouble shooting  
|                           | • Interact with external researchers                                  | Project financing  
|                           |                                                                      | May be aided by research grants                                                  |
Table B.20 Research players, their role, source of funding (continued.)

<table>
<thead>
<tr>
<th>Project staff – operations</th>
<th>Government researchers Fundamental research</th>
<th>Government researchers Contract research</th>
<th>Independent research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manage pilot and verification tests</td>
<td>Plan, execute and interpret fundamental research programs, Identify operations needing improvement, Add to knowledge base, Check on direction of projects, Advise regulators</td>
<td>Advise projects, Undertake specific programs for projects</td>
<td>Usually focus on near term improvements</td>
</tr>
<tr>
<td>Identify operations needing improvement</td>
<td></td>
<td></td>
<td>Self financing Research Grants</td>
</tr>
<tr>
<td>Develop cost data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project financing May be aided by research grants</td>
<td>Government funding</td>
<td>Project financing May be supplemented by matching funds from government.</td>
<td></td>
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Table B.21 How R&D funding is subsidized

Project funding is subsidized by:

- Fiscal offsets that, after project payout amount to 45% to 56% of project costs,
- Some research projects qualify for royalty offsets,
- SR&ED income tax credits,
- Fund matching if government research facilities or granting agencies are involved,
- University research may be guided by industry advice while paid for by the government.
- The net result is that oil sand projects only pay 25% to 50% of the cost of research and development. The public, via government funding and fiscal sharing, pays the rest.
B.14 Oil sand tailings R&D

B.14.5 Large scale tailings technology research

Table B.22 lists major tailings technologies that have been evaluated in large scale field tests.

Table B.22 Major tailings technologies studied in large field pilot programs.

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<thead>
<tr>
<th>Developer</th>
<th>Large tailings research programs</th>
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<tr>
<td>Syncrude</td>
<td>Maintain a large research facility</td>
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<td></td>
<td>Tailings technologies studied in large scale field tests (Fair, 2008)(Lahaie, 2008):</td>
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<tr>
<td></td>
<td>• Sand stacking</td>
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<td></td>
<td>• Thickener performance tests</td>
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<td></td>
<td>• CT demonstration and commercial operations</td>
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<td></td>
<td>• MFT under a water cap</td>
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<td></td>
<td>o Tested in field scale facilities</td>
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<td></td>
<td>o A full scale demonstration test is planned</td>
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<tr>
<td></td>
<td>• Use of swelling clay to solidify MFT</td>
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<td></td>
<td>• Freeze-thaw tests</td>
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<tr>
<td></td>
<td>• Accelerated reclamation (drying)</td>
</tr>
<tr>
<td>Suncor</td>
<td>Do not have a dedicated research facility but have field tested the following:</td>
</tr>
<tr>
<td></td>
<td>• CT commercial operations</td>
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<tr>
<td></td>
<td>• Freeze thaw tests</td>
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<tr>
<td></td>
<td>• Drying tests</td>
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<tr>
<td></td>
<td>• Thickener densification followed by deposition on a gradual slope to enhance runoff and solidification by drying.</td>
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<td></td>
<td>• Novel mining equipment that can process oil sand in the mine and avoid transportation to and from the central plant.</td>
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<td>Shell</td>
<td>Have a large dedicated research facility</td>
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<td></td>
<td>• Have adopted thickened tailings for their commercial facility</td>
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<td></td>
<td>• Have a large field pilot facility</td>
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<tr>
<td>Imperial Oil</td>
<td>Have a large dedicated research facility</td>
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<td>• Researched low temperature, non caustic extraction and tailings</td>
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<td>Cooperative Research</td>
<td>Cooperative research programs are undertaken through organizations such as the Canadian Oil Sands Network for Research and Development, and the Petroleum Technology and Research Consortium. In addition to shared work programs the organizations host seminars to share information. The web site does not allow public access.</td>
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B.14.6 Independent Research

Many industries make good use of independent research. Our government expects there to be a role for independent research because government agencies such as the Alberta Energy Research Institute and
B.14 Oil sand tailings R&D

federal Industrial Research Program fund independent research. The oil sands industry makes good use of research facilities that use other peoples money but little use is made of private research facilities.

New Technology Magazine (New Technology, May, 2009) reports increasing frustration over the apparent closed door attitude of oil sand operations against new approaches proposed by outside researchers. Reasons for the closed door image are described in the next section.

Some novel third party technologies that should be appraised, and if successful, adopted include:

The Sethi-Strand process, (Sethi, 2009) - solidifies fluid tailings, while making some of the major contaminants insoluble. Use is not limited by the availability of sand.

R.J. Oil Sands (R.J. Oil Sands, 2009) use the turbulence of a jet pump to separate bitumen from slurries - including MFT. (Bitumen should be recovered if MFT is solidified.)

Gradek Energy (www.Gredekenenergy.com) offer oleophilic beads to extract bitumen or solvent from tailings waste streams. A technology is needed to remove solvent present in the tailings pond.

Centrifuge processing, described in the Part A report establishes a benchmark that industry is invited to beat.

It is not necessary for each candidate technology to repeat everything that an oil sand extraction facility does. Integrating key components may be more useful.

B.14.7 An illustration of the difficulty integrating independent research

The fictional story that follows illustrates why it is difficult to integrate independent technology.

From the inventor's point of view
An inventor is aware that commercial oil sand plants have large volumes of fluid tailings that should be solidified before the land can be reclaimed.

The inventor obtains funding to develop a process to solidify fluid tailings. An "angel" investor provided most of the funding that was supplemented by funding from a government agency. In addition the inventor contributed years of his own time.

The inventor developed a novel process that solidifies fluid tailings and recovers bitumen contained in it. Anticipating 2% bitumen in tailings the expected bitumen recovery is one 6th of a barrel of bitumen per cubic metre of tailings processed. The process is protected by patents owned jointly by the inventor and the "angel" investor. The angel investor would like to license the process to a commercial project at a rate that provides a risk adjusted return on his investment.
B.14 Oil sand tailings R&D

The inventor seeks an opportunity to demonstrate the process at a commercial oil sand facility. In an honest discussion with the commercial facility he expresses his expectations that include:

- Support for a test to demonstrate the ability to solidify fluid tailings and to recover bitumen.
- If the test is successful the inventor will license the technology to the oil sand project. The oil sand operator will bear the cost of constructing and operating the facility and will pay a royalty equal to the perceived value of the bitumen recovered - about $50 per barrel.

The operator of the commercial plant suggests that a price of $5 or $10 per barrel of bitumen would be more realistic.

The inventor leaves, convinced that big business is gouging him and convinced that the operator has no real interest in reclaiming fluid tailings. The "Angel" is similarly convinced that this is a poor place to invest and withdraws funding support.

From the oil sand operator's point of view

The operator believes that the inventor does not understand the complexity of an oil sands plant and how the invention might fit into it. Factors that the inventor does not understand:

- The developer has invested in an integrated production facility.
- Bitumen production is designed to keep the upgrader supplied with bitumen.
- The posted operating cost for the integrated facility is $35 per barrel of synthetic oil.
- The cost of producing bitumen is one third of the total or about $12 per barrel.
- Each barrel of bitumen received from other sources idles the operator's installed facilities.
- The quality of bitumen produced from the inventor's facility has unknown properties that pose a risk to upgrading. Any adverse impact on production from the integrated facility has real cost implications so must be avoided.
- Potential problems from the inventor's bitumen:
  o Process aids used in the inventor's process could affect extraction and/or upgrading.
  o Production continuity is unknown. The project's idled facilities must be kept on standby to replace any shortfall in production from the inventor's facility.
  o Recovered bitumen could be oxidized and not suitable for upgrading.
  o Recovered bitumen could contain solids that will have to be removed before the bitumen can be upgraded.
- The operator will probably reprocess the inventor's bitumen through his extraction plant to ensure that it is suitable for upgrading.
- Under the above circumstances the value of new bitumen to the developer is probably $10 per barrel at the most. The inventor has an inflated opinion of the value of his bitumen.
- It is difficult for an operator to work with an inflexible licensed technology. It would be better if the project owned the technology outright so it could be changed and integrated with other plant components.
- Under the circumstances there is little room for an agreement here.
- The parties can help one another - but...
B.14 Oil sand tailings R&D

B.14.8 Effectiveness of Oil Sands Research Programs.

A lot of oil sand research is ongoing at the universities, government research facilities and at project facilities. Operators have tested the main technologies to densify MFT in field pilots.

Research effectiveness is irrelevant if industry refuses to improve its practice. So far, the results of research to density tailings are on the shelf and the inventory of fluid tailings grows. As one oil sand practitioner stated when asked about the fluid tailings challenge: "We know what to do. What we lack is management prepared to spend money".

Assuming that fluid tailings will be addressed in the near future, it is relevant to appraise the effectiveness of R&D programs. In the author’s opinion:

- Research and development programs suffer from a lack of clear goals, (see Table B.18)"
- Economic assessments of future options should not discount the future and remove the very topic under investigation. They should recognize liabilities by assuming that funds of equivalent value are placed in a qualifying environmental trust at the time the liability is created. Proper economic assessments are needed to guide research needs.
- Excellent research has probably been done. Unfortunately, results are not available to the public.
- The industry needs public support for its activities. Information about reclamation and closure plans, and technologies that the plans rely on should be documented in public, peer reviewed technical journals.
- Research is not effective if there is no public information on technologies that are key to the success of current closure plans. Examples of missing information:
  - Operating experience with CT technology. It was shocking to learn that Suncor was only achieving 20% of planned CT production after 10 years of commercial use. (Houlihan et.al., 2008).
  - Permanent storage of fluid tailings under a water cap is a key part of industry's plans.
    - Site selection standards assumed for permanent surface storage of contaminated materials.
    - Address and resolve issues associated with gas release from fluid tailings.
    - Several decades to qualify for a reclamation certificate mentioned in the latest paper on this option (Clearwater Consultants, 2007) appears unacceptably long and raises questions about how closure activities will be funded for several decades after income stops.
- The industry is closed to outside influence. That is unfortunate because it raises concerns about the potential for too much control. Internal practices that are amateur and inappropriate exist because staff lack exposure. (see Section B.A4.8.3 in Appendix B.4 on misleading grain size measurements).
- The industry is not making effective use of third party research. They should. Development of an independent body that can support projects in time of need could be very useful.
B.15 Summary and Conclusions

**Key findings:**

B.15.1 ABOUT PROJECTS AND PRACTICE

- Oil sand projects are big and becoming bigger. Three of the four existing commercial mineable oil sand projects are evolving into 100 year, 500,000k barrels per day projects.
- Production of each barrel of synthetic oil creates 0.26 cubic metres of fluid tailings.
- Fluid tailings has been accumulating since commercial production started. Today the inventory is 750 million cubic metres.
- To date no tailings pond has been reclaimed.

B.15.2 ERCB DIRECTIVE 074

- In February 2009 the ERCB issued Directive 074. It requires oil sand operators to begin solidifying fine tailings. The amount to be treated rises from 20% to 50% over the next three years. The target strength is a minimum of 5 kPa in the first year and a minimum of 10 kPa by year three.
- Directive 074 also requires operators to inventory their tailings ponds each year and report their observations annually.

B.15.3 ABOUT THE SOIL PARTICLES

Tailings are composed of sand, silt and clay. Soil properties are described in Appendix 4. Sand and silt are inert, equidimensional, coarse particles with frictional strength. Clays are very fine grained platy particles that interact with the surrounding water and ions, exhibit plasticity, and cohesive strength.

**About Fines and Clay**

Fines are particles finer than 44 microns. Clays are particles finer than 2 microns. The clay content of fines can range from 0% to 100%. Operators in extraction deal with "fines" and do not measure the clay content. That is unfortunate because it is difficult to forecast MFT volumes without the clay content.

B.15.4 BUILDING TAILINGS DEPOSITS

When tailings are discharged they form a sand pile. Sand is captured in construction cells or allowed to overboard onto adjacent beaches. Sand forms 75% of the waste deposit and has predictable properties.

**Disposition of Fines**

Water and suspended fines are captured in sand voids. Material surplus to those needs overflows into the tailings pond. In the pond fines slowly settle into denser and denser material. Finally at 30% by weight solids, repulsive forces between particles prevent closer approach and densification stops. This weak material is called mature fine tails or MFT.

Fines that are captured in sand voids are not available to make fluid tailings in the pond. Only one third of the fines make MFT. The rest are captured in sand voids or act as inert silt that occupies little space.

Clay, with its complex interacting force fields is the primary cause of fluid tailings.
B.15 Summary and Conclusions

Disposition of water and bitumen
In the pond, fines settle out leaving clarified water. Water surplus to MFT needs is recycled to the plant. Bitumen tends to follow the water, so most of it accumulates in the pond.

B.15.5 HOW TO LIMIT FLUID TAILINGS
If the density of the tailings discharge from extraction is increased:
- there will be less heat loss due to less discharged hot water.
- There will also be more fines captured in the sand.
- There will be less fines to make MFT in the pond.

B.15.6 PROPERTIES OF FLUID TAILINGS

Volume relationships
- The solids form a very weak soil structure and tend to hold that structure and density.
- Fluid tailings are 6 parts by volume water and one part solid material.
- Solidified fine grained tailings has about 1.5 volumes of water per unit of solid material.
- Densification requires removal of a lot of water and shrinkage to one third of the original volume.

Strength
- The undrained shear strength of MFT is about 5 pascals.
- The limiting strength for pumps to transport slurries is about 100 pascals.
- The target strength for solid reclaimed tailings is a minimum of 10 kPa.

Strength indicators
- Atterberg limits are indicators of undrained shear strength
  (Liquid limit = 1.7 kPa, Plastic Limit = 170 kPa)
- For sand/fines ratios below two, the solid content that relates to strength is (weight of clay/weight of water). Addition of sand adds to volume and density but not to strength.
- Chemical treatment that causes a water release (e.g. adding a coagulant) reduces the equilibrium water content, Liquid Limit, and relationships between solid content and strength. This change should be appreciated by those planning chemical treatment.

Zero water discharge policy
Oil sand projects operate under a zero water discharge policy. All process affected water must be retained. That policy inhibits plans for MFT densification because water removed cannot be discharged.

B.15.7 DIRECT METHODS FOR DENSIFYING FLUID TAILINGS
- Direct mechanical methods, listed in order of increasing density capability include thickeners, filter belts, centrifuges, filter presses and brute force heating. Mechanical processes can approach the density required for reclamation but will probably require assistance to achieve the target strength for reclamation.
B.15 Summary and Conclusions

- Natural processes include: consolidation, *drying, hydroponics, freeze/thaw*, and blending with dry swelling clay. Consolidation is natural self-weight densification. Tailings deposits are not configured to use consolidation to advantage. The other processes exert very high loads on the soil so are capable of significant densification. The underlined processes involve surface effects so require work in thin lifts. The swelling clay can work in thick layers.
- There is no single, silver bullet to cure fluid tailings. It will probably require opportune use of a number of processes working in their best “range”.

B.15.8 PASTE and MIXED SOIL CASES - CT Process

- CT processing involves treating MFT with a coagulant, and 3 to 6 parts sand. The non segregating mix can be pumped to disposal where it releases surplus water. In time (several years) the fines consolidate and the mix develops strength. The initial volume per cubic metre of MFT treated is about 2.2 cubic metres for fresh CT and 1.2 cubic metres for consolidated CT.
- Initially the plan was to solidify MFT with the CT process which has been in commercial use at Syncrude and Suncor for over 10 years.
- Challenges with CT:
  - There is insufficient sand to treat all MFT with the CT process. Another technology will be required to process the rest of the MFT.
  - CT is a fluid so requires containment for several years.
  - Operators are having difficulty producing on-spec CT in quantity.
  - There is some concern that the process may not be permanent.

Substitution of ore for sand in dyke-building.

- To maximize sand availability for CT processing, some operators propose to build dykes of overburden. That could be counterproductive.
- Overburden dykes require a different design and construction is significantly more expensive than it is with sand.
- Without sand voids to capture fines, the fines available to make MFT will increase by 30+%.

B.15.9 STORING MFT UNDER A WATER CAP

- Syncrude proposed to store MFT below a water cap in 1992. They are preparing for the test now. Two concerns:
  - Biogenic gas release could mix MFT with the overlying water cap.
  - Site selection criteria for permanently storing contaminated waste on surface have not been shared with the public.

B.15.10 ECONOMIC SCREENING OF PROJECT OPTIONS

- Oil sand projects have a life of 100 years. The time between disturbance and repair can be 30+ years.
- The traditional approach to economic evaluation uses discount analysis of cash flow related to the topic under study. When applied to the long time frame of oil sand projects the future liabilities are discounted substantially. That removes the key action that is under study so the
result is very misleading. Traditional assessment favours: deferred reclamation, accumulating tailings, adding to risk of seepage and catastrophic failure, and intergenerational transfer of reclamation liabilities. Aside from early profits, the cases preferred by this approach do not make sense.

- Economic analysis that recognizes reclamation liabilities as they are created by placing funds of equivalent value in a qualifying environmental trust retains the liability. This approach favours progressive reclamation, limiting stored tailings, limiting risk, and there is no intergenerational transfer of liabilities. Cases preferred by this approach do make sense.

**B.15.11 FISCAL TERMS**

Oil sand projects are highly taxed. After payout, fiscal sharing means that the developer retains 45% to 56% of profit and pays 45% to 56% of expenses. Governments receive/pay the rest.

**Public disclosure**

Public data about reclamation and closure plans, contingencies, and the technology that the plans rely on is limited. That is contrary to an underlying principle of the Alberta environmental protection and enhancement act that invites Albertans to input on environmental matters. Similarly, there is little or no data on the performance of the CT process that has been in commercial use for over 10 years.

**B.15.12 RESEARCH AND DEVELOPMENT**

Considerable research is underway at universities and on the project sites. Large scale pilot tests have been performed on the main technologies that could be used to densify fluid tailings. Research results are not available to the public. Results are not being used because the volume of fluid tailings continues to accumulate.

**Research goals**

The author is not aware of specific goals for oil, sand research. Goals listed in Table B.18 would provide focus and prevent some of the missed opportunities.

**Use of third party technology**

Oil sand projects are not making good use of technology developed by independents. There are processes that warrant a close review.

**B.15.13 INSULAR CHARACTER**

The oil sand business is quite insular. In that environment there is always a danger of having a controlling management develop that works to corporate advantage (e.g. profit now, pay later) and that is not aware of when practice is substandard (e.g. improper grain size measurement). The business would benefit from exposure.
This is an overview report about tailings.

The intent is to acquaint the reader with the history, the issues, and what lies ahead for oil sand tailings.

I coach people on how to write technical reports. Twenty pages of text is a comfortable length. This report is 66 pages long. I do not apologize for the length of the report. The tailings story is a broad subject that involves many disciplines and professions. Solutions are not simple, technical applications. They are multidisciplinary, and complex.

The first challenge to solving the tailings challenge is to recognize how we must approach economic analysis to guide management and planning decisions. Traditional economic analysis that discounts expenditures over longer periods than most interest rate tables cover, does not make sense. Discounting over long periods devalues and trivializes the very subject, we are analysing. Analysis that recognizes reclamation liabilities as they are created does make sense. It retains the focus on closure and guides us to do what we must do.

The second challenge is to find the right path to timely closure. That will be relatively easy once we correct the first challenge.

We can look forward to exciting changes ahead in oil sand tailings practice.

I hope that this report will help us make the right choices.

Respectfully submitted

David Devenny PhD P Eng P Geol
Past President of the Canadian Geotechnical Society
Past President of the Association of Professional Engineers, Geologists, and Geophysicists, of Alberta.
Fellow of the Engineering Institute of Canada
Fellow of Engineers Canada
Fellow of the Canadian Academy of Engineering
## Appendix B.2 The Dry tails Case

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B.2.1 Introduction to Dry tails

This section provides a summary description of the Dry Tails Case. The full report was prepared by Brian Raymond P Eng. “The Dry Tails Prefeasibility Study, 2009.”

The Dry Tails Case was added to the studies of tailings technologies to provide one case that had a high probability of successfully converting fluid tailings to a solid suitable for reclamation.

Solidification by centrifuging may fall short of the target needed to create a strong solid. This study added “dry swelling clay” to remove that last bit of water. Other finishing approaches such as natural drying and freeze/thaw treatment are also being explored by others.

This report contains the following sections to describe the Dry Tails Case.

- Goals
  - Plan, layout, steps
  - How “dry swelling clay” extracts water from MFT
  - Planning guide and assumptions
  - Equipment lists
  - Capital and operating steps
  - Cash flow vs time
  - Economic assessment
  - Conclusions
  - Next steps
  - Program to precede a full scale centrifuge test
  - Full scale centrifuge test program

Project details are also summarized in section A.4.6 of Report A. Detailed work plans, material balances, cost vs. time and derivation of unit costs are provided on the electronic work sheet in Appendix B.1.

B.2.2 Goals of the study

Goals of the study included:

1. Design a system to convert fluid tailings to a solid state suitable for reclamation.
2. Identify equipment needed, requirements, capacities, support required (e.g. power), manpower. Then derive capital and operating costs so economic evaluations can be made. The level of accuracy is compatible with a prefeasibility study.
3. Document the design
4. Recommend next steps.
B.2.3 The Dry Tails Case – concepts, layout and process steps.

The basic plan involves dredging MFT that is then centrifuged. “Dry swelling clay” is then added to reduce the water content to target levels and the blended waste is conveyed to a disposal site.

Figure A.15 shows the site layout. Figure A.16 shows the process flow sheet.
Appendix 2 – The Dry Tails Case

Detailed steps are described in Table B.2.1

Table B.2.1 Detailed steps in the Dry Tails Case

1. Build a robust dredge to reclaim MFT from an existing deposit.
2. Decant the water off the top of the pond and transport it to another pond.
3. Dredge the MFT and pump it to the processing facility on land.
4. On land, MFT is placed in one of two thickeners. The thickeners can be used to densify any MFT diluted in transit. They also act as a surge facility ahead of the centrifuges.
5. Centrifuge the MFT using the largest centrifuges available. Densities of about 60% can probably be achieved on a sustainable basis. 70% is probably needed to achieve the strength target of 10 kPa.
6. Blend “dry swelling clay” with the centrifuge cake in accordance with Figure A.15 to remove the targeted amount of water from the cake. When “dry swelling clay” is added to the cake, water transfer will occur until an equilibrium state is reached between the two materials. The “dry swelling clay” is obtained from an adjacent pit and conveyed to the centrifuge facility.
7. Convey the blended cake and clay to a disposal site. There it will be spread over a large area using stacking conveyors.
8. The study included 4 kilometres of conveyor to transport ‘dry swelling clay’ to the centrifuge processing site and 4 kilometres of conveyors to transport the blended product to the disposal site.
9. It is assumed that the plant will have to be moved about every 10 years.

Water is removed from the pond surface to prevent dilution as the dredge mines MFT.

The dredge has a “roadheader type” cutter capable of chewing through bitumen mats and other “surprises” in the tailings pond. The special cutter is provided aid uninterrupted production.

Three 6,000 m pipelines are used to transfer surface water from the pond to an adjacent pond, MFT from the dredge to the plant, and return water recovered from the centrifuges to the water transfer site.

Two thickeners receive MFT at the plant. They act as a surge receiving system. If the MFT is diluted it will be densified by the thickener before it is fed to the centrifuges.

15 of the world’s largest centrifuges process the MFT. Sparing capacity assures adequate on-line processing capacity.

The Clearwater mine includes a mining system, a hopper to receive Clay “ore” and a 4 km long conveyor to move the product to the centrifuge plant. Figure B.2.1 illustrates activity at the mine site.
At the Plant the Clearwater blend is added to centrifuge cake and then conveyed 4 km. to the disposal site.

At the disposal site stacking conveyors allow placement in 15m thick lifts. Two stacking conveyors add to on-line capacity. Initially the disposal site will have to be placed on a waste dump. Later it can be moved to the depleted tailings pond.

The system is designed to be moved to a new site every ten years or so. Production is halted for a year while the facility is moved to a new site.

**B.2.4 How “dry swelling clay” extracts water from centrifuge cake.**

Some definitions pertinent to this discussion:

- **Extractor** – soil that will remove water from a donor soil.
- **Donor** – soil that will yield water to the extractor.
- **Water retaining potential** – ability of a soil to retain water.
- **Water extraction potential** – ability of a soil to extract water from another soil
- **Swelling potential** – potential of a soil to attract water and increase volume while doing so.

Other terms are defined in Appendix B.3.
An “extractor” soil has a water deficiency. It seeks water to overcome the deficiency. The ideal “extractor” has a high clay activity, a high extraction potential, a low existing water content, and a low liquidity index.

The ideal “donor” soil has opposite characteristics - a low clay activity, a low water retaining potential, a high water content, and a high liquidity index.

When the two soils are mixed the “extractor” will attempt to remove water from the “donor” soil. The donor soil will resist water removal. Water will flow from the donor to the extractor if the extraction potential exceeds the water retaining potential of the donor. Eventually a state of equilibrium will be reached. At equilibrium the overall soil will still have a solid consistency – with more water in the “extractor” component, and less water in the “donor” component.

“Dry swelling clay” exists in the Clearwater Formation that surrounds the mineable oil sand area. (Figure B.8 in Section 5, Report B). Syncrude studies reveal that Clearwater clays have suitable “extractor” capabilities (Lord et. al.,1989). In contrast centrifuge cake with its relatively high water content is an ideal “donor”.

The water extracting capability is expressed in units of tonnes of water per tonne of extractor soil. Figure A.17 assumed that the Clearwater clay has a water extracting capability of 0.15 cubic metres of water per tonne of extractor soil. Figure A.17 suggests that the addition of 0.3 tonnes of extractor clay per tonne of cake will increase the cake solid content from 60% to 70%.

![Figure A.17 Dry clay required to dewater MFT](image-url)
B.2.5 Planning guide and assumptions

Soil planning assumptions are parameters are described in Table B.2.2

Table B.2.2 Soil planning assumptions

<table>
<thead>
<tr>
<th>Component</th>
<th>Target strength or solid content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum strength for solid waste disposal</td>
<td>10 kPa undrained shear strength</td>
</tr>
<tr>
<td>Corresponding solid content of waste</td>
<td>70% (weight clay/weight of clay + water)</td>
</tr>
<tr>
<td>MFT density</td>
<td>30 % solids</td>
</tr>
<tr>
<td>Density change due to centrifuge</td>
<td>30% to 60%</td>
</tr>
<tr>
<td>Density change due to “dry clay”</td>
<td>60% to 70%</td>
</tr>
</tbody>
</table>

Design parameters are summarized in Table B.2.4

Table B.2.3 Design parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFT process capacity</td>
<td>17.48 million m$^3$ per year</td>
</tr>
<tr>
<td>MFT solids converted to cake</td>
<td>95%</td>
</tr>
<tr>
<td>On line time</td>
<td>85%</td>
</tr>
</tbody>
</table>

B.2.6 Equipment Lists

This section presents equipment lists – type and size of equipment planned for each project component.

Table B.2.4 Equipment list for each relocatable pumping station (three required)

| Warman Pumps                           | 3 18/20 Slurry Pumps (Warman), 1500 HP |
| Gland Water System                     | lot 100 HP                               |
| Receiving Tank                         | 1 10’ x 20’ cw rupture disc              |
| Murray Lotta Valves                    | 2                                           |
| Bridge Crane                           | 1 25T/ST 40’ span 35 HP                  |
| Pipelines                              | 1 6,000 m of tie mounted pipeline, 20”    |
Table B.2.5 Equipment list for the dredge facility

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Quantity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derrick (enclosed)</td>
<td>1</td>
<td>similar to oil rig for hauling pipe and lifting hydraulic hoses</td>
</tr>
<tr>
<td>Hull</td>
<td>1</td>
<td>2700T Displacement, Pontoon chambers which can be pumped out</td>
</tr>
<tr>
<td>Hoists</td>
<td>3</td>
<td>50T/35T/20T cw hydraulic hangers &amp; pipe clamps</td>
</tr>
<tr>
<td>Bitumen “Pineapple” Cutter</td>
<td>1</td>
<td>cw Hydraulic Drive, 100HP</td>
</tr>
<tr>
<td>Hydraulic Pumps</td>
<td>2</td>
<td>7,000 USgpm, submersible, 250HP</td>
</tr>
<tr>
<td>Hydraulic Pumps</td>
<td>3</td>
<td>cw Tanks</td>
</tr>
<tr>
<td>Vertical Slurry Pump</td>
<td>1</td>
<td>20&quot;, 1000HP, Hazelton or equal</td>
</tr>
<tr>
<td>Bridge Cranes</td>
<td>2</td>
<td>15T/10T two hoists per bridge</td>
</tr>
<tr>
<td>Misc</td>
<td>lot</td>
<td>trash screens, gland water system, etc</td>
</tr>
<tr>
<td>Hoists &amp; Monorails</td>
<td>1</td>
<td>10T above derrick hoists</td>
</tr>
<tr>
<td>HVAC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pontoon Bridge</td>
<td>1000'</td>
<td>May need a lot more</td>
</tr>
</tbody>
</table>

Table B.2.6 Equipment list for the MFT treatment plant

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Quantity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screens</td>
<td>4</td>
<td>10’ x 24’ low head vibrating (AC or Equal)</td>
</tr>
<tr>
<td>Sieve Bend Screens</td>
<td>4</td>
<td>10’ wide</td>
</tr>
<tr>
<td>Discharge Conveyor &amp; Stockpile</td>
<td></td>
<td>not sized</td>
</tr>
<tr>
<td>Thickeners</td>
<td>2</td>
<td>210’, 2,500,000 ft. lb. Torque Rakes</td>
</tr>
<tr>
<td>Thickener Roof Structures</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Thickener UF Pumps &amp; CW Pumps</td>
<td>4</td>
<td>not sized, about 6500 USgpm</td>
</tr>
<tr>
<td>Centrifuges</td>
<td>15</td>
<td>Andritz Bird, 55” x 220”, 800HP</td>
</tr>
<tr>
<td>Centrate Pump</td>
<td>1</td>
<td>18/20, 500HP</td>
</tr>
<tr>
<td>Centrate Tank</td>
<td>1</td>
<td>20,000 bbl, insulated on concrete pad</td>
</tr>
<tr>
<td>Clear H₂O Pump</td>
<td>1</td>
<td>18/20, 1200HP</td>
</tr>
<tr>
<td>Gland H₂O System &amp; Tank</td>
<td>lot</td>
<td>not sized</td>
</tr>
<tr>
<td>Cleanup Pump</td>
<td>1</td>
<td>16” vertical + 4” water injector</td>
</tr>
<tr>
<td>Hoists &amp; Monorails</td>
<td>8</td>
<td>10T</td>
</tr>
<tr>
<td>Bridge Cranes</td>
<td>2</td>
<td>20T/5T</td>
</tr>
<tr>
<td>Fire Protection</td>
<td>lot</td>
<td>1500 USgpm, + Jockey Pump connected to centrate tank</td>
</tr>
<tr>
<td>Electrical (in plant only)</td>
<td>lot</td>
<td>15,650 HP</td>
</tr>
<tr>
<td>Controls (see control room)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instrumentation</td>
<td></td>
<td>180 Loops</td>
</tr>
<tr>
<td>HVAC</td>
<td>lot</td>
<td>4 million BTU/hr</td>
</tr>
</tbody>
</table>
Table B.2.7 Equipment list for the Clearwater mine

<table>
<thead>
<tr>
<th>Description</th>
<th>Number</th>
<th>Size/Capacity</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sizers</td>
<td>1</td>
<td>84” Stamler Feeder Breaker</td>
<td>600 HP</td>
</tr>
<tr>
<td>Hoppers</td>
<td>1</td>
<td>800 Tonne single dump capability, 50’ x 40’</td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td>1</td>
<td>Not Sized</td>
<td>50 HP</td>
</tr>
<tr>
<td>Foundation</td>
<td>1</td>
<td>850 M³ concrete</td>
<td></td>
</tr>
<tr>
<td>Tunnel</td>
<td>1</td>
<td>100m csp super pipe</td>
<td></td>
</tr>
<tr>
<td>Sump Pump</td>
<td>1</td>
<td>4” slurry</td>
<td>10 HP</td>
</tr>
<tr>
<td>Hoist</td>
<td>1</td>
<td>not sized</td>
<td>10 HP</td>
</tr>
<tr>
<td>Hydraulic Ram Plows</td>
<td>2</td>
<td>cw hydraulic pump</td>
<td>25 HP</td>
</tr>
<tr>
<td>Tramp Iron Magnet</td>
<td>1</td>
<td>Eriez D-875, 6 kw</td>
<td></td>
</tr>
<tr>
<td>Clearwater Conveyor</td>
<td>1</td>
<td>60” x 3000m, 4.8 mps, 2000 mtph</td>
<td>3000 HP</td>
</tr>
<tr>
<td>Belt Scale</td>
<td>1</td>
<td>60”</td>
<td></td>
</tr>
<tr>
<td>Moisture Analyser</td>
<td>1</td>
<td>Gamma Metrics</td>
<td></td>
</tr>
</tbody>
</table>

Table B.2.8 Equipment list for the blended waste conveyor system

<table>
<thead>
<tr>
<th>Description</th>
<th>Number</th>
<th>Size/Capacity</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Products Conveyor</td>
<td>1</td>
<td>60” x 4000m, 4.8 mps, 3000 mtph</td>
<td>6,000 HP</td>
</tr>
<tr>
<td>Belt Scale</td>
<td>1</td>
<td>60”</td>
<td></td>
</tr>
<tr>
<td>Moisture Analyser</td>
<td>1</td>
<td>Gamma Metrics</td>
<td></td>
</tr>
<tr>
<td>Stacker Feed Conveyors</td>
<td>2</td>
<td>60” x 3000m, 4.8 mps, 3000 mtph</td>
<td>4,500 HP</td>
</tr>
<tr>
<td>Tripper Cars</td>
<td>2</td>
<td></td>
<td>25 HP</td>
</tr>
<tr>
<td>Stackers</td>
<td>2</td>
<td>60” x 62m, luffing and slewing, track mounted, 3000mtph</td>
<td>200 HP</td>
</tr>
</tbody>
</table>

Table B.2.9 Equipment list for infrastructure and offsites

- Control Room – 3 control rooms – one each at the dredge, the plant and mine
- Gland Water Distribution - for pipelines
- Potable Water - for personnel and for site use
- Natural Gas supply
- Power Lines for electrical supply
- Electrical Substations – tie in to external power
- Emergency Electric Power, Communication Systems & Yard Lighting
- Laboratory - for all facilities
- Camp
B.2.7 Capital and operating costs

Estimates are in 2009 dollars. Costs assume a Canada US exchange rate of $1 Canadian = $0.80 US.

Table B.2.10 Capital costs

<table>
<thead>
<tr>
<th>Plant</th>
<th>Installed</th>
<th>Horsepower</th>
<th>$ K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredge</td>
<td>1800</td>
<td>24,639</td>
<td></td>
</tr>
<tr>
<td>(3) Pump Stations</td>
<td>14620</td>
<td>27,633</td>
<td></td>
</tr>
<tr>
<td>(3) 6000m Pipelines (20”)</td>
<td></td>
<td>52,128</td>
<td></td>
</tr>
<tr>
<td>Dry Tailings Plant</td>
<td>15650</td>
<td>206,023</td>
<td></td>
</tr>
<tr>
<td>ROM Dump Pocket, OB Conv, &amp; FEL</td>
<td>700</td>
<td>34,195</td>
<td></td>
</tr>
<tr>
<td>Stacking Out System</td>
<td>18450</td>
<td>146,150</td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td></td>
<td>23,874</td>
<td></td>
</tr>
<tr>
<td>Control Room</td>
<td></td>
<td>12,000</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>51,220</strong></td>
<td><strong>526,642</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table B.2.11 Overall operating costs

<table>
<thead>
<tr>
<th></th>
<th>$ k</th>
<th>$/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplies and wages</td>
<td>11,755</td>
<td>$0.67</td>
</tr>
<tr>
<td>Materials &amp; supplies</td>
<td>19,708</td>
<td>$1.13</td>
</tr>
<tr>
<td>Natural Gas (plant heating only)</td>
<td>204</td>
<td>$0.01</td>
</tr>
<tr>
<td>Electric Power</td>
<td>11,018</td>
<td>$0.63</td>
</tr>
<tr>
<td>Chemicals</td>
<td>3,785</td>
<td>$0.22</td>
</tr>
<tr>
<td>Sustaining Capital Projects</td>
<td>1,500</td>
<td>$0.09</td>
</tr>
<tr>
<td>Rental &amp; Leases</td>
<td>150</td>
<td>$0.01</td>
</tr>
<tr>
<td>Travel &amp; Training</td>
<td>150</td>
<td>$0.01</td>
</tr>
<tr>
<td>Allocated Shop Costs</td>
<td>1,750</td>
<td>$0.10</td>
</tr>
<tr>
<td>Mobile Equipment</td>
<td>2,940</td>
<td>$0.17</td>
</tr>
<tr>
<td>Administration</td>
<td>1,763</td>
<td>$0.10</td>
</tr>
<tr>
<td>Other</td>
<td>600</td>
<td>$0.03</td>
</tr>
<tr>
<td><strong>Total Operating Costs</strong></td>
<td><strong>$ 55,323 K</strong></td>
<td><strong>$3.16</strong></td>
</tr>
</tbody>
</table>
Appendix 2 – The Dry Tails Case

Table B.2.12 Operating costs allocated to project components

<table>
<thead>
<tr>
<th>Component</th>
<th>$k</th>
<th>$/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine MFT</td>
<td>6,638</td>
<td>$0.38</td>
</tr>
<tr>
<td>Pumps and pipelines</td>
<td>7,414</td>
<td>$0.42</td>
</tr>
<tr>
<td>MFT dewatering facility</td>
<td>16,652</td>
<td>$0.95</td>
</tr>
<tr>
<td>Clearwater mine</td>
<td>4,981</td>
<td>$0.28</td>
</tr>
<tr>
<td>Clearwater conveyor</td>
<td>4,910</td>
<td>$0.28</td>
</tr>
<tr>
<td>Stacking out facility</td>
<td>14,728</td>
<td>$0.84</td>
</tr>
<tr>
<td><strong>Total operating costs</strong></td>
<td>$55,323 k</td>
<td>$3.16</td>
</tr>
</tbody>
</table>

B.2.8 Relocation costs

The MFT source is assumed to have a life of 10 years. Then the treatment facilities will have to be moved to a new location.

The estimated cost of moving treatment facilities to a new location are summarized on Table B.2.13

Table B.2.13 Relocation costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredge</td>
<td>$4,000 + $800 Project Management</td>
<td>$4,800</td>
</tr>
<tr>
<td>Pump Stations (3)</td>
<td></td>
<td>$ 300</td>
</tr>
<tr>
<td>Pipelines (3) x 6000m</td>
<td>$6,480 General Earthworks, + $10,630</td>
<td>$17,110</td>
</tr>
<tr>
<td>Dry Tailings Plant</td>
<td>General Earthworks</td>
<td>$3,056</td>
</tr>
<tr>
<td></td>
<td>Foundations</td>
<td>$3,718</td>
</tr>
<tr>
<td></td>
<td>Dismantling &amp; Construction</td>
<td>$25,000</td>
</tr>
<tr>
<td></td>
<td>Contractor’s Supervision O&amp;H</td>
<td>$30,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$61,774</td>
</tr>
<tr>
<td>Stacking Out System</td>
<td>$38,000 Site Prep + $14,000 Relocation</td>
<td>$52,000</td>
</tr>
<tr>
<td>ROM Hopper</td>
<td>$7,500 + OB Conv &amp; Site Prep $7,500</td>
<td>$15,000</td>
</tr>
<tr>
<td>Control Room</td>
<td></td>
<td>$ 5,000</td>
</tr>
<tr>
<td>Infrastructure</td>
<td></td>
<td>$15,000</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td></td>
<td>$170,984</td>
</tr>
</tbody>
</table>
B.2.9 Cash Flow

Table B.2.14 summarizes cost vs. time for Dry Tails Case.

Table B.2.14  Cash flow vs. time for solidifying MFT

<table>
<thead>
<tr>
<th>Year</th>
<th>Capital Cost (k)</th>
<th>Operating Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Engineering</td>
<td>55,000</td>
<td>550</td>
</tr>
<tr>
<td>2 - Construction</td>
<td>200,000</td>
<td>550</td>
</tr>
<tr>
<td>3 – Construction &amp; Startup</td>
<td>271,642</td>
<td>9,500</td>
</tr>
<tr>
<td>4/13 – Operate</td>
<td>-0-</td>
<td>55,323</td>
</tr>
<tr>
<td>15 – Relocate</td>
<td>170,984</td>
<td>13,000</td>
</tr>
<tr>
<td>16/25 – Operate (cycle begins again)</td>
<td>-0-</td>
<td>55,323</td>
</tr>
</tbody>
</table>

B.2.10 Economic assessment

Appendix 1.1 contains available information on our assessment of the Dry Tails Option. That includes activities, work, quantities processed, capital and operating costs vs. time.

Simple unit costs are summarized in Table B.2.15. The table shows simple average costs per cubic metre of MFT and average unit cost per equivalent barrel of synthetic oil. The net present value unit cost, discounted at 10% is 45% higher, because of the impact of front end capital.

Table B.2.15 Unit cost for solidifying MFT in the Dry Tails Facility

<table>
<thead>
<tr>
<th>Simple average unit cost</th>
<th>NPV$_{10}$ Unit cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$/m^3$ MFT</td>
<td>$$/bbl SCO equivalent</td>
</tr>
<tr>
<td>$5.07$</td>
<td>$1.19$</td>
</tr>
<tr>
<td>$7.38$</td>
<td>$1.73$</td>
</tr>
</tbody>
</table>

The full project economic model that represents the fiscal environment that an operating oil sand project experiences was not used because there was no competing technology to compare.
Appendix 2 – The Dry Tails Case

B.2.11 Conclusions

The appraisal of the Dry Tails Case was a credible evaluation.

The appraisal sets an economic standard for solidifying MFT. Industry is invited to find a more cost effective one with equivalent risk.

Centrifuge treatment appears promising and should be investigated further.

There is a need to understand the cost of a commercial facility capable of processing large volumes of MFT to create solid waste suitable for reclamation.

Centrifuge processing appears to be the most capable mechanical system available. It may fall short of the final density required to provide the target strength. However, options are available to remove the final bit of water. Options include drying, freeze-thaw treatment, and blending with a “dry swelling clay”.

Centrifuge treatment appears promising so the Dry Tails Case should be explored further.

B.2.12 Next steps

Centrifuges have been used extensively in treating oil sand froth. However, there is no commercial experience with treating MFT to make a reclaimable solid. Pilot programs have been conducted (Fair, 2008), (Logan et.al, 1984). A commercial centrifuge facility would need many of the world’s largest centrifuges. That represents a considerable investment.

Small centrifuges can exert larger G forces than large centrifuges. Consequently, it is difficult to scale performance observed from small pilot tests to the large units that will be needed to manage the large tonnages required in a commercial facility.

A large demonstration test is needed to properly evaluate the potential; of large centrifuges and to provide data for design.

Section B.12.13 describes small research programs that should be part of preparing for a full scale demonstration test. Section B.12.14 suggests a program for a full scale centrifuge demonstration test.

B.2.13 Program to precede a full scale centrifuge pilot

An evaluation of the potential for centrifuge treatment to solidify fluid tailings at commercial scale requires a full scale demonstration test. Full testing is needed because:
Appendix 2 – The Dry Tails Case

- Large commercial sized centrifuges are needed to achieve throughput. However, they do not exert as many G's as the smaller pilot centrifuges, hence the need for a full scale test.
- Mechanical performance (equipment on-line time) and internal erosion is best evaluated in the large scale demonstration test.
- Scale-up from pilot sized units to commercial sized units is difficult.

The logical approach to evaluate commercial viability involves:

1. Background tests
2. Small scale pilot tests
3. Full scale demonstration test

This section describes smaller experiments that can be used to prepare for the large scale test.

Table B.2.16 Clearwater evaluations to precede a full scale centrifuge demonstration test

<table>
<thead>
<tr>
<th></th>
<th>Clearwater Formation Geology</th>
<th>Study the location and character of the Clearwater Formation so suitability for dewatering centrifuge cake can be appraised.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- Proximity of outcrops to the operating site&lt;br&gt;- Character of facies present and their properties. Profile: &lt;br&gt;</td>
</tr>
<tr>
<td>2</td>
<td>Verify the water removal potential of Clearwater clay/shale</td>
<td>Measure the water extracting potential of the Clearwater &lt;br&gt;- Ability to extract water from centrifuge cake&lt;br&gt;- Tones of blend vs. tones of cake vs. water content change</td>
</tr>
<tr>
<td>3</td>
<td>Characterize centrifuge cake</td>
<td>Sand, silt and clay content&lt;br&gt;Atterberg limits&lt;br&gt;Density vs. strength relationship&lt;br&gt;Further dewatering desired by adding Clearwater clay/shale.</td>
</tr>
<tr>
<td>4</td>
<td>Character of the Clearwater/cake blend</td>
<td>Strength and index properties of the Clearwater/cake blend&lt;br&gt;For different blends determine&lt;br&gt;- Governing properties&lt;br&gt;- Atterberg limits&lt;br&gt;- Liquidity index&lt;br&gt;- Basic strength characteristics</td>
</tr>
<tr>
<td>5</td>
<td>Conclusions</td>
<td>Conclusions on overall feasibility of dewatering cake by adding Clearwater clay/shale</td>
</tr>
</tbody>
</table>
B.2.14 Full scale centrifuge demonstration program

This demonstration test will demonstrate the capability of the world's largest centrifuge (55" X 220" 800 HP) using a unit no smaller than 44" X 132".

An barge will obtain MFT from the tailings pond and deliver it to a thickener. The thickener will be capable of delivering thickener feed to the centrifuge at rates of 400 to 1250 USGPM.

The program should be developed designed, operated and evaluated in close cooperation with centrifuge manufacturers who have an incentive to make the program succeed.

Phase I Program

The main purpose is to establish the following:

1. Properties of the MFT to be processed,
2. Develop operating performance curves for the centrifuge including:
   a. Feed rate,
   b. Product cake quantity and properties - especially moisture content of the clay,
   c. Centrate quantity and properties - especially solids content,
   d. Particle size distribution of the feed, cake and centrate and their associated partition curves.
3. Geotechnical characteristics of the cake and after blending with Clearwater clay/shale if needed - index properties, PSD, Atterberg Limits, liquidity index, undrained shear strength.
4. Flocculent testing - develop curves for cake moisture and recovery for various flow levels. Both anionic and cationic floe agents will be tested.
5. Determine the degree of disaggregation and dispersion of fluid tailings processed.
6. Determine particle size distribution of the feed material using various representative techniques.
7. Determine the strength of the blended cake - required to appraise stackability and for foundation design of the stackers.
8. Hydrocarbon content of the centrifuge streams - so hydrocarbon recovery can be appraised.

The estimated duration of Phase I programs is as follows:

- 7 days  Plant modification and start-up
- 7 days  Test the bowl and scroll differential speed
- 30 days Establish operating parameters for a wide range of feed rates, recoveries etc.
- 30 days Test flow program to determine effect on above
- 30 days Optimize centrifuge performance
Phase II – Program - Process and Wear Testing

Purpose - demonstrate that the centrifuge plant can operate on a relatively continuous basis and establish wear patterns within the machine before commercial units are ordered.

1. **Run continuously** for 30 days while monitoring changes in all operating conditions. Get a feel for how the commercial plant will perform.
2. **Test the second Scroll** for 14 days in order to optimize the screw design.
3. **Wear test the best Scroll** for an additional 30 days.
4. **Dismantle** and photograph the following to determine armouring requirements for commercial machines: gear box components, pillow block roller bearing, thrust bearing housing, shafts, bushings and seals, feed box (and accelerator), scrolls, bowl, ports and weirs.
5. Measure strength of the blended cake-determine stackability of the product and bearing capacity for stacker foundations.
6. **Characterize properties of the MFT feed to be processed** - solid content, particle size distribution, mineralogy and character of the clays (mineralogy, activity, cation exchange capacity), character of the make-up water-soluble salts and variation vs. time.

Table B.2.17 Cost estimate for the full scale centrifuge demonstration test

<table>
<thead>
<tr>
<th>Capital Cost estimate ($ thousand)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredge (use existing barges)</td>
<td>(no capital cost)</td>
</tr>
<tr>
<td>Site Preparation</td>
<td>$ 500</td>
</tr>
<tr>
<td>2000 m Pipelines (12&quot; sch 40)</td>
<td>$4,600</td>
</tr>
<tr>
<td>Dry Tailings Plant</td>
<td></td>
</tr>
<tr>
<td>Building &amp; Installation (structural, piping, electrical, inst.)</td>
<td>$8,000</td>
</tr>
<tr>
<td>Centrifuge (2 scrolls) + parts</td>
<td>$2,375</td>
</tr>
<tr>
<td>Thickener &amp; Tanks</td>
<td>$1,000</td>
</tr>
<tr>
<td>Floe Systems</td>
<td>$ 300</td>
</tr>
<tr>
<td>Misc Equipment (conv., pumps, HVAC, etc.)</td>
<td>$2,000</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>$1,000</td>
</tr>
<tr>
<td>Mobile Lab &amp; office Trailer</td>
<td>$1,000</td>
</tr>
<tr>
<td>Control Room</td>
<td>$1,000</td>
</tr>
<tr>
<td><strong>TOTAL CAPITAL COST</strong></td>
<td><strong>$21,775</strong></td>
</tr>
</tbody>
</table>

Operating cost estimate ($ thousand)

Assume daily operating cost $30
Test duration 200 days

**TOTAL Operating Cost** $6,000
Appendix 3 Definitions

**Accelerated densification techniques** – techniques used to accelerate densification of MFT such as drainage and exposure, drying, freeze/thaw cycles.

**Accelerator** – factor accelerating consolidation of MFT – drainage path shortened by bubble paths from bacterial action in MFT

**Airborne emissions (trucks)** – exhaust emissions from mine trucks

**Alberta Environmental Protection and Enhancement Act** – primary act defining the role of Alberta Environment

**Albian Sands** – mineable oil sand project operated by Shell and others

**Alluvium** – soil of recent age found in a river flood plain

**Angle of internal friction** – strength property of granular material, depends on surface properties and density of packing of the soil particles

**Approval** – cabinet – approval to proceed with a project granted at the highest level

**Aquifer** – subsurface layer that conducts water

**Asset value** – value of an asset (should consider environmental liabilities)

**Assimilative capacity** – ability of a body of water to receive contaminants without becoming overloaded

**Aurora Project** – Syncrude’s satellite mine and extraction facility

**Backfill** – material placed to fill an existing excavation

**Barren** – refers to oil sand areas not underlain by mineable ore

**Base level** – local erosion base – e.g. the Athabasca River

**Base Project** – initial oil sand project – before expansions

**Basement (geology)** – granite base underlying sedimentary rock profile

**Basement (dropping)** – phenomenon where the basement was subsiding while younger strata were being deposited

**Beach** – sandy shore of a body of water

**Beach (tailings)** – sandy shore of a tailings pond

**Beach above water** – tailings beach that forms above the pond level - generally rewashed by stream

**Beach below water** – tailings beach that forms below the pond level. Generally looser, traps fines.

**Bentonite** – a highly plastic clay mineral. Found in the Clearwater formation.

**Best Available Economic Technology – BAET** – what oil sand projects are expected to use

**Bitumen** – Viscous hydrocarbon found in the Alberta oil sands

**Bitumont Basin** – basin 75 km north of Fort McMurray where geological profile has dropped 100m

**Bitumen recovery** – % of bitumen in ore recovered by mining and extraction

**Capital Cost** – expenditure on equipment or construction – not an operating expense

**Capital Cost Allowance – CCA** – treatment of capital investment for income tax purposes

**Capital – Canadian Development Expense CDE** – treatment of pre development capital for income tax purposes.

**Capitalize expenditures** – put pre production expenses in a CDE capital pool for income tax purposes

**Canadian Oil Sands Trust** – symbol COS.UN- the largest owner of Syncrude (36.74%) – an energy trust

**Cap** – covering material,

**Card house structure** – delicate, unstable structure of clay particles in MFT
Appendix 3 Definitions

*Centrifuge* – a rotating device that applies many times the force of gravity to its contents. A brute force method of removing water from MFT.

*Channel* – valley of a water course  
*Channel – pre glacial* – abandoned channel filled with gravel or other soil located under glacial deposits

*Clarify* – remove suspended solids from water

*Clay – activity* – relative activity indicated by (plasticity index/% of solid material that is clay)

*Clay – calcium* – clay in which calcium ions dominate the pore water-

*Clay content* – percent of mineral matter that is clay

*Clay-shale* – shale bedrock that has clay like properties

*Clay – size* – particle of average size less than 2 microns

*Clay – sodium* – clay in which sodium ions dominate in the pore water

*Clay/water ratio* – ratio of weight of clay/weight of water – ignoring weight of sand and silt

*Closure* – the condition when the project is finally reclaimed, the act of final reclamation

*Closure – goals* – a statement of what closure is intended to accomplish – timely reclamation certificate

*Closure and reclamation plan* to manage reclamation activities to closure at which time the project will qualify for a reclamation certificate.

*Closure plan clearly defined* – well defined closure plan that stakeholders can understand

*Closure stage* – stage of the project after operations

*Collapse features* – geology disrupted by collapse into caverns and other undermining phenomena

*Coagulant* – chemical addition that causes dispersed structure in clay to collapse due to inter particle forces of attraction.

*Cohesion* – strength in a clay deposit that is independent of normal stress

*Coke* – waste product from upgrading – mostly carbon

*Communication failure* – fail to communicate key project information to stakeholders

*Compliance report* – report from operators certifying that work is proceeding as directed

*Condition ore* – prepare ore for extraction. Break it down into individual particles in a slurry.

*Conditioning agents* – chemicals used to condition ore

*Conditions (attached to permits)* – conditions that regulators add to permits and that must be followed

*Continuity (of clay deposit)* – clay surrounds other solid materials so dominates strength

*Connate water* – formation water in ore. May be from original deposit.

*Consolidation* – natural densification of soil through expulsion of water in response to a surface load

*Containment* – support provided to a deposit too weak to support itself

*Contingency plan* – back-up plan to be used if the base plan does not work.

*Conveyor* – a moving belt used to transport solid material

*Cretaceous Period* – Period about 100 million years ago when the McMurray Formation was deposited.

*Cross section* – a view of vertical section of the earth.

*Crusher* – large smasher used to break oil sand ore down into small pieces

*CT process* – Process used to solidify MFT by adding a coagulant and adding 3 to 6 parts sand

*CT production targets* – planned level of producing volumes of CT, or achieving a % of on line time making CT, or converting a given quantity of MFT to a solid CT material.

*CT treatment* - solidifying MFT in CT.
Appendix 3 Definitions

Cut face (mining) – (mining) slope or pit wall
Cut off grade – (mining) ore grade (% bitumen) below which mining is not economical
Decommissioning removing infrastructure and reclaiming the site
Deer Creek Energy – name under which Total is developing the Joclyn oil sand project
Deferral – postpone or put off
Deluge – flood
Demonstrate – verify, show viability
Demonstration test – large scale test used to verify a process, develop cost data, develop design data
Depositional Environment – geological environment in which a sedimentary deposit formed. 28 such environments are recognized in the McMurray Formation
Depressurize (mining) – reduce pressure in groundwater – needed to stabilize the base and walls
Developer – owner or operator of a project
Development – (site) undertake site improvements such as install drainage.
Dewater – remove groundwater to depressurize formations.
Dilution extraction – use more water in extraction circuits to improve bitumen recovery.
Dip (bedding) (geology)- angle of inclination of a sedimentary layer
Directive – order from a regulator required practice
Disclosure – reveal information
Discount – diminish cost or value due to time factor
Discount factor – percentage discount applied per year
Discretionary expenditure or spending – expenditure that may be spent now or at another time
Discretionary income – income that may be spent on operation or retained as profit
Dispersant – chemical that causes clay particles to disperse due to repulsive forces between particles
Dispersed (as in clay structure) particles are separated because of repulsive forces between them
Dozer – bull dozer
Drainage (as in consolidation) release of excess pore fluid causing a drop in pore water pressure
Drainage path (as in consolidation) distance water must travel to escape from consolidating soil
Drainage wick – permeable material installed to facilitate drainage
Due diligence – thorough check to ensure conditions are as they should be
Dyke (tailings) – perimeter structure that supports contained material
Early stage operations – stage of project at start of operations
Economic assessment – appraise relative merits on the basis of economics
Effective stress (soil mechanics) – applied stress minus offsetting pore water pressure
Environmental Impact Assessment – appraise impact of planned development on natural conditions and how to mitigate adverse effects
End-pit-lake - a lake that will be left in the last area to be mined at the end of a project. It may be used to collect and clean runoff before discharge, store MFT in the base etc.
Energy Resources Conservation Board – Alberta crown corporation responsible for managing technical aspects of energy development.
Environmental standards – standards to be met in reclamation, stress or chemical equilibrium. If above the equilibrium content – drainage will take place, if below the equilibrium, soil will attract more fluid.
Appendix 3 Definitions

**Estuary (geology)** mouth of a river, where a river enters the sea, often a flooded channel.

**Expansion programs** – new projects added to a base project to expand life or production.

**Expectations (of reclamation)** – stakeholder expectations of performance in reclaiming a site – standards to be achieved, timing, share information on what is to be done.

**Expense** – a cost incurred, also treat as an expense (for tax purposes).

**Expert advisory board** – panel of external experts who advise project personnel.

**External tailings pond** – pond constructed on surface and used until there is room for tailings in the mined out area.

**Extraction** – oil sands extraction facility

**Extraction designer** – engineer who designs extraction facilities

**Extraction operator** – person who operates the extraction facility

**Extraction efficiency** - % of bitumen in ore that is recovered by the extraction facility.

**Extraction process** – specific configuration used in an extraction facility

**Fault (geology)** – break in bedrock on which movement has occurred.

**Filter belt** – a pervious belt used to suction water from soil placed on it.

**Filter press** – a device used to compress soil to drive water from it

**Filtrate** – liquid stream after filtration or centrifuge treatment

**Financial assurance** – assurance given by a developer that funds will be available to undertake reclamation in the future. Assurance may take the form of a promise, a guarantee, a posted bond, cash or a Qualifying Environmental Trust.

**Financial reversal** – change in financial status,

**Fine grained sand** - sand of grain size at the lower size range for sand 74u to 200u

**Fine grained stream (extraction)** - stream in extraction that processes “fines”

**Fines** – (extraction) material finer than 44 micron size. Amount of silt or clay unknown.

**Fines capture (beach)** – fine grained material captured in void space in a sand beach. MFT material captured in the beach is not available to make MFT in the tailings pond.

**Fiscal offset** – method by which governments share in reclamation expenses

**Fiscal regime** – overall system of royalty and tax applicable to oil sands development

**Fiscal terms** - specific royalty and taxes applied.

**Flocculating agent** – chemical that causes soil particles in suspension to be attracted to each other

**Fluid tailings** – MFT, wet weak tailings that has fluid like properties, requires containment.

**Fluvial sand** (geology) sand deposited in a river channel environment

**Flyway** – route used by migrating birds

**Footprint (of a typical oil sands plant)** – disturbed area related to an oil sands project

**Forecast model** – predictive model used to identify future behavior, volume storage needs etc.

**Foregone profit** – discretionary money spent on operations instead of taken as profit.

**Freeze/thaw treatment (geotechnical)** – system used to densify soil, freezing extracts clean water. Associated suction causes the soil to compress. When the soil thaws water is released.

**Friction angle** – property of a soil with frictional strength. It is related to the surface of soil particles and to the density of packing of soil particles.
Appendix 3 Definitions

**Froth flotation** – technique used to extract bitumen. Small bubbles are attracted to bitumen causing it to separate from water that has the same density.

**Fugitive emissions** – airborne contaminants such as methane and solvent lost from tailings ponds.

**Future generation (as in inheriting environmental liabilities)** – next or subsequent generation of financial managers. Assume a generation is from one manager to the next is about 20 years.

**Gentle conditioning (extraction)** – use gentle action to leave clay lumps intact and thereby avoid their dispersion and availability to make MFT.

**Glaciation** – continental – glaciation that covered most of Canada during the Pleistocene Epoch. Much of the ice was over a mile thick.

**Glaciolacustrine clay** – clay deposits that formed in lakes associated with the dying stages of glaciation,

**Glacial till** – see till,

**Grain size distribution** – range of grain sizes present in a soil sample.

**Granite** – type of igneous rock

**Gravity separation** – simple process used to separate sand from slurried oil sand ore.

**Gross Revenue Royalty Rate** – royalty applied until payout. It is a percent of gross revenue.

**Groundwater** – extractable subsurface water

**Gully** – erosion channel cut into soil. Difficult to control once started.

**Gypsum** – hydrous calcium sulphate. Acts as a coagulant for MFT.

**Halo (clay surface)** – body of water and ions in the water form a halo surrounding a clay particle,

**Heat recovery (extraction)** – in plant water recycle recovers water but also the heat contained in it.

**Hectare** – unit of land area measurement. Hectare contains about 2.5 acres. A hectare measures 100 metres by 100 metres.

**Hindered settling** – particles settling in a suspension sufficiently concentrated that hey interact and hinder one another.

**Historic inventory (MFT)** – large volume of stored MFT waiting for a solution.

**Hold developer accountable** – ERCB remind oil sand developers that they own reclamation liabilities and are obliged to reclaim them.

**Horizon Project** – fourth mineable oil sand project just in start-up mode.

**Hydrottransport** – transport ore in a water slurry using a pipeline.

**Imperfect (tailings forecast model)** – polite way of saying it does not wok very well.

**In-situ** – in the ground.

**Independent review** – review by an external knowledgeable reviewer who has no ties to the project.

**In-pit** – within the mine pit

**Integrated facility (as an oil sand plant)** – integrated has mining, extraction and upgrading on one site.

**Interburden (mining)** – waste zone within an ore body

**Intergenerational transfer (reclamation)** – transfer liabilities for clean up to a future generation.

**Interlaminated (geology)** – fine interlayered deposit

**Karst** – (geology) – possesses solution features such as caves, sink holes and collapse structures.

**Lean oil sand** – low grade, bitumen content too low to mine as ore.

**Legacy inventory** – historic accumulation (of MFT)

**Liability** – an obligation to do future work
Appendix 3 Definitions

Light components (in oil) – light hydrocarbons such as naphtha
Liquefaction – phenomenon whereby a sand deposit loses all strength and behaves as a liquid.
Liquid limit- water content of soil that separates liquid from plastic behavior
Maintenance free – does not require maintenance
Mature fine tails – tailings that has settled to about 30% by weight solid and resists further densification.
Also known as MFT
Methodology – procedures used
MFT growth – increase in MFT inventory
Micron- unit of measurement – one millionth part of a metre.
Middlings (extraction) slurried ore after bitumen and sand have been removed.
Mine – pit where ore is mined
Mine – active – mine that is still in use
Mine – base – mine that supported the base or first oil sand project
Mine bench – working surface in a mine
Mined out area – part of mine where ore has been removed.
Muskeg – organic deposit that accumulates at surface in northern areas.
Naphthenic acids – natural compounds found in the Fort McMurray deposits. Must be removed from tailings water before it can be released to adjacent areas.
Net income – income less operating expenses
Net revenue royalty rate – profit based royalty. It is applied after payout.
Net present Value NPV – value today of a future income stream – discounted to today
Non segregating mix (tailings) – a mix of soil components that does not segregate in a slurry, during pipeline transport or when placed. A specific mix of sand, fines and water is required to achieve this.
Also called NST.
Normal stress (soil mechanics) -stress or load applied at surface
Off shore (geology) – deposition environment off-shore as opposed to on land or on a beach
Off shore bar (geology) – a sand bar that forms off shore
Operating permit – regulatory approval required for most operations
Operator (oil sands) –organization that manages an oil sand project
Order of magnitude – size, factor of 10.
Ore (mining) – material that can be mined and the contents extracted profitably
Ore free zone – area that is not underlain by ore
Ore grade (in oil sands) - % of total weight that is bitumen
Outwash (geology) – soil deposited by water exiting from a glacier, usually refers to sand and gravel
Overburden (mining) – material above ore – must be removed before ore can be mined.
Overburden of good quality – overburden that is suitable as a construction material
Overdose (extraction) – adding too much reagent, often has adverse side effect
Oxidized ore (mining) – ore that has been exposed to weathering and has degraded as a result
Packing (sand) – arrangement of sand particles and the density that provides frictional strength
Appendix 3 Definitions

Paleozoic (geology) – span of time from roughly 120 to 500 million years ago
Partial solution – only solves part of a problem. Require something additional
Particle shape (soil mechanics) – e.g. equidimensional, elongated, rounded, flat, high width to thickness
Particle size (soil mechanics) average diameter of an equivalent sphere,
Path to closure – route that a project is taking to achieve acceptable closure when reclamation is completed
Payout – project financial status – when cumulative income exceeds development costs
Peak strength – maximum strength achieved on a stress strain curve
Permanent storage (reclamation) – placement that will last forever
Permeability (hydraulic conductivity) ability of a material to transmit fluid or water
Perpetual care – requires maintenance forever. Require an endowment to fund the work.
Pipeline – pipe conduit to transport fluid, also can mean the act of transport by pipeline
Pipeline specification – specification governing allowable solid and water content of material that will be allowed in a pipeline.
Plastic clay – clay that exhibits plastic characteristics –
Plasticity – ability of a material to deform a significant amount without rupturing
Plasticity Index -liquid limit minus plastic limit
Plastic limit – water content separating plastic behavior from solid behavior
Pledge project assets (reclamation)– provide project infrastructure as collateral for a reclamation bond
Polluter – the one that caused pollution.
Pore space – open space between soil particles
Pore water pressure – pressure acting on water contained in port space. It can offset normal stress.
Pre Cretaceous river – a historic river that existed before the Cretaceous period
Pre development baseline–study to document natural conditions that existed before project development started
Pre glacial channel (geology) a channel that existed before continental glaciations
Pre production (project) – project stage before operations produce a marketable product
Primary separation vessel – first step in oil sand extraction, used to separate sand from the rest
Prime responsibility – most important assignment
Privilege (legal) – custom whereby information provided to a lawyer in trust is not available for disclosure
Probability – statistical chance of an event occurring
Process affected water – water exposed to oil sand or processes, judged to be contaminated.
Process aids (extraction) – chemicals added to facilitate separation of bitumen from oil sand
Production – making product
Profit – income after deduction of expenses, royalty and taxes
Progressive reclamation – reclamation that is undertaken at the first opportunity
Progressive reclamation approach –progressive as opposed to deferred approach to reclamation
Project approval – process of obtaining regulatory approval for commercial development
Project life cycle – the full cycle extends from initial planning through development, operations and closure
Appendix 3 Definitions

Projected inventory (tailings) – forecast volume of fluid tailings in the years ahead if there is no change in current operations

Proliferation of tailings ponds – rapid growth or expansion perhaps in excess of need or capability of the landscape to host them

Public hearing – hearing into a project application that is open to the public.

Pump – move by pipeline, motor that does the pumping

Qualifying Environmental Trust - a trust established to fund future reclamation activities. Covered by federal law.

Quartz (geology) – common mineral in oil sands – composition silicon dioxide

Rate of return (economic)- financial return to investor considering all investment, expenses, royalty and taxes.

Reclamation and Closure Plan – a plan outlining goals, procedures, and schedules to reclaim a disturbed site so it will qualify for a timely Reclamation Certificate.

Reclamation Certificate – a certificate granted by regulators attesting to the fact that the disturbed site has been satisfactorily reclaimed. It also means that the developer’s reclamation liabilities are over.

Reclamation cost – the cost of reclaiming a site to a satisfactory condition

Reclamation Security Agreement RSA – agreement between the developer and the regulators that defines what a qualifying environmental trust is to accomplish.

Reclamation standards – standards governing reclamation.

Recycle water (extraction) – process water that is recycled for re use.

Recycle water – in-plant – process water that is captured and recycled in the extraction plant. An advantage – the contained heat is also captured. Normal extraction discharges the water and heat to the tailings pond.

Registered Trust Company – a company registered to legally manage trust accounts.

Regulator – one who administers project licensing and review on behalf of the government

Rehandle (mining) – handle material a second time , also applies to the material

Remould – thoroughly mix so as to destroy previous structure

Reprocessed – process for a second time

Repulsive forces – interparticle forces that prevent particles from approaching one another. Opposite of attractive forces.

Reserves – quantity of recoverable product in owned ore – measured to a given standard

Reservoir – geological trap that holds oil resource

Residual bitumen (tailings) – unrecovered or extracted bitumen that remains in waste streams

Residual solvent – unrecovered solvent that remains in waste streams

Residue – solid component after filtration or centrifuge treatment

Responsible goals (project) overall goals that will direct project operators to do the right thing

Restore to an improved state – reclaim to a standard higher than required

Review Board – panel of independent experts that reviews and advises on project matters

Risk (dam failure) – risk of a tailings dam breaching and releasing contents

Risk (unnecessary) – unnecessary risk due to deferred proof that reclamation plans are viable

Risk premium – added financial assurance need to cover uncertainty in planning basis or cost
Appendix 3 Definitions

Saline – contains a high concentration of dissolved salt
Sand – granular material with a grain size of between 74 and 1,000 microns
Sand dune – deposit of wind blown sand
Sand to fines ratio – weight of sand sized material/weight of fine grained material
Sandstone – bedrock of cemented sand
Satellite (mine) – remote mine that is related to but separate to the base mine
Scanning electron microscope – very high powered microscope
Screen (ore) – pass ore through a screen to remove lumps.
Screen (sieve) – device with holes in it to catch and remove particles above a given size
Sea Shore (environment) – deposition environment at the edge of the sea – beach, shallow water etc.
Sedimentary rock – rock composed of transported and deposited fragments of previous rock
Seepage – water issuing from a face or base of a mine
Selective mining – mining that removes select material such as a problem ore or clay bed
Self supporting solid- material that possesses sufficient strength that it can stand without support
Separation cell (extraction) – cell where rising air bubbles attach themselves to bitumen and separate it from waste material
Sequence of land use – typical sequence – clear overburden, mine ore, backfill with tailings, reclaim.
Settling speed (extraction) speed at which a particle will sink to a lower level
Shale – compressed or cemented clay rock
Shareholders – owners of shares on a company
Shear strength drained – strength of material loaded at a rate that is slow enough that it can drain excess pore water pressure
Shear strength (undrained) strength of material loaded at a rate too fast to permit drainage
Shovel (mining) – large excavator used to load trucks
Silt – granular material with a particle size between 2 and 74 microns
Silt content – % by weight of solid material that is silt,
Sink hole – vertical solution chamber leading to solution activity at depth
Site development – preparing a site for another use – drainage, level surface, provide work pads
Sludge – weak, wet, fine grained tailings, MST
Slurry – suspension of soil material in water
Socio economic assessment – study of effect of a proposed development on local social infrastructure and economic well being of the surrounding community
Sodium adsorption ratio (SAR) – a measure of the concentration sodium vs. calcium and magnesium ions in pore water. \(\text{SAR} = \frac{\text{Na}/(\text{Ca}^2 + \text{Mg}^2)}{0.5}\) SAR levels over 12 to 15 adversely affect plant growth, soil is dispersive, highly erodible and unsuitable for use in water retaining dykes.
Sodium clay – clay surrounded by pore water in which sodium is the dominant dissolved ion.
Sodium hydroxide – Chemical with the formula NaOH
Soil skeleton – structure of soil particles that forms in sedimenting soil
Soil – sodic – soil in which the dominant dissolved ion in the pore water is sodium chloride
Soil structure – structure formed by soil particles
Soil structure collapse – (geotechnical) collapse of a weak soil structure if unable to support load
### Appendix 3 Definitions

**Solid component** – solid mineral weight % of a soil/water mixture  
**Solid deposit** – deposit that possesses sufficient strength that it can stand without external support  
**Solid waste** – waste deposit that possesses sufficient strength that it can stand without external support  
**Solid weight %** - Weight % of solid mineral matter in a mixture of solid and water  
**Solid content** – weight % of a soil that is solid matter  
**Solution** – mixture of solid material and water, or mixture of chemicals dissolved in water  
**Solvent** – substance that will dissolve another  
**Scientific Research and Experimental Development** – SR&ED federal research incentive program  
**Stakeholder** – any person with an interest in a project  
**Starter pond** – tailings pond used until there is room for tailings in the mine.  
**Start-up** – turn on, start production of a new facility  
**Start-up stage** - stage of a project at the start of operations.  
**Status quo** – current conditions  
**Sterilize (mining)** – prevent access to ore,  
**Stock exchange** – market where shares of public companies are traded  
**Stoke’s Law** – law that governs the rate at which a particle will settle in a fluid.  
**Strength** – ability of a material to resist deformation  
**Suspension** – mixture of solid particles in a dilute slurry  
**Syncrude** – Syncrude Canada Limited – the largest oil sand developer  
**Surcharge** – weight applied at surface  
**Surface activity (soil mechanics)** – small forces active on the surface of clay particles because of the large surface area  
**Surplus water (in CT)** water above the equilibrium water content, it will drain off  
**Swamp deposit** – sediments that form in a swamp, organic, clay rich  
**Syncrude Crown Agreement** – agreement that gave Syncrude a legal status  
**Tailings** – waste derived from oil sand extraction – sand, silt, clay, water, some bitumen.  
**Tailings beach** – beach deposit at the edge of a tailings pond  
**Tailings pond** – waste facility involving perimeter dykes and a central pond. Fluid tailings is contained in the pond.  
**Tailings Pond** – active – tailings pond that is in use  
**Till** – soil deposited by a glacier  
**Till** – basal – soil deposited at the base of a glacier – generally dense, strong and well graded  
**Till - ablation** – soil that was in or on the glacier when the ice melted.  
**Timely dewatering** – remove water in time for the project to benefit from it  
**Timely Reclamation Certificate** – qualify for a reclamation certificate within a few years after the end of operations  
**Top soil** – organic top layer of soil that supports plant growth  
**Traditional economic model** – computes return based on income and expenses vs. time (ignores liabilities)
Appendix 3 Definitions

**Transition layer** – layer of water in a tailings pond between overlying zone where particles settle freely and an underlying zone where settlement is hindered

**Trust and Loans Company Act** – legislation governing establishment of a Trust and Loan financial institution

**Turbulent processing (extraction)** – highly agitated slurries that may break up and disperse clays

**TV/BIP** – dimensionless ore body characterization term – total volume of material to be moved/volume of bitumen in place

**Unconformity (geology)** – gap in the sedimentary column where a period of time is not represented.

**Underflow** – stream issuing from the base of a thickener or cyclone (the coarse stream). Fine grained material exits via the overflow.

**Uniform grain size** – soil with only one grain size.

**Upgrade (refining)** – convert bitumen to a light synthetic crude

**Upgrading yield (refining)** – volume of product out/volume of product in – measured in %

**Verify feasibility** – demonstrate that it is feasible to reclaim using approach proposed.

**Volatile Organic Compounds (VOC’s)** – Volatile organic compounds - deleterious emissions associated with oil sand tailings. Examples Light hydrocarbon emissions such as

**Void space** – pore space between soil particles

**Void ratio** (soil mechanics) (volume of void space)/(volume of solid)

**Volume %** - % of a particular component in a soil – volume measure

**Waste** – by product of oil sand processing that has no value

**Waste dump** – place where solid waste is stored

**Waste dump** – out-of-pit. A waste dump located outside the mine.

**Water chemistry** – type and concentration of chemicals present, pH

**Water sands** – water bearing sands below the bitumen saturated zone.

**Water clarification facility** – facility to clarify water – usually in the plant as opposed to tailings pond.

**Weight %** - percent of the total weight due to a specific component.

**Weight % clay** – percent of total weight due to clay. Sometimes computed without considering contribution of sand and silt as it is the clay component that matters.

**Weight % fines** – percent of total weight due to fines

**Well sorted** – uniform grain size – usually a term applied to sand

**West Texas Intermediate crude** – crude oil used to describe standard price of oil

**Zero water discharge policy** – policy that prohibits oil sand projects from discharging process affected water during the operating phase of a project.
Appendix 3 Definitions

Symbols
AEPEA \ Alberta Environmental Protection and Enhancement Act
AENV – Alberta Environment
bbl – barrels
BML – Base Mine Lake (Syncrude)
BAET – Best available economic technology
C&R Plan – Closure and Reclamation Plan
CCA – Capital Cost Allowance
CDE – Canadian Development Expense
COS – Canadian Oil Sand Trust (the proper stock symbol is COS.UN)
CWR – clay to water ratio
EIA – Environmental Impact Assessment
ERCB – Energy Resources Conservation Board
GJ - Giga Joule – measure of energy, 10^9 joules
ha – hectare, area measuring 100 m by 100m
ITC – investment tax credit
LTP – long term plan
MFT – mature fine tails
NGO – Non Government Organization
QET – Qualifying Environmental Trust
RSA – Reclamation Security Agreement
SAR – sodium adsorption ratio
SFR – sand to fines ratio
NaOH – sodium hydroxide
SRD – Alberta Sustainable Development
SR&ED – Scientific Research and Experimental Development
TV/BIP – total volume /volume of bitumen in place
VOC’s Volatile organic compounds
WOR – waste to pre ratio
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<td>Photo B.A3.2 with sand and silt superimposed to scale</td>
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<td>Illustration of sand and silt surrounded by clay</td>
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Appendix B.4 Soil Properties and Behaviour

B.4.1 Introduction

This appendix deals with soil properties and behaviour pertinent to tailings. Topics covered include:

1. Introduction
2. Contrasting characteristics of sand, silt and clay (The building blocks)
3. Behaviour of soil in a dilute suspension (Activity in a tailings pond)
4. Effect of adding sand to clay and vice versa (What dominates soil behaviour)
5. Permeability and gradient (What controls the rate of consolidation)
6. Consolidation (Natural densification of MFT)
7. Strength (What we need for reclamation)
8. Swelling clays
9. Measuring properties
10. Closure on soil properties

The Appendix should be read along with Chapter B.10 on processes that densify MFT.

Geotechnical work in oil sands tailings is complicated by a number of factors as noted below:

1. Bitumen
   a. Bitumen complicates material handling, sample preparation and testing
   b. Bitumen is usually treated as part of the water
   c. Bitumen removal to prepare a sample for testing often changes the basic behaviour of the material.
2. Competing classification systems use the same terminology but have different meanings. Process engineers are in charge of extraction and tailings. Their simple needs and terminology are compared with geotechnical definitions in Table B.A4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Extraction Use and Approach</th>
<th>Geotechnical Use and Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use</td>
<td>Simple application</td>
<td>Understand material properties Predict behaviour Predict how to improve character of tailings and prepare for closure. Forecast the volume of MFT</td>
</tr>
<tr>
<td></td>
<td>• Does it settle quickly in water or not</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Simple measure of slurry density</td>
<td></td>
</tr>
<tr>
<td>Focus</td>
<td>Bitumen extraction</td>
<td>Deal with tailings Optimize path to closure</td>
</tr>
</tbody>
</table>
Table B.A4.1 Comparison of Extraction vs Geotechnical definitions (cont.)

| Relevant particle size | Coarser or finer than 44 microns to identify which circuit in extraction will handle it. | Sand - > 74 microns (inert, settles rapidly, high permeability) Silt <74 and > 2 microns (inert, settles slowly, low permeability Clay > 2 microns (not inert, important in the formation of fluid tailings, large volume, low permeability) |
| Relevant materials | Coarse (sand) (> 44 microns) Fines (< 44 microns) (“Fines may contain 0 to 100% clay sized material) | Sand > 44 microns Silt (< 74 and > 2 microns) Clay (< 2 microns) |
| Water content | (wt water +bitumen)/ (wt sand + fines + water + bitumen) | Wt water/wt solids |
| Clay content | No equivalent “wt fines”/(wt solid +water + bitumen) | Weight clay/wt all solid |

3. Widespread use of improper measurement of particle size distributions that seriously under-report the amount of clay sized material. (see Section B.A4.9.3).
4. Variable soil. The geological environment in which the McMurray Formation was deposited is highly variable. As a result measurements and forecast material properties are highly variable. Variability is an important aspect that researchers ignore at their peril.

Table B.A4.2 lists some geotechnical correlations that depend on accurate measurement of key parameters.

Table B.A4.2 Parameters used in geotechnical correlations to forecast behaviour.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Derivation and how it is used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen content</td>
<td>Often treated as part of the water. Misleading when water content is used to forecast behaviour.</td>
</tr>
<tr>
<td>Water content</td>
<td>Key component of many parameters used to forecast geotechnical behaviour. The geotechnical water content is used in the parameters noted below.</td>
</tr>
</tbody>
</table>
Appendix B.4 Soil Properties and Behaviour

Table B.A4.2 Parameters used in geotechnical correlations to forecast behaviour (continued).

<table>
<thead>
<tr>
<th>Property/Material</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Size</td>
<td>&gt;75 µ</td>
<td>2 µ to 75 µ</td>
<td>&lt; 2 µ</td>
</tr>
<tr>
<td>Visible to naked eye</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Particle shape</td>
<td>Equidimensional L/D ~1</td>
<td>Equidimensional L/D ~1</td>
<td>Plate shaped L/D ~ 10 to 100</td>
</tr>
<tr>
<td>Surface activity</td>
<td>Inert</td>
<td>Inert</td>
<td>Active</td>
</tr>
<tr>
<td>Surface area</td>
<td>Low</td>
<td>Low</td>
<td>Increases exponentially as size decreases</td>
</tr>
<tr>
<td>Cohesive</td>
<td>No</td>
<td>No</td>
<td>Cohesive</td>
</tr>
</tbody>
</table>

B.A4.2 Characteristics of sand, silt and clay (the building blocks)

The following discussion is a generalization of soil components and the behaviour of each. The discussion relates to individual particles. Materials are distinguished according to grain size, although the mineralogy of clay is usually different from that of silt and sand.

Table B.A4.3 Contrasting characteristics of sand, silt, and clay.

<table>
<thead>
<tr>
<th>Property/Material</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Size</td>
<td>&gt;75 µ</td>
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<td>Equidimensional L/D ~1</td>
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</tr>
<tr>
<td>Surface area</td>
<td>Low</td>
<td>Low</td>
<td>Increases exponentially as size decreases</td>
</tr>
<tr>
<td>Cohesive</td>
<td>No</td>
<td>No</td>
<td>Cohesive</td>
</tr>
</tbody>
</table>
Table B.A4.3 Contrasting characteristics of sand, silt, and clay. (cont.)

<table>
<thead>
<tr>
<th>Property/Material</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasticity</td>
<td>No</td>
<td>No</td>
<td>Plastic</td>
</tr>
<tr>
<td>Origin of strength</td>
<td>Frictional</td>
<td>Frictional</td>
<td>Cohesive</td>
</tr>
<tr>
<td>Permeability</td>
<td>High</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>Affected by water chemistry</td>
<td>Inert</td>
<td>Inert</td>
<td>Highly Affected</td>
</tr>
</tbody>
</table>

Legend for Table 6.1

\[ \mu = \text{micron, (one millionth of a metre)} \]
\[ L = \text{Length or width of a particle} \]
\[ D = \text{Thickness of a particle} \]
\[ \text{Cohesion} = \text{possesses strength independent of normal stress} \]
\[ \text{Plasticity} = \text{able to undergo large strain without rupture} \]

Sand is composed of visible equidimensional particles.

Silt is much like sand, but finer grained and with lower permeability.

Clay is composed of very fine, plate shaped particles. It possesses cohesion and plasticity due to its high surface area and interaction with water and water chemistry. Clay mineralogy often favours the flat particle shape.

Interaction between the surface of clay particles, adjacent water, and ions dissolved in that water, affect clay behaviour. Figure B.A4.1 indicates that surface area increases exponentially as the particle size decreases. The larger the surface area, the larger the effect of small surface forces. Figure B.A4.1 also indicates a low surface area for sand and silt sized materials. That explains their inert behaviour.

Ultrafine particles have a diameter of less than 0.2 microns. They have an extremely high surface area and can dominate soil behaviour if present (Tu et.al., 2005).

**B.A4.3 Behaviour of soil in dilute suspensions (tailings pond activity)**

Table B.A4.4 illustrates behaviour in a dilute suspension. Sand and silt behave as inert granular materials. Stoke’s law states that the rate of settlement is proportional to the particle diameter squared. (Terzaghi et al, 1996). As a result, sand, with its large sized particles, settles out of suspension rapidly. Silt, because of its finer particle size, settles at a slower rate, but it will eventually settle out of suspension. A practical example of behaviour in a dilute suspension is the behaviour in the primary settling vessel in extraction. There sand settles rapidly and can be removed from the ore slurry. Silt and clay sized particles remain in suspension.
Table B.A4.4 Behaviour of soil in a dilute suspension.

<table>
<thead>
<tr>
<th>Property/Material</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling speed</td>
<td>Rapid</td>
<td>Slow</td>
<td>Very slow</td>
</tr>
<tr>
<td>Water chemistry</td>
<td>No effect</td>
<td>No effect</td>
<td>Large effect</td>
</tr>
<tr>
<td>Time to settle out of suspension</td>
<td>Rapid</td>
<td>Requires time</td>
<td>Requires a lot of time</td>
</tr>
<tr>
<td>Nature of settled material</td>
<td>Loose granular</td>
<td>Looser granular</td>
<td>Develops a weak open structure</td>
</tr>
<tr>
<td>Time for settled material to develop strength</td>
<td>Short time</td>
<td>Longer time</td>
<td>Very long time</td>
</tr>
</tbody>
</table>

Surface charges on a clay particle attract a halo of surrounding water and dissolved ions. The size of the halo depends on the water chemistry. The halo is broad if the ions are monovalent and dilute. The halo is compact if the ions are multivalent and concentrated. The clay particles with their attracted halos interact with other suspended clay particles and their attracted halos.

Near the surface of a tailings pond, clay particles and their attracted halos are so far from their neighbours that they do not interact. They settle freely. As the concentration of particles increases at depth, the particles interact and settlement is ‘hindered’. The particles orient themselves with one another according to the forces of attraction and repulsion between particles. Eventually a weak structure forms. Repulsive forces that increase as particles come closer together prevent further densification.
‘Mature Fine Tails’ or ‘MFT’ has that structure. Figure B.A4.2 (Reeravipool et. al., 2008) shows a pair of scanning electron microscope photos of soil structure in fluid tailings. The sample was prepared for viewing using techniques that remove water without disturbing the soil structure. The photo on the left represents a magnification of 500 times. The photo on the right represents a magnification of 2,000 times. Scale bars in the upper right corners of the photos are 10 and 1 microns long respectively. The photos show individual plate shaped particles and the trend of the soil skeleton. Water occupies most of the volume. In MFT, solid particles only occupy 15% of the volume.

The MFT structure is extremely weak. It is postulated that recently formed MFT is too weak to support an individual grain of sand. If a grain of sand drops into the tailings pond, it will settle through the upper water zones until it reaches the MFT. There the sand grain will overload and break the MFT structure and gradually drop through the deposit. Eventually the sand grain will sink to the bottom of the deposit, 10’s of metres below.

At some point in the future, the repulsive forces separating clay particles will be overcome. Then the particles will move closer together and develop strength. Initially they will only be strong enough to support light loading. Applied loads will push particles closer together to a stronger packing.

Figure B.A4.3 is photo B.A4.2 with a scale sized sand particle superimposed on it.

If the clay particles in suspension occur in lumps or booklets of particles instead of as individual particles, the surface effects will be reduced and the lumps will behave like coarser sand particles.
Appendix B.4 Soil Properties and Behaviour

B.A4.4 Effect of adding sand to clay and vice versa (what dominates behaviour)

B.A4.4.1 Effect of adding sand to clay

Clay structure controls the strength of a clay deposit. It is proportional to the relative amounts of clay and water present. The proportions are indicated by the weight ratio: clay/(clay + water) or water/(clay plus water).

If one grain of sand is added to a clay deposit, it will add to the volume and to the weight % solids. However, clay that surrounds it will dominate strength. The sand acts as inert filler. Adding more sand will have the same effect. The clay component will dominate strength as long as the clay phase has continuity. Figure B.A4.4 illustrates the geometry of sand particles suspended in a clay soil.

Sand will begin to contribute to strength when there is so much sand that the sand particles touch and interact with each other. The concentration when that will happen depends on the grain size distribution of the sand. Sand particles are expected to start interacting with each other when the sand concentration is over 50%.

The effect of adding silt to a clay deposit will be similar to the effect of adding sand.
Figure B.A4.4 Illustration of sand and silt surrounded by clay

Figure B.A4.5 shows the effect of adding sand to an MFT deposit that contains 30% by weight clay. Adding sand increases the volume, the weight, and the weight % solids. However, the clay content (clay/(clay + water)) and the water content (water/(clay+water)) do not change. As a result, we should not expect the addition of sand at these concentrations to affect strength.
Appendix B.4 Soil Properties and Behaviour

The latter point is important because many who are studying fluid tailings assume a direct relationship between strength and overall density. Indeed some operations report improved performance by adding sand to a thickener. The sand may aid processes in the thickener, and will increase the overall solids content but, unless they increase the \((\text{clay}/(\text{clay} + \text{water}))\) ratio they will not improve strength.

**B.A4.4.2 The relevance of “fines”**

Fines are the amount of material smaller than 44 microns. The relative amounts of silt and clay sized particles present in “fines” are not defined. They can vary from 0% to 100% each.

The preceding sections showed the importance of clays. Clay is a major contributor to the formation of MFT and gives it such unique properties. The clay component will dominate strength as long as it exceeds about 50% of the total soil present. Terms that describe the character of the clay component are: \((\text{clay}/(\text{clay} + \text{water}))\) and \((\text{water}/(\text{clay} + \text{water}))\). Those ratios are calculated as if the silt and sand were absent.

In the preceding examples the “fines” content is somewhat irrelevant. Similarly weight % solids or weight % water (as a percent of the total weight), as an indication of strength, is misleading.

**B.A4.4.3 Effect of adding clay to sand**

The effect of adding a clay/water mix to a sand deposit is as follows:

- The clay/water mix acts as a pore space filler.
- A minor amount of pore filler will reduce permeability proportional to the amount of pore space that it occupies. The effect on frictional strength of the sand will be negligible.
- When the pore filler fills the void space in the sand (20% to 40%) it will dominate permeability. Initial peak strength of the sand should be unchanged as long as the original packing of the sand is unchanged. Leakage along the sand surface may keep permeability higher than it would be through the clay alone.
- The volume of the pore filler can only exceed the pore space of the sand if it pushes the sand grains to a looser packing. That will reduce contact between the sand grains and reduce frictional strength accordingly. The pore filler will dominate permeability when it exceeds 30% to 50% of the volume.
- Adding even more pore filler will cause additional strength loss in the sand. When the pore filler has continuity, it will dominate the strength of the deposit. (>50% pore filler)

The relative amount of pore filler that sand can tolerate depends on the grain size distribution of the materials involved. Approximate concentrations of pore filler, where we expect to see effects, are indicated by bracketed percentages in the preceding discussion.
Appendix B.4 Soil Properties and Behaviour

A practical example of the effect of adding fines to sand is what happens on a tailings beach. Operators seek to maximize fines capture in the sand voids because fines captured in the beach are not available to make MFT. The outcome is less MFT.

A beach can tolerate limited amounts of captured fines, as long as the sand is free to settle to a dense strong state and as long as the sand retains adequate permeability.

Fines will dominate properties of the beach if capture is too successful. A low beach angle, reduced trafficability, reduced permeability, and low strength indicate that fines are dominating behaviour. If the goal is to create a solid self-supporting soil, it might be best to limit fines capture in a beach to 20% of solids in the beach deposit. That can still represent 50% of the MFT forming material so is a valid step.

B.A4.5 Permeability (What affects the rate of consolidation)

Hydraulic conductivity, or permeability, is the capacity of a material to transmit fluid. The velocity at which water flows in a soil is described by equation 1 below:

\[ V = K \cdot I \]  
(equation 1)

Where:
- \( V \) = flow velocity
- \( K \) = coefficient of permeability
- \( I \) = hydraulic gradient = head loss/length

Hydraulic conductivity relates to properties of the fluid and of the material it is passing through. Permeability only relates to properties of the material. The two terms are interchangeable where fluid properties are essentially constant.

Permeability is an important parameter because it affects the rate at which water will drain from a tailings deposit. Permeability affects the feasibility of timely dewatering, densification and strength gain in tailings.

Permeability also affects frictional strength. Permeability controls the rate at which excess pore water pressure that reduces normal stress can dissipate. In the worst case, where the pore water pressure matches the normal pressure, strength drops to zero and liquefaction occurs.

Figure B.A4.6 shows a plot of hydraulic conductivity vs. void ratio for fluid tailings (Scott et al, 2008). The hydraulic conductivity decreases by several orders of magnitude as the soil densifies to a condition representing soil with strength. This suggests that the rate of consolidation will slow considerably as fine tailings densify to a solid state.
B.A4.6 Consolidation (natural densification of MFT)

Consolidation takes place when a new layer is added on top of an existing saturated soil deposit. Initially, the new load is carried by an increase in pressure in the pore water. The increase in pore pressure causes some water to drain from the system. Drainage reduces pore pressure, which transfers its share of the load to the soil skeleton. Additional load pushes particles in the skeleton to a denser, stronger position. Densification of the soil skeleton loads the pore water and the process repeats itself until the new surface load is supported entirely by the soil skeleton (Devenny et. al., 1993).

Conditions necessary for consolidation to occur:

- There must be an applied load at surface,
- A soil skeleton must develop that is strong enough to support part of the load,
- Drainage must be able to occur.

The deposit will undergo considerable volume reduction as consolidation occurs. Permeability will decrease by several orders of magnitude as it consolidates from MFT to a solid state. (Suthaker et.al., 1996). Permeability is further reduced if bitumen is present in the pore space (Suthaker et.al., 1996) or as layers in the soil profile.

In general, the time for a deposit to consolidate is proportional to the length of the drainage path squared. The drainage path of MFT deposits is quite long so does not favour consolidation in reasonable
time for closure. The length of the drainage path can be shortened by wick drains or by internal drainage paths such as paths created by gas escaping from bacterial action.

Forecasting the time for fine grained tailings to consolidate is complicated by:

- Variations in material composition and stratigraphy.
- Repulsive forces that delay development of a soil skeleton needed to support applied loads.
- The presence of bitumen – in pores and in discrete layers.
- Uncertainty over the effective length of the drainage path.
- Material properties that vary by several orders of magnitude as the deposit becomes denser.

Simple models based on field observations suggest relatively fast rates of consolidation that appear to be linear with time - 100 year time frame. In contrast most geotechnical forecast models predict exponential slowdowns as the deposit consolidates.

Considering the limited amount of field consolidation to date, and the slow-down resulting from a decrease in permeability as the deposit becomes denser, we should be cautious about forecasts about rapid consolidation.

When an electrical field is applied to a mixture of clay and water, it acts as an extra force. Clay particles with their negatively charged surfaces are attracted to the anode. Water, with its attracted ions, is attracted to the cathode.

Application of the electrical field to a dilute suspension is called electrophoresis. Application to a solid mix is called electro osmosis. Both processes speed water removal.

**Summary on consolidation**

Consolidation is the natural process that will dewater and strengthen MFT. The time for consolidation to take place depends on the magnitude of the applied load, the permeability of the deposit, and the length of the drainage path.

The MFT deposits have not been designed to facilitate consolidation in a time frame that will benefit expectations for closure. Deterrents include:

- The weak soil structure that impedes the onset of consolidation,
- A drainage path that is 10's of metres long and therefore requires a very long time to consolidate.
- Decreasing permeability as the deposit consolidates.

Bubbling activity from bacteria in the MFT are creating very short drainage paths that are accelerating consolidation. That benefit could halt when the MFT develops sufficient strength to stop the
propagation of bubble channels.

Steps that could speed the consolidation process

• Place MFT in thinner layers between sand layers.
• Increase the surcharge applied at surface.
• Provide drainage at the bottom to increase effective stress throughout the profile.
• Install drainage wicks to reduce the length of the drainage path.
• Supplement the effectiveness of drainage wicks with layers of sand in the MFT profile.
• Apply an electrical field to speed drainage by electro osmosis.
• Make full use of drainage path reduction created by bubble paths.

A perpetual maintenance program would allow time for consolidation to strengthen the MFT. If that is not feasible, the weak deposits will probably require reprocessing before they will qualify as a strong self supporting material.

B.A4.7 Strength (what we need for reclamation)

B.A4.7.1 Strength in General

Equation 2 defines frictional strength...

\[ \tau = (N-\mu)\tan \varnothing \]  \hspace{1cm} \text{(equation 2)}

Where
\[ \tau = \text{shear strength} \]
\[ N = \text{normal stress} \]
\[ \mu = \text{pore water pressure} \]
\[ \varnothing = \text{angle of internal friction} \]

Frictional strength depends on two parameters: effective stress (normal stress minus pore water pressure) and \( \varnothing \), which is a function of the mineral grain surface, and the density of particle packing. The pore water pressure is important because it can reduce the effective stress. Liquefaction occurs when the pore water pressure offsets the normal stress and the strength drops to zero.

Clays are relatively impermeable so strength depends on whether drainage can occur or not. Equation 3 describes the strength in clay under drained conditions.

Drained shear strength: \[ \tau = C+(N-u)\tan \varnothing \] \hspace{1cm} \text{(equation 3)}

Where \( \tau, \mu, \) and \( \varnothing \) are as defined in equation 2
\[ C = \text{cohesive strength} - \text{independent of normal stress} \]

Under rapid loading, the clay does not have time to drain. Then the undrained shear strength applies. It is determined in tests that duplicate rapid loading such as an unconfined compression test, a vane shear...
Appendix B.4 Soil Properties and Behaviour

test or a falling cone test.

**B.A4.7.2 Thixotropy**

Thixotropy is a strength gain that develops spontaneously with time in some weak clay soils. The strength gain can be an order of magnitude. (Suthaker et al., 1997). Implication: the plot of strength vs. weight % solids indicated by Figure B.A4.7 in the next section could be shifted by one log cycle.

Thixotropic strength disappears if the soil is remoulded.

**B.A4.7.3 Strength of fine tails**

Very little information is available on the strength of fluid tailings and how strength develops as water is removed from MFT. Figure B.A4.7 shows the trend of undrained shear strength for fine tailings vs. weight % solid. As the solid is clay, the weight % solid in Figure B.A4.7 is equal to (clay/(clay + water)). The author derived the trend curve from a number of sources reporting work on Syncrude MFT, so clay will form much of the solids and will dominate strength (Fine Tails Fundamentals Consortium, 1995e). Strength at the left side of the figure is reliable because it was derived from liquid and plastic limits.

![Figure B.A4.7 Strength vs. density of MFT](image)

Strength indicated in Figure B.A4.7 spans five orders of magnitude. The lower strengths represent materials that are mostly water. There the strength, if it can be called strength, is miniscule. The figure also indicates the strength associated with MFT and the target for solid waste desired for reclamation. A lot of water must be removed from MFT before it will acquire the strength desired for reclamation.
Appendix B.4 Soil Properties and Behaviour

B.A4.7.4 Strength of some tailings deposits

Table B.A4.5 indicates the strength associated with some known tailings deposits. It was derived from Figure B.A4.7 and known concentrations of solids. Table B.A4.6 indicates the strength required for different applications. Comparison of the two tables reveals a huge gap between the strength available in fluid tailings today and the strength desired in a self-supporting reclaimed material.

Table B.A4.5 Estimated strength of various clay/fine tails streams.

<table>
<thead>
<tr>
<th>Parameter Type of material</th>
<th>Water content [(water/(fines + water)]</th>
<th>Solid content [fines/(fines + water)]</th>
<th>Undrained Shear Strength kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal plant effluent</td>
<td>90%</td>
<td>10%</td>
<td>0.002</td>
</tr>
<tr>
<td>MFT</td>
<td>70%</td>
<td>30%</td>
<td>0.005</td>
</tr>
<tr>
<td>Thickener discharge</td>
<td>70%</td>
<td>30%</td>
<td>0.005</td>
</tr>
<tr>
<td>Centrifuge cake</td>
<td>40% - 50%</td>
<td>60%</td>
<td>0.5</td>
</tr>
</tbody>
</table>

B.A4.7.5 Strength required for different applications

Table B.A4.6 Strength required for different applications.

<table>
<thead>
<tr>
<th>Application</th>
<th>Required undrained Shear Strength (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit – water content separating liquid from plastic behaviour of a soil. Strength required for transport of soil in an open truck</td>
<td>1.7</td>
</tr>
<tr>
<td>Strength required to transport soil on a conveyor with a slope of 15 degrees</td>
<td>5 to 10</td>
</tr>
<tr>
<td>Strength required to support a person standing on the surface</td>
<td>10</td>
</tr>
<tr>
<td>Strength required to consider a material self supporting</td>
<td>10 to 50</td>
</tr>
<tr>
<td>Minimum strength required for subgrade to support a haul road</td>
<td>50 to 100</td>
</tr>
<tr>
<td>Plastic limit – water content of a soil separating plastic from solid behaviour</td>
<td>170</td>
</tr>
</tbody>
</table>

According to Figure B.A4.7, the minimum density (measured as [clay/(clay+water)]) that will achieve the target strength for reclamation as a solid material is 72%. As was noted previously, more information is needed on this topic.

B.A4.7.6 Water removal from MFT required to achieve the desired strength

Figure B.A4.8 summarizes the behaviour of an MFT suspension, as water is removed and the solid content increases. Data plotted on the figure include:
Appendix B.4 Soil Properties and Behaviour

1. The solid content increases from low values with liquid like properties at the top of the page to solid material with strength, at the bottom of the page.

2. Horizontal bars across the page represent the relative amount of water and solid corresponding to the solid or water content indicated.

3. The middle column describes behaviour of the slurry as it progresses from a liquid to a solid.

4. The column on the right describes mechanical processes that are used to densify materials like MFT and indicates the range of effectiveness of each.

5. The column on the left shows natural processes that densify MFT suspensions. It also indicates the water content of MFT and the target for solid MFT.

Horizontal bars on Figure B.A3.8 represent the void ratio of the material. The void ratio is defined as the volume of voids (or water) per unit volume of solid material. The top bar corresponds to suspended solids entering a tailings pond. It has a solid content of 5% to 10% and a void ratio of 24. That means 24 volumes of water for each volume of solid material.
Appendix B.4 Soil Properties and Behaviour

MFT is shown with a solids content of 30% and a void ratio of 6.

The target material for reclamation as a solid material has a solid content of about 70% and a void ratio of about 1.5.

**Middle column - Behaviour as MFT densifies.**

The middle column describes behaviour as a material changes from a dilute slurry to a strong, solid material. At the top of the chart particles experience free settling in water. The next state is “hindered settling” as particle spacing diminishes and particles interfere with each other. Finally, at about 30% solids settling stops because repulsive forces between particles prevent a denser packing.

30% solids corresponds to MFT where a soil skeleton and the beginnings of soil strength develop.

With increasing density, strength develops and the behaviour progresses from liquid, to plastic, to solid behaviour. The liquid and plastic limits define the water content between those zones.

**Right column – mechanical processes to densify MFT.**

Mechanical processes to densify MFT are described in Section B.10.3.

Mechanical processes are often aided by process aids such as coagulants and flocculants that change the properties of the soil. A description of process aids is provided in Section B.A4.7.7 below.

**Left column – natural processes to densify MFT**

Natural processes to densify MFT are also described in Section B.10.4.

Consolidation, one of the natural processes is described in section B.A4.6 of this Appendix

**B.A4.7.7 About coagulants and flocculating agents and strength.**

Coagulants change the equilibrium water content of MFT by collapsing the halo of water and dissolved ions that surround each clay particle. The collapse is caused by:

- An increase in the concentration of ions present and/or
- An increase in the valence of the ions present (more concentrated charge per unit volume).

Flocculants change the surface properties of the clay particles, enhancing forces of attraction that lead to a denser material in a short period of time.

Some flocculating agents behave differently at different temperatures. (Li et.al., 2008) At high temperatures (such as those used in extraction) the flocculating agent agglomerates particles. Later as the deposit cools the flocculating agent enhances consolidation.

Two stages of flocculation treatment are in common use in other industries such as coal processing. (Raymond, 2008)
Appendix B.4 Soil Properties and Behaviour

Super flocculating agents exist that are capable of creating higher densities. They are approached with caution in case their presence in recycle water adversely affects extraction (Gu, 2009).

When coagulants or flocculating agents are added to MFT they change the soil-water interaction. Collapsing the water halo that surrounds particles produces free water that facilitates pipeline transport. A reduced equilibrium water content also results in a reduction in the liquid limit. As a result there will be an increase in the solid content associated with the target strength desired for reclamation.

The relationship between clay water chemistry, effect on the liquid limit, and effect on the solids content related to the target strength is important and requires study.

B.A4.7.8. Summary on strength

The minimum undrained shear strength for reclaiming MFT as a solid is 10 kPa. That is the strength required to support a man standing on surface.

MFT is mostly water. It is a very weak material. Much of the water must be removed before MFT will acquire the strength desired for reclamation.

The Atterberg Limits - Liquid and Plastic Limits accurately indicate the water content at the target strength.

Strength at low sand/fines ration is dominated by clay and is related to the weight ratio [clay/(clay + water)]. Adding sand at low sand/fines ratios increases the volume and the density but not strength unless the [clay/(clay + water)] ratio increases.

Adding coagulants and flocculants changes the equilibrium water content, reduces the Liquid Limit and raises the solid content associated with the target strength for reclamation.

B.A4.8 Measurement

B.A4.8.1 The relevance of measurement in soil properties

Some soil properties are noted by observation. However, many depend on measurement and interpretation of results by trained professionals.

B.A4.8.2 Characterizing clay

Clay properties create the soil structure that causes MFT. Part of the solution to MFT lies in knowing how much clay is present, its character, how it affects MFT, and how to reduce undesirable properties.
Appendix B.4 Soil Properties and Behaviour

A variety of test methods can provide insight into the amount of clay present and its character:

**Grain size analysis:** indicates the sizes present and hence, the amount of clay sized material present.

**Activity:** is a measure of the amount of clay present and the relative strength of surface forces associated with it. In soil mechanics practice, activity is defined as the plasticity index divided by the % of solids that are clay sized material. (Skempton, 1953). Activity is indicated by tests that measure surface area and the cation exchange capacity of a soil. The Methylene Blue test is commonly used in oil sands practice to indicate activity.

**Index tests:** **Atterberg Limits:** identify the moisture content at which material properties change. The limits are also strength tests. The undrained shear strength is 1.7 kPa at the “liquid limit” and 170 kPa at the “plastic limit.” Despite the value to geotechnical professionals, Atterberg Limits are rarely reported in the literature on oil sands.

The **Sodium Adsorption Ratio** is another useful indicator. It indicates the tendency of clay soils to behave as dispersed soils – leading to erosion and poor performance in water retaining structures.

Some challenges in oil sand work include:

- Bitumen gets in the way. Its presence and steps to remove it can alter surface properties.
- Clay lumps may not disperse in extraction and if so will not contribute to MFT formation.
- Standard test procedures have a preparation step that disperses clay particles before particle size measurements are made. That does not represent conditions in extraction so most oil sand operators avoid using dispersing agents.

Most clay samples contain clay lumps to varying degrees. Standard test procedures, used to determine the particle size distribution of a sample, disperse the clays before the particle size is measured. The samples are dispersed so results will be repeatable from test to test. Otherwise, with variable dispersion, results will not be repeatable.

Investigating the behaviour of particles in extraction vessels is a separate issue from characterizing clays. The appropriate method to explore conditions in extraction involves a double test. The first test should characterize the sample – using dispersants. The second test can explore conditions in extraction by testing without dispersants.

The needs of sample characterization and exploring conditions in the extraction plant are quite different. Those needs should be evaluated separately.

**B.A4.8.3 Measuring particle size distribution**

Figure B.A4.9 shows particle size distribution of MFT measured by two techniques. The solid curve represents measurement using the sieve and hydrometer technique. The technique halts size measurement at about one micron because it takes too long for finer grained material to settle out. The
amount of finer material is determined by weighing the amount of material still in suspension. As a result the sample shows that 58% of the particle sizes are clay sized and 40% are finer than one micron.

The other curve represents rapid methods that are used to measure the grain size distribution. The techniques use laser scattering or electrical inductance techniques in a dilute slurry. The tests take many measurements of particle size and compute the statistical distribution of particle sizes. The technique can give an accurate indication of the distribution of grain sizes between the scanning limits of the equipment. Problems arise when results are plotted on a grain size plot, such as a percent finer than plot, and the size at the lower scanning limit is artificially set to zero.

Figure B.A4.9 shows the two grain size distributions. The plot for the sieve hydrometer method shows that 58% of the sample is clay sized material. The quick method shows that 18% is clay sized material – a 70% error. An experienced geotechnical engineer would expect the material that is plotted incorrectly, to behave as a silt. The same person would expect the material that is plotted correctly to behave as a clay. The behaviour of the two materials is very different.

Some projects apparently know how measure and plot particle size distributions correctly. Some do not.

The problem does not significantly affect operations in the extraction plant. However, it has serious implications to understanding the properties of fluid tailings and estimating their volume.
B.A4.8.4 Characterizing samples used in research

Considerable effort is spent on researching characteristics of oil sand. Unfortunately, there are many, many types of oil sand. It is impossible to extrapolate results from one sample to the next, unless simple index tests show that the samples have similar characteristics.

Minimum indexing that should accompany research includes:

- The origin of the sample and prior activity that could affect behaviour,
- The geological facies – if the sample was obtained from undisturbed ground,
- Sampling techniques, transportation and storage before testing,
- How the sample was prepared for testing,
- Index tests:
  - Natural water content,
  - Unified soil classification,
  - Colour,
  - Bitumen content,
  - Representative grain size distribution and method used,
  - Clay mineralogy (if determined),
  - Methylene Blue Index,
  - Type and concentration of ions present in the pore water (and how they were extracted),
  - pH,
  - Atterberg Limits,
  - Sodium Adsorption Ratio.

More than one simple test is needed to characterize oil sand.

Index tests provide a reference so results can be compared with performance experienced elsewhere. Without index tests, research efforts may be wasted.

B.A3.9 Closure on Soil Behaviour

Soil properties are an important part of understanding tailings and how to manage them to a condition that will qualify for a timely reclamation certificate.

Some key areas requiring further attention:
Appendix B.4 Soil Properties and Behaviour

- Strength requirements for reclaimed solid MFT and how to achieve it;
- Relationships between undrained shear strength, Atterberg Limits and \( \frac{\text{clay}}{\text{clay} + \text{water}} \);
- Steps required to achieve the target strength in time for closure;
- How to treat and release surplus water;
- Somehow, induce industry to deal with key parameters that affect tailings – notably the clay content, how to measure it, and how to work with those properties to advantage;
- A better understanding of the effect of chemical treatment on full cycle (i.e. long-term) properties of material. Specifically, the effect of coagulants and flocculants on the Liquid Limit and the corresponding effect on the density related to the target strength.
- What can be done in extraction to improve the properties of tailings without compromising bitumen recovery.

Weak force fields in the clay – water system give MFT its undesirable properties. The potential prize for finding a simple process to overcome the force fields is huge. Stockpiling huge inventories of MFT while ignoring the presence and role of clay does not solve the problem.
This Appendix lists suggested research topics for oil sand tailings.

Recommendations for a demonstration centrifuge test are provided in Appendix B.2.

<table>
<thead>
<tr>
<th></th>
<th>Mining</th>
<th>Value and feasibility of selective mining to reduce MFT</th>
</tr>
</thead>
</table>
| 2 | Effect of processing on dispersion | Factors causing clay dispersion  
• Chemical dispersing agents  
• Turbulent vs gentle conditioning  
• Time in tailings pond (assume clay will exfoliate and become fully dispersed in the pond) |
| 3 | Extraction | Factors that enhance dispersion of clays, the practicality and cost benefit of reducing dispersion in:  
• Hydrotransport  
• Turbulent vs. gentle processing  
  o Effect of hydrocyclones  
• Use of dispersing agents in extraction  
  o Are there process aids that do not disperse clays  
  o Side effects of process aids  
  • E.g. food for bacterial action |
| 4 | Extraction | Value of knowing instantaneous clay content and activity:  
• In extraction (e.g. chemical dosage)  
• In tailings management |
| 5 | Extraction | Merits of adding sand to thickeners:  
• Effect on thickener performance  
• Effect on the volume of fluid tailings  
Effect on strength for S/F ratio < 2 |
| 6 | Extraction | Characterize the different streams in extraction  
• Clay  
  o Clay content  
  o Clay mineralogy  
  o Clay activity  
• Heavy minerals  
  o Minerals present  
  o Concentration of each  
• Radioactive minerals  
  o Minerals present  
  o Concentration  
  o Effect on geophysical monitoring tools used to characterize tailings deposits |
|   | Extraction | Merit of keeping tailings streams from extraction separate (if some contain most active clays or undesirable contaminants) |
|   | Thickener operation |  
• Advantage of adding sand  
• Clay/water ratio reasonably achievable  
• Potential for higher density clay/water ratio with  
  o Super floc agents  
  o Two stage floc treatment as used in the coal industry |
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>
| 9 | Extraction Discharge | • Optimum solid content for tailings discharge considering:  
  |   | o Heat loss  
  |   | o Enhanced fines capture in sand voids  
  |   | o Minimizing clay available to make MFT |
|10 | Extraction Discharge | • Chemical treatment  
  |   | o Enhance fines capture in sand  
  |   | o Reduce repulsion forces between MFT particles  
  |   | • Optimum method of densifying plant discharge  
  |   | o Thickener  
  |   | o Hydrocyclone to dewater sand  
  |   | o Centrifuge  
  |   | o Chemical treatment (coagulant) |
|11 | Fines capture | Characterize fines capture in sand voids  
  |   | • Silt and clay content and clay activity vs. distance from the tailings discharge point  
  |   | o In construction cells  
  |   | o Beach above water  
  |   | o Beach below water  
  |   | o Entering the tailings pond  
  |   | • Develop a system to model clay capture and availability to make MFT |
|12 | Fines capture | Determine optimum fines capture in sand deposits and how to achieve it  
  |   | • Avoid so much capture that the beach assumes clay properties |
|13 | Fluid tailings | Chemical treatment options  
  |   | • To maximize contact between solid particles  
  |   | • Speed formation of a strong soil  
  |   | • Enhance permeability and drainage  
  |   | • Cause contaminants to precipitate out of solution |
|14 | Tailings bitumen | Distribution of bitumen in tailings:  
  |   | • Verify conclusions that bitumen concentrates in the pond |
|15 | Tailings bitumen | Characterize bitumen in the tailings pond  
  |   | Suitability as upgrader feed |
|16 | Tailings bitumen | Verify the forecast bitumen content of the tailings pond and the potential concentration in densified MFT |
|17 | Consolidation | Screen options to enhance consolidation fines  
  |   | • Chemical treatment to speed settlement of fines  
  |   | • Effectiveness of systems to reduce the length of the drainage path  
  |   | o Install sand drains  
  |   | o Install wick drains  
  |   | o Install combination drains  
  |   | • Vertical wick drains  
  |   | • Horizontal sand layers to feed the wick drains  
  |   | o Utilize drainage paths introduced by escaping bubbles  
  |   | • Add surface surcharge to speed consolidation  
  |   | • Induce basal drainage to double applied effective stress |
| 18 | Measurement | Proper determination of the amount of clay sized material present  
• Research the challenges with quick determination of clay sized materials  
• Identify and correct inappropriate procedures indicated in Appendix B4 |
|---|---|---|
| 19 | Instrumentation | Develop on-line monitors to show instantaneous material balance components at the following locations:  
• Hydrotransport  
• PSV discharge  
• Secondary extraction discharge  
• Froth treatment discharge  
• Combined tailings  
Record the following  
• Weight % water  
• Weight % bitumen  
• Weight % sand and silt  
• Weight % clay  
• Clay activity  
• pH  
• major ions present in process water  
• resistivity/conductivity  
(the above information will assist meeting the new ERCB reporting requirements). |
| 20 | Exploration | Make better use of surface geophysics to characterize ore bodies |
| 21 | Exploration | Make better use of surface geophysics to identify weak zones in the foundation soil below tailings dykes |
| 22 | Exploration | Rapidly profile tailings ponds using geophysical probes (with regular calibration against bore holes) to indicate:  
• Weight % water  
• Weight % solids  
• Weight % sand and silt  
• Weight % clay  
• Bitumen content  
• Clay activity  
• pH  
• major ions present in water  
• resistivity/conductivity  
(Rapid profiling will aid meeting the new ERCB directive on reporting character of tailings) |
| 23 | Asphaltenes | Explore the potential to upgrade asphaltenes to a more valuable product  
• e.g. microwave treatment to generate light oil |
<p>| 24 | Asphaltenes | Can asphaltenes be concentrated in the current waste streams |
| 25 | Asphaltenes | Explore strength properties of deposits that contain more than 50% by volume asphaltenes |</p>
<table>
<thead>
<tr>
<th>No.</th>
<th>Topic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>Water treatment</td>
<td>Identify requirements for water release:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• potential contaminants present</td>
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<td></td>
<td></td>
<td>• quality requirements for water release</td>
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<td></td>
<td></td>
<td>• treatment options to upgrade water for release</td>
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<tr>
<td></td>
<td></td>
<td>• optimum water treatment program</td>
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<tr>
<td>27</td>
<td>Water storage</td>
<td>Screening study to determine the cost of storing water on site vs treat and</td>
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<tr>
<td></td>
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<td>release on an ongoing basis.</td>
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<tr>
<td>28</td>
<td>Dewatering sand</td>
<td>Appraise options to remove surplus water from sand because it is probably</td>
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<tr>
<td></td>
<td></td>
<td>easier to dewater sand than clay.</td>
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<tr>
<td></td>
<td></td>
<td>• Hydrocyclone potential</td>
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<tr>
<td></td>
<td></td>
<td>• Gravity drainage with stacked sand</td>
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<tr>
<td></td>
<td></td>
<td>• Ortner treatment (American Aggregates Ltd. 2009)</td>
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<tr>
<td>29</td>
<td>Remove solvent</td>
<td>Appraise the potential of Gradek Energy device to remove solvent from</td>
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<td></td>
<td></td>
<td>tailings</td>
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<tr>
<td></td>
<td></td>
<td>• Recovery efficiency</td>
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<tr>
<td></td>
<td></td>
<td>• Effect on bacterial activity</td>
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<tr>
<td>30</td>
<td>Extract bitumen</td>
<td>Appraise the potential of R.J Oil Field jet pump to removing bitumen from</td>
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<td></td>
<td>MFT.</td>
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<tr>
<td>31</td>
<td>Sethi guidelines</td>
<td>Appraise the potential of the Sethi guidelines for tailings</td>
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<tr>
<td></td>
<td></td>
<td>• Process must work under aerobic and anaerobic conditions</td>
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<td></td>
<td></td>
<td>• Bacteria should be put in a dormant condition</td>
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<td></td>
<td></td>
<td>• Treatment should be permanent</td>
</tr>
<tr>
<td>32</td>
<td>CT treatment</td>
<td>Verify challenges associated with CT processing to solidify MFT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Optimum sand/fines ratio to achieve timely solidification</td>
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<td></td>
<td></td>
<td>• Target strength and feasibility of achieving it in a defined time.</td>
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<td></td>
<td>• Practical on-line efficiency of CT operations</td>
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<td>• Permanence of CT treatment</td>
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<td></td>
<td></td>
<td>• Potential problem with gypsum as a source of bacterial food.</td>
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<tr>
<td>33</td>
<td>CT</td>
<td>Relevance of clay content and activity on the use of ternary charts to</td>
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<tr>
<td></td>
<td></td>
<td>identify the appropriate CT mix</td>
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<tr>
<td>34</td>
<td>Strength</td>
<td>Identify the strength required for a material to be considered a:</td>
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<tr>
<td></td>
<td></td>
<td>• Self supporting solid</td>
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<td></td>
<td>• Trafficable solid</td>
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<tr>
<td>35</td>
<td>Strength</td>
<td>Verify the target strength for reclamation – minimum 10 kPa</td>
</tr>
<tr>
<td>36</td>
<td>Strength</td>
<td>Research the relationships between:</td>
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<tr>
<td></td>
<td></td>
<td>• undrained shear strength</td>
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<td></td>
<td></td>
<td>• Solid content (clay)/(clay + water)</td>
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<tr>
<td>37</td>
<td>Strength</td>
<td>Study the effect of adding coagulants on:</td>
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<tr>
<td></td>
<td></td>
<td>• Atterberg Limits</td>
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<td></td>
<td></td>
<td>• Target solids content to achieve reclamation strength goals</td>
</tr>
<tr>
<td>38</td>
<td>Methane generation</td>
<td>Bacterial generation of methane:</td>
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<tr>
<td></td>
<td></td>
<td>• Disclose methane generated per unit area of the tailings pond surface</td>
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<td></td>
<td></td>
<td>• Expected duration of methane generation</td>
</tr>
</tbody>
</table>
| 39 | Permanent storage of MFT under a water cap | Feasibility of the concept considering:  
| | | • Mixing associated with methane generation  
| | | • Challenge to find a suitable site near the river that is not a water discharge zone  
| | | • Lack of criteria for site selection for permanent storage of contaminated liquid on surface |