Accelerated Dewatering and Drying Treatment of Oil Sands Tailings by Electrical Resonant Auto-Transformer

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Chemical Engineering

Department of Chemical and Materials Engineering

University of Alberta

Abstract

Canada has world's third largest oil reserves in the form of oil sands and 20% of those are easily accessible by surface mining. The hot water bitumen extraction process has been used since 1967 and the process produces vast amount of tailings which are stored in ponds. Tailings ponds pose a grave challenge towards sustainable development of Alberta's mined oil sands. For every barrel of bitumen produced, nearly 15 barrels of tailings including 2 barrels of Mature Fine Tailings (MFT) are generated. Though about 7 barrels of process water is recycled, the rest of the tailings pose complex challenge to faster reclamation. The fine non-settling particles in the tailings are mainly sub-micron size clay particles with repulsive charges. Aggregating these fine suspended particles together holds a key to tailings sedimentation problem. It has been observed that settling of fine particles can be achieved by high electric field treatment by newly developed electrical Near-field Resonant Auto-Transformer (NRAT) system. The NRAT system can produce alternating electric field in order of 10^6 V/m for a resonant frequency of about 250 kHz. The voltage and current are out of phase and very little energy is consumed with rest stored back in the system. It was observed that high electric field and field gradient can treat fine tailings in few hours compared to couple of years of gravity treatment. The decanted water can be recycled back while the thickened tailings can be further dielectrically heated with the same NRAT system and dried out. Thus, NRAT system seems to offer a complete solution to tailings problem. We propose to demonstrate usefulness of NRAT system as a cost effective, energy efficient and a safe way for complete treatment of tailings.

Preface

The work done in this thesis is original work carried out in Nano-Interfaces & Molecular Engineering (NIME) group under supervision of Professor Thomas Thundat in Department of Chemical and Materials Engineering at University of Alberta. The novel idea of Near-field Resonant Auto-Transformer (NRAT) has been pursued by our Research Associate, Dr. Charles van Neste since many years. The electrical Resonant Auto-Transformer used in this work is developed by Dr. Neste and used by group for various experiments. He has been kind to provide us his system and discuss the fundamentals and ideas involved. The experiments with tailings were carried out and settling phenomenon & drying was observed.

The Mature Fine Tailings (MFT) sample for this project was purchased from Alberta Innovates Technology Futures (AITF) and some of it was previously available from Suncor. We are thankful to both for these samples.

Dedication

I dedicate this work to my family and friends

who support me in every endeavor I seek.

Acknowledgement

I would like to thank my supervisor Professor Thomas Thundat, Canada Excellence Research Chair (CERC) in Oil Sands Molecular Engineering, for giving me the opportunity for my Master's thesis under his guidance and also helping me every bit with completion of this work. With his help, I am motivated to give my best, explore new ideas and find better solutions to real world problems faced by oil sands industry. I would also like to thank my colleagues especially Ms. Ghazaleh Haghighat, Mr. Rohan Gaikwad, Ms. Tinu Abraham, Mr. Ravi Gaikwad, Mr. Arindam Phani, Mr. John Hawk and Mr. Charles van Neste for giving me ideas, insights and direction towards the completion of this work. I would also like to thank our industry mentor, Mr. Sundeep Srinivasa whose in-field expertise helped us to identify the problem faced by industry and the work that needs to be done to solve this problem. I am also grateful to all other NIME group members who gave their valuable inputs and guided me in right direction throughout the duration of this work. I also wish to thank our group's executive secretary Ms. Elizabeth Adolf for her help with most of the paperwork, ordering materials and proofreading our work.

I would like to extend my sincere gratitude to Professor John Shaw's group here in CME department for letting me use DSC apparatus from his lab for MFT heat capacity measurement, special thanks to lab manager Ms. Becerra Mildred who carried out these experiments. The particle size analysis & zeta potential measurement and XRD experiments were carried out in OSCIEF group labs, my sincere thanks to lab technicians Ms. Ni Yang and Mr. Shiraz Merali for helping me out with these experiments.

I am very thankful to people from my social circle who made me feel home even after being halfway across the world. Finally and most importantly, I am sincerely grateful to my family who always stand beside me in every endeavor and adventure I seek in life.

Aharnish Hande

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List of Abbreviations

AER	Alberta Energy Regulator
AITF	Alberta Innovates Technology Futures
CHWE	Clarke Hot Water Extraction process
CNRL	Canadian Natural Resources Ltd.
COSIA	Canada's Oil Sands Innovation Alliance
CSS	Cyclic Steam Simulation
CT	Composite Tailings
DDA	Dedicated Disposal Area
DilBit	Diluted Bitumen
DSC	Differential Scanning Calorimetry
ERCB	Energy Resources and Conservation Board
GHG	Greenhouse gases
IOSI	Institute for Oil Sands Innovation
MFT	Mature Fine Tailings
NA	Naphthenic Acid
NIME	Nano-Interface and Molecular Engineering group
NRAT	Near-field (Non-radiative) Resonant Auto-Transformer
OSTC	Oil Sands Tailings Consortium
PSV	Primary Separation Vessels
r.m.s	root mean square
SAGD	Steam Assisted Gravity Drainage
SFR	Sand to Fines Ratio
TRO	Tailings Reduction Operation
TT	Thickened Tailings
WWF	World Wide Fund for Nature / World Wildlife Fund

1. Introduction

1.1 Statement of Challenges

Bituminous or Oil Sands are deposits of heavy bitumen mixed with water, sand and clay primarily found in Alberta, Canada. Bitumen is a brownish-black highly viscous oily substance that can be processed to obtain conventional oil fractions such as gasoline, diesel, kerosene, lubricants etc. The proportion of bitumen in oil sands varies; still typically on average wt% it has 83% sand, 10-12% bitumen, 4% water and around 3% clays (Natural Resources Canada. 2013).

Alberta's Oil Sands are a key to Canada's economic development with 3rd largest proven oil reserves of 173.2 billion barrels (including 5 billion barrels of conventional crude oil) after Venezuela (297.74 billion barrels) and Saudi Arabia (265.85 billion barrels) (Canadian Association of Petroleum Producers. April 2014, CIA Factbook., Xu and Bell. 2013, Dec 2, Oilsands.Alberta.ca. 2013b). The 'Proven Reserves' are the deposits of petroleum that are estimated with high degree of confidence and can be extracted with current geological knowledge, present engineering technology and known reservoir and economic conditions. On the other hand, 'Resources' are the total amounts that are estimated to be in place but not readily extracted with current knowledge but could be a viable option in the future with advancement in the knowledge, technology and economic conditions. Canada, primarily Alberta is estimated to have 1.84 trillion barrels of crude bitumen in place. Thus, only 9.4% of total resources are considered as reserves at present (Oilsands.Alberta.ca. 2013b, Oil Sands Discovery Center. 2014).

The following Table 1-1 shows top 10 countries with their percent share of total world proven oil reserves.

Country	Oil Reserves (billion barrels)	% world share
1) Venezuela	297.74	18.11
2) Saudi Arabia	265.85	16.17
3) Canada	173.20	10.53
4) Iran	157.30	9.57
5) Iraq	140.30	8.53
6) Kuwait	101.50	6.17
7) United Arab Emirates (UAE)	97.70	5.94
8) Russia	80.00	4.86
9) Libya	48.47	2.95
10) Nigeria	37.14	2.26
Rest of the world	245.31	14.92
Total World	**1644.51**	**100.00**

Table 1-1 Top 10 countries with their oil reserves and percentage share of total world oil reserves (Xu and Bell. 2013, Dec 2)

The Canadian oil sands are spanned across 142,200 km^2 area of land in the Athabasca River (largest reserves), Peace River and Cold Lake areas in central-northern Alberta. There are also major oil sands deposits on Melville Island in the Canadian Artic, however it is unlikely they will see commercial production in foreseeable future because of extremity of weather and location (Oilsands.infomine.com. 2014). Presently, Alberta's oil sands produce about 1.97 million barrels of oil per day of which 1.4 million barrels are shipped to United States on daily basis, thus having high economic impact (Oilsands.Alberta.ca. 2013a, Canadian Association of Petroleum Producers. April 2014). By 2021, it is expected that crude bitumen production will almost double to 3.7 million barrels of oil per day.

Out of 173.2 billion barrels proven reserves, 20% are considered shallow (less than 75 meters in depth) and can be processed by surface mining techniques present since the introduction of oil sands as bitumen reserve (circa 1967). 80% of total oil sands reserves is considered too deep (more than 75 meters below ground level) to be economically mined and is processed by in-situ methods that are developed quite recently. As of January 2013, there were 127 operating oil sands projects in Alberta out of which only 5 are surface mining. Still, surface mining accounts for 51% bitumen production and in-situ accounts for 49% (Figure 1-1). This is because of the large scale operating size of mining, processing plants and their high bitumen recovery ratio (around 95%) from extraction processes.

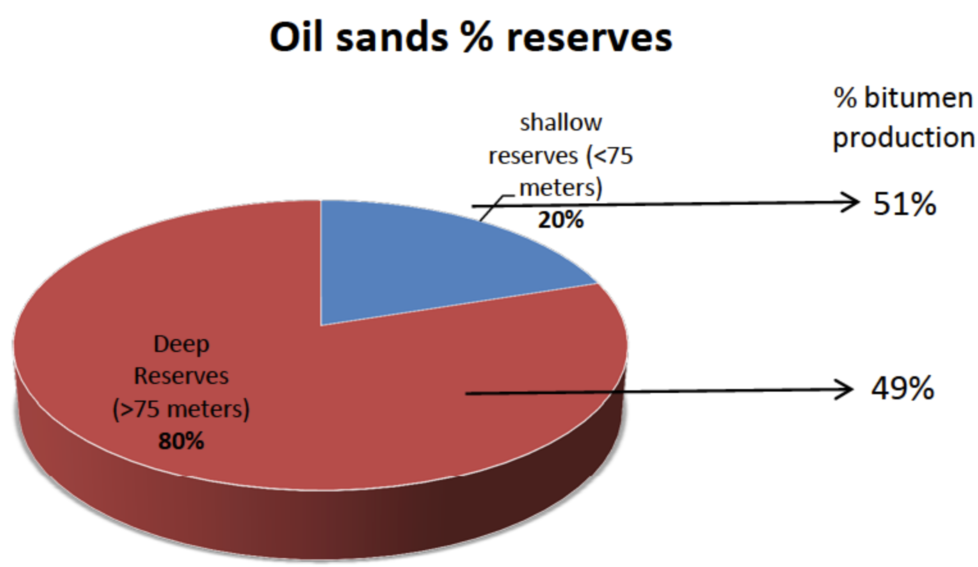


Figure 1-1 Percentage distribution of bitumen reserves in oil sands and percentage bitumen production from it

As of July 2013, five major operators (Suncor Energy Inc., Syncrude Canada Ltd., Shell Albian Sands, Canadian Natural Resources Ltd. (CNRL) and Imperial Oil Ltd.) perform open-pit mining to excavate and process oil sands (Junewarren-Nickle's energy group. 2014, August).

Once the shallow oil sands are identified and excavated, the ore is crushed and washed with hot water at 35 - 80^{0}C with Caustic, NaOH i.e., sodium hydroxide by a process known as Clarke Hot Water Extraction (CHWE) process (World Wildlife Fund (WWF) Canada. October 2010). The oil sands being hydrophilic while the bitumen being hydrophobic; it is liberated in the process floats on the top as froth and is removed off and further treated.

On average, 2 tonnes of ore mined for every barrel of bitumen produced. The CHWE process requires around 15 barrels of water for one barrel of bitumen produced. Though around 75% the input water i.e., 12 barrels are recycled back, it requires 3 barrels of fresh water each time for one barrel of produced bitumen (Canadian Association of Petroleum Producers. April 2014). Thus, not only extraction mining landscape disruptive, it is also heavily water intensive.

The by-product of this hot water extraction process is slurry like material known as tailings. It is a fluid mixture of water (60-80%), sand & clay (20-40%), residual bitumen (1-3%) and some organic chemicals such as naphtha (0-1%). Tailings are stored in lakes or ponds and widely known as tailings ponds. The sludge known as tailings does not settle readily and can take decades and even centuries to completely do so. One barrel of bitumen production approximately produces 15 barrels of tailings (including 2 barrels of Mature Fine Tailings (MFT)) (BGC Engineering. July 2010). Tailings remediation is a major challenge for the oil sands mining industry and a part of Alberta's goal of sustainable development of oil sands. In earlier days, tailings were only supposed to have a perceived image problem but only quite recently they have been identified as an environmental challenge because of rapidly growing sizes of all tailings ponds across Alberta. Only one tailings pond (Suncor pond-1) has been reclaimed till date in more than 40 years since the start of bitumen production from oil sands by surface mining.

1.2 Proposal

As gravity settling is not fast enough to solve the problem of non-settling tailings, an external measure will be required to accelerate the settling. Though many technologies have been studied for solving this problem, most of them have some limitations. Also, Oil Sands industry has a very conservative approach towards this growing problem because of large capital costs involved with implementing new technology at plant-scale or because of lack of stringent requirements from the government. This scenario is bound to change as the search for a viable technology intensifies amidst the growing need to solve the tailings issue. The government regulations & directives involving environmental liability are getting stricter day-by-day.

Mature Fine Tailings (MFT) is dried off by natural evaporation of any remaining water after polymer treatment. The process is in turn hampered by Alberta's harsh weather that allows running this process for maximum of 3-4 summer months. So after identifying the need to find out ways that could accelerate this drying, and at the same time work with the current infrastructure; it has been proposed to use a novel technique developed by Nano-Interface and Molecular Engineering (NIME) group at University of Alberta. The technique has shown accelerated settling of Fluid Fine Tailings (FFT) portion and complete drying of mature tailings portion. The methodology for the NRAT technique is described below.

1.3 Methodology

An electrical device known as Near-field Resonant Auto-Transformer (NRAT) was built in the lab. It can produce high voltage standing quarter waves with low current and low power consumption. The alternating high electric field in order of 10^6 V/m can be used for treatment of tailings. This near-field, non-radiating, energy efficient electrical setup was observed to cause settling of very fine clay particles under high electric field because of AC dielectrophoretic force acting on charged clay particles. The system was also observed to have shown rise in temperature because of power dissipated in the dielectric medium given by Poynting factor. This temperature rise further helped with complete drying of settled mature tailings. Thus, the NRAT system helps with the tailings treatment objectives.

1.4 Original Contribution

The novel technologies & instrumentation, discoveries and methodologies as original contribution and part of this work are as follows:

- The electrical system of the study, Near-field Resonant Auto-Transformer (NRAT) was devised by Dr. Charles van Neste, a member of Nano-Interface and Molecular Engineering (NIME) group.
- The use of NRAT system for accelerated dewatering of oil sands tailings was studied.
- It was also discovered that the NRAT can be used for complete treatment of oil sands tailings right from rapid settling of fines in tailings to accelerated drying of thickened tailings obtained with the electrical treatment.
- The feasibility of the electrical system for tailings treatment with respect to energy requirement and cost effectiveness was studied.

1.5 Project Significance to Canada and overall oil sands industry

Tailings remediation is one of the absolute essential areas for Canadian oil sands development. Tailings are causing serious environmental concerns such as seepage into groundwater and freshwater streams, proving harmful to biological and aquatic life and causing disasters such as duck deaths from 2008 and 2010 after landing in these ponds. Oil sands mining and tailings ponds also tarnish Canada's image at international level where once Canada was considered environment protection leader, but not anymore. So it is absolutely essential for Canada and its oil sands industry that proactive measures are taken against environmental damage before a major disaster strikes. Also, tailings treatment problem being one of the leading challenge, this work will try to contribute a little to find a possible solution for this growing problem.

1.6 Thesis Structure

This thesis is divided into 7 chapters.

'Chapter 1: Introduction' gave an overview of challenges faced by oil sands industry and opportunities that lies ahead of us. The technique and methodology that will be used for tailings treatment are also described.

'Chapter 2: Oil Sands and Tailings Technologies' provides an overall idea about processes used for bitumen extraction from oil sands, current tailings processing technologies used in industry, their challenges, government regulations and characteristics of an ideal technique.

'Chapter 3: Electrical Resonant Auto-Transformer' provides an overview of the novel electrical NRAT system used for tailings treatment. The chapter describes system's functioning that is used for tailings treatment.

'Chapter 4: Tailings Treatment Experiments' provides an idea about equipment, setup and experiments carried out for tailings treatment. It lists the experiments carried out along with the observations made.

'Chapter 5: Tailings Characterization' provides an idea about the various physical, chemical, electrical properties of the tailings and also its content. This will give us a better understanding the tailings that are to be treated.

'Chapter 6: Results and Discussions' focuses on the observations made and their implications. It also looks into various aspects of the problem, working mechanisms and possible permutations to solve the problem in the most effective way.

'Chapter 7: Conclusions and Future Work' concludes the observations and finding from this work. More possible experiments that might further improve upon the existing system are also discussed.

2. Oil Sands and Tailings Technologies

2.1 Introduction

Conventional crude oil has been a source of most of the petroleum based need of mankind since its introduction. Only recently oil sands from Canada, extra-heavy oil from Venezuela and Shale-oil from United States are identified as petroleum resources. Oil can be recovered from the Canadian oil sands deposits through surface mining and in-situ extraction processes. Athabasca oil sands contain bitumen from 0-16 wt % (~average 12%), water from 3-6 wt % and mineral content (mainly quartz, sand and clay) from 84-86 wt % (Cabrera. 2008). Bitumen content decreases as the water content in oil sands increases. Oil sands can be further classified into three types of ores.

i. Rich grade: Bitumen 13-16 wt %
ii. Medium grade: Bitumen 10-12 wt%
iii. Low grade: Bitumen 7-9 wt %

Bitumen wt % of lower than 7% is not considered ore-grade as the production will not be economically viable. For the minerals, the major clays are 40-70 wt % kaolinite, 28-45 wt % illite and 1-15 wt % montmorillonite (Chalaturnyk et al. 2002). These clays are important cause for fine suspension formation in tailings ponds. The clays are sheets of silicon-oxygen tetrahedrons and sheets of aluminum/magnesium-oxygen octahedrons (Chan. 2011). It appears in fine fraction and has very low settling velocity because of their small size as well as negative repulsive charges on their face-structure (LONG et al. 2006, Voordouw. 2013). In industry, particles bigger than 44 μm are known to settle readily while particle sizes less than 2 μm are termed as fines and sizes less than 0.3 μm are termed as ultra-fines. A stable colloidal system is formed by these ultra-fines that strongly enhance the stability of the oil sands tailings and mainly hinders settling.

2.2 Oil Sands structure

The Athabasca oil sands are composed mainly of sands grains that are hydrophilic in nature and 99% water wet. Thus sand particles are surrounded by a thin water layer which is then surrounded by bitumen. This water film is stabilized by an electrical double layer between sand/water and water/bitumen. A modified representative of typical oil sands is shown in Figure 2-1 (Takamura. 1982, Shaw et al. 1996).

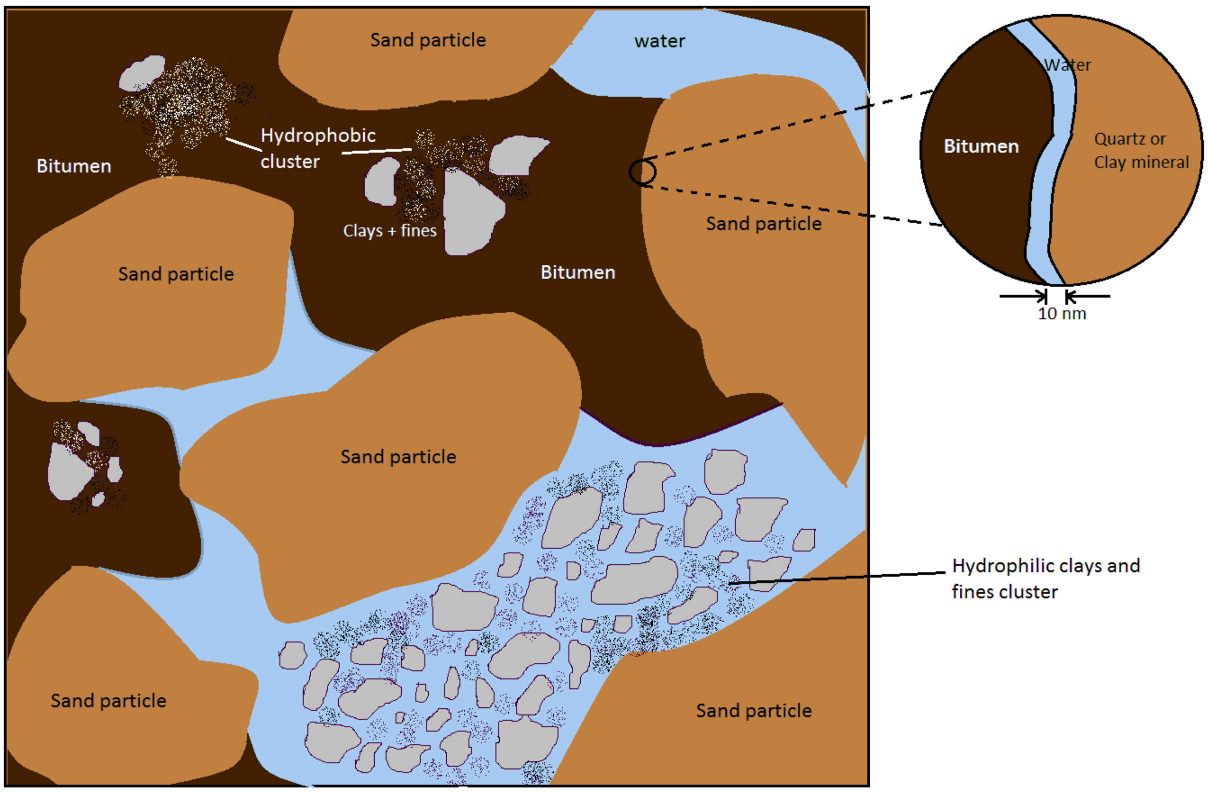


Figure 2-1 Microscopic structure of Athabasca oil sands

Bitumen is chemically similar to conventional crude oil and has a density slightly less than or close to water i.e., 1000 kg/m^3. The scale for density measurement for oil in petroleum industry is defined as ^{0}API. The ^{0}API is related to density or specific gravity as follows (Gray. 2014):

$$^0\text{API} = \frac{141.5}{\text{specific gravity at } 15.6^0\text{C}} - 131.5 \;=\; \frac{1.415*10^5}{\rho(\frac{\text{kg}}{\text{m}^3})} - 131.5$$

Thus the ^{0}API scale bears an inverse relation with density. Higher the density, lower will be ^{0}API number and vice versa. The bitumen with lower density, i.e., higher ^{0}API is ideally desired. The bitumen is defined as heavy if it has dynamic viscosity > 100 cP (or mPa.s) and density < 22 ^{0}API (~922 kg/m^3) (Canadian Heavy Oil Association. 2013). Water with specific gravity of about 1 at room temperature has density of 10^{0}API.

The Canadian heavy bitumen (about 6 to 12 ^{0}API) is highly viscous in nature but its viscosity drops exponentially with temperature. The dynamic viscosity (μ) of bitumen is about 10^6 mPa.s (or 10^6 cp) at reservoir temperature thus making it practically immobile, but this also gives oil sands enough strength to make it mineable. The Figure 2-2 shows the graph of dynamic viscosity as a function of temperature (graph from (Canadian Heavy Oil Association. 2013).

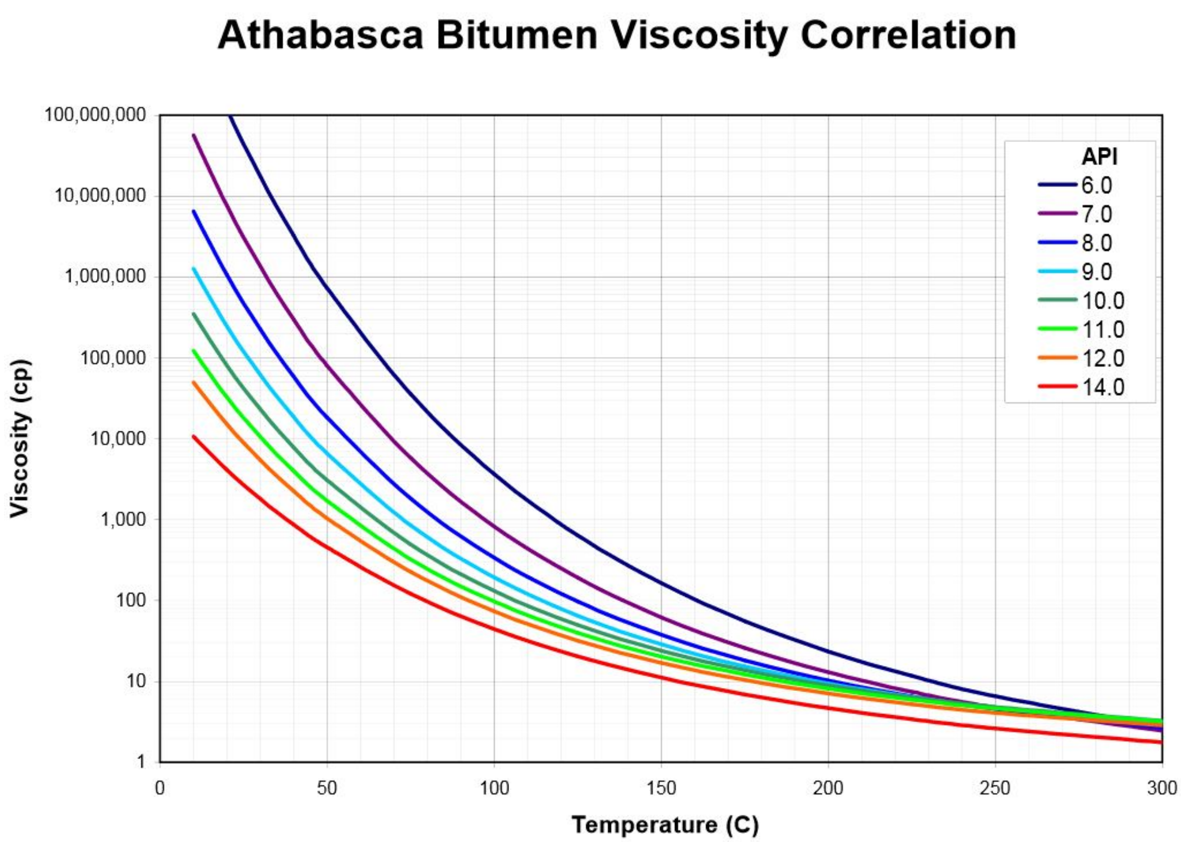


Figure 2-2 Dynamic viscosity for Alberta bitumen as a function of temperature (graph taken from Canadian Heavy Oil Association. 2013)

2.3 Surface mined oil sands treatment

Oil sands deposit of less than 75 meters depth are excavated by surface mining, and bitumen is extracted by Clark Hot Water Extraction (CHWE) treatment (Figure 2-3). Bitumen is extracted by in-situ methods (Cyclic Steam Stimulation (CSS), Steam-Assisted Gravity Drainage (SAGD)) from deposits of oil sands below 75 meters in depth.

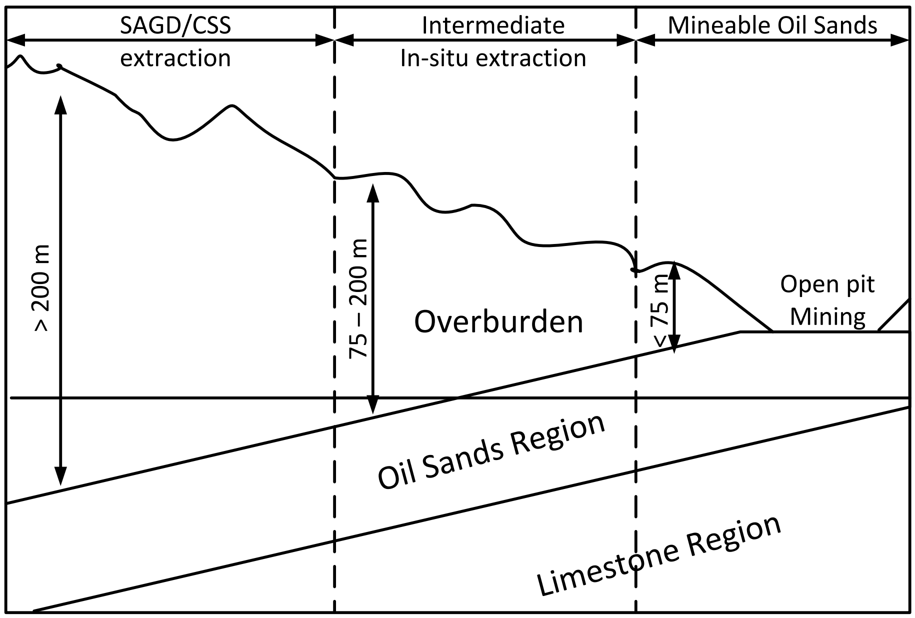


Figure 2-3 Principal zone of oil sands

The first step in the bitumen extraction from surface oil sands deposits is to clear the overburden material prior to mining. This overburden can be as much as 30 meters. Once the overburden is removed, oil sands deposits are excavated with help of giant industrial shovels and carried to treatment plant in the huge hauler trucks unlike used anywhere in any other industry. A typical mined oil sands transport truck can carry as much as 400 tonnes of oil sands in a single trip. The current technique, considered more cost effective, has replaced the previous bucket-wheel excavator and conveyor system (Oil Sands Discovery Center. 2014).

Once mined, oil sands are conditioned by slurrying with recycle water and fed into cyclo-feeders, i.e., horizontal rotating drums where heat and shear break the oil sands lumps. This mass is then washed with Sodium Hydroxide (NaOH), commonly known as Caustic Soda to raise the pH of the solution. The typical proportion of oil sands : water : NaOH (20 wt%) is 1 : 0.2 : 0.0012 (Shaw et al. 1996). The temperature of the slurry is 80-85^{0}C and pH of 8.0-8.5 (Cabrera. 2008).

The Clark Hot Water Extraction (CHWE) process was patented in 1929 by Dr. Karl Clark and has been used in oil sands mining industry since 1967. Hot water and Caustic Soda are two main components of the CHWE process. The Caustic Soda is adjusted according to input batch to maintain a solution pH that gives maximum bitumen recovery. This process works because oil sands are hydrophilic (attracted to water) while bitumen is hydrophobic, thus repels wetted surfaces. The mixture of caustic soda and water acts as a detergent that provide optimal conditions for repelling bitumen from water film surrounding the sand.

This washed mixture is stored in large separation vessels where settling time is provided for components to separate. The heavier slurry along with any sediment such as rocks etc. settles in these tanks. The bitumen liberated from this process starts separating from water forming droplets and coalescing with other droplets. At this point, bitumen is only slightly lighter than water. To drive these droplets upwards, air is sparged through this mixture and bitumen droplets attach with the air bubbles and travel upwards. The bitumen froth thus floats to the top and is skimmed off and treated further. The froth typically contains 60 vol% bitumen, 30 vol% water and 10 vol% solids. (Masliyah et al. 2011)

The heavier discharged slurry contains about 50% sand, clay and other suspended solids; 43% water and about 7% residual bitumen. It is then discharged to vibrating screens where it is washed again with hot water sprays to recover untreated oil sands lumps. The then treated slurry is diluted with water to about 1450 kg/m^3 and fed into large settling tanks (Cabrera. 2008). These tanks are known as Primary Separation Vessels (PSV) or primary separation cells. These vessels/cells are maintained at quiescent conditions and separation time of around 45 minutes as allowed in case of Syncrude's process (Shaw et al. 1996). The aerated bitumen droplets have density of around 500 – 700 kg/m^3 while solid minerals have density around 2650 kg/m^3 (Cabrera. 2008). Thus, a gravity settling process takes place in these tanks. The extremely slow-settling middle portion from this process is known as 'tailings' and is a by-product of the entire process. This run-off can't be discarded back into the environment and is stored in giant ponds for gravity separation treatment to take place over decades.

The recovered bitumen from the above process is very thick for any practical purposes such as handling and transportation so it is diluted with naphtha and paraffinic solvents. The so called Diluted Bitumen (DilBit) is sent to the upgrader for further processing via pipelines where it flows at about 5 km/h. The Upgrader unit processes this DilBit, sends back the transportation solvents and converts it into Synthetic Crude Oil (widely known as SCO) which is further marketed to refineries. On an average, bitumen is composed of the following: (Timoney and Lee. 2009, Oil Sands Discovery Center. 2014)

Carbon: 83.2%

Hydrogen: 10.4%

Oxygen: 0.94%

Nitrogen: 0.36%

Sulphur: 4.8%

Others: 0.3%

2.4 Tailings

The run-off from this extraction process, slurry like waste, also known as tailings stream is hydraulically transported and stored in open areas known as tailings ponds or tailings lake. Apart from being mainly aqueous, this stream typically contains the whole range of particle size distribution for coarse sands, quartz and clay particles. It also contains small portion of unrecovered bitumen and naphthenic acids. Sand grain particles and other coagulated particles with particle size greater than 44 μm settle relatively easily and are easy to reclaim. They form dikes and sand beaches that are used to contain the unsettling portion of the tailings, known as fine tailings. The fines are usually clay particles that are under 44 µm and are relatively uniformly suspended within the water. The lightest fraction of this whole tailings slurry, water and a part of the bitumen slowly forms a top layer over the tailings lake. The water from the top portion is recycled back to the plant and used for washing the new ore as described for the initial stages of CHWE process. Typical tailings samples are shown in Figure 2-4.

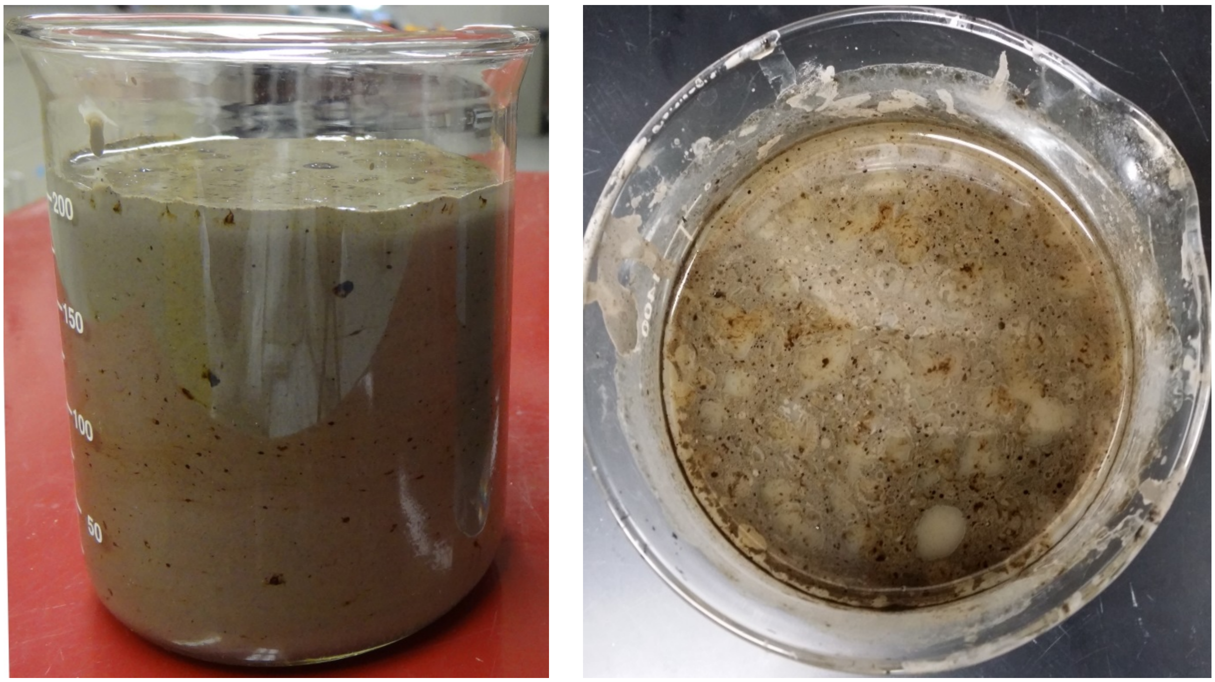


Figure 2-4 Typical tailings samples

Tailings ponds cover more than 182 km^2 surface area in northern Alberta (Alberta Environment and Sustainable Resource Development. 2014). The schematic for a typical tailings pond is shown below. The dyke basin usually has a 5^0 slope (Dusseault and Don Scott. 1983). The hydrotransported slurry is slowly allowed to flow down from the top of the ponds. Typical schematics of tailings ponds modified from works of (Beier and Sego. 2008, BGC Engineering. July 2010) and (Flint. 2005) is shown in Figure 2-5.

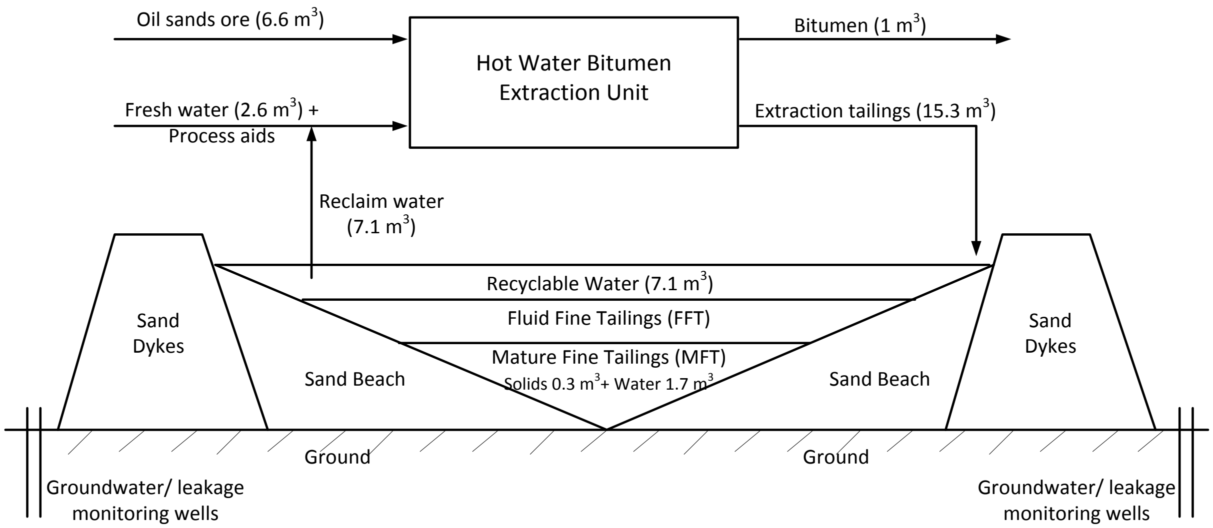


Figure 2-5 Tailings pond schematics

For every barrel of bitumen produced, 15 barrels of tailings are produced including 2 barrels of Mature Fine Tailings (MFT) (i.e., 0.32 m^3 of MFT produced per barrel for 0.16 m^3 of bitumen produced). The tailing ponds are expected to grow with increase in production capacity over the next coming years, thus pose an environmental challenge towards sustainable development of oil sands (Masliyah et al. 2011).

The brief sum-up schematics of tailings production from oil sands mining is given in Figure 2-6 (adapted from 'Handbook on theory and Practice of Bitumen Recovery from Athabasca Oil Sands' by (Masliyah et al. 2011).

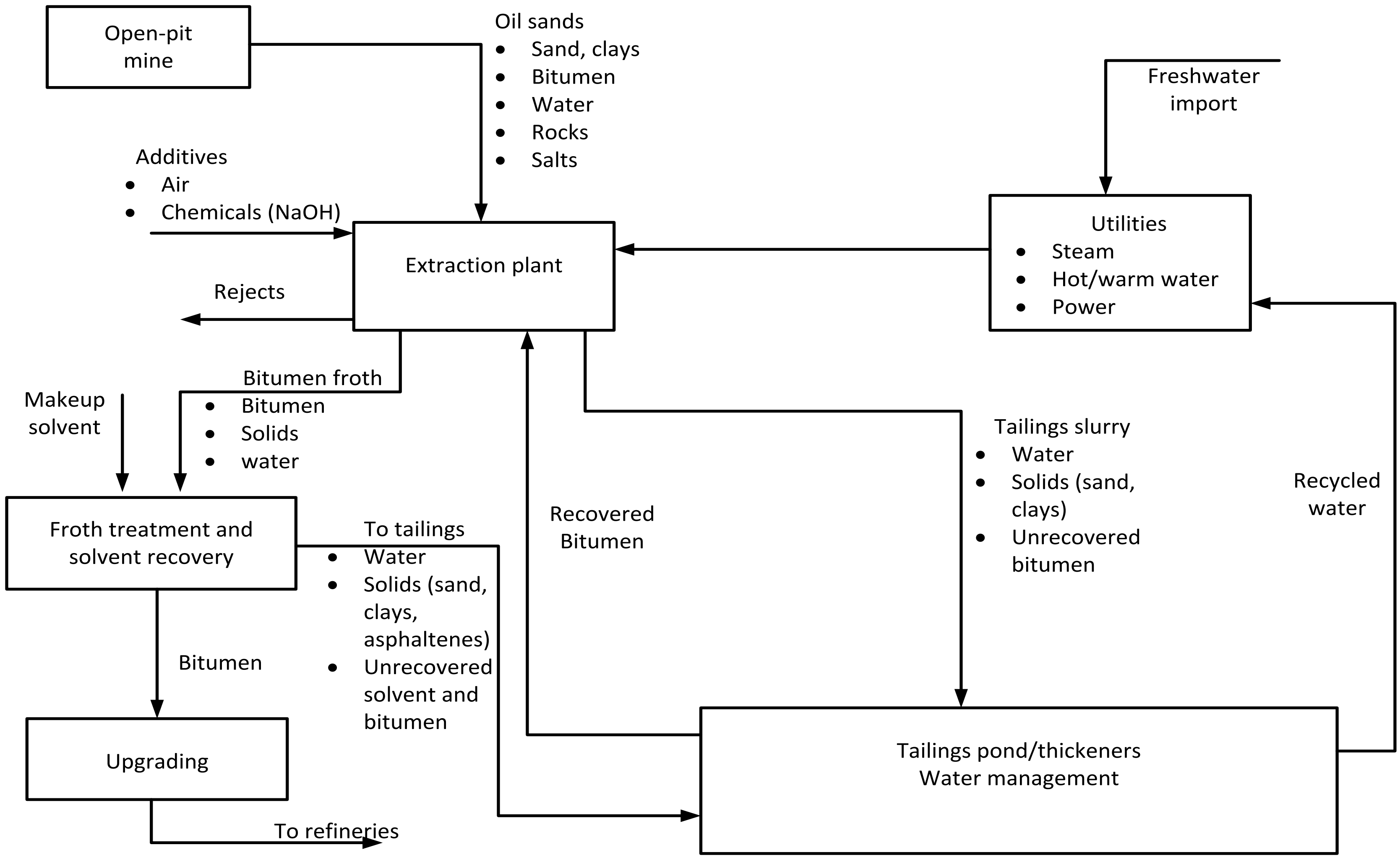


Figure 2-6 Schematics of surface mined oil sands treatment (Masliyah et al. 2011)

2.5 Regulatory Requirements

Although many technologies have been studied, there has not been a ‘silver bullet’ technology to solve this tailings problem as of now. A comprehensive report – ‘Oil Sands Tailings Technology Deployment Roadmap (TTDR)’ by six leading industry consulting firms to Alberta Innovates – Energy and Environment Solutions (AI-EES) lists 500+ technologies studied till 2012 (Golder Associates Ltd. et al. June-2012). But only handful of them is implemented and some of them are currently pilot projects (BGC Engineering. July 2010). It is because of the capital costs associated with these technologies often run in billions of dollars, which creates inertia for oil sands operators. Also, there have not been any strict regulations from government that holds the operators liable for any environmental damages and demands complete landscape remediation. After death of 1600 migratory ducks in a tailings pond in 2008, directive 74 was issued in 2009 by the government.

Alberta Energy Regulator - AER (previously known as ERCB: Energy Resources and Conservation Board) approved Directive 74: ‘Tailings Performance and Requirements for Oil Sands Mining Schemes’ in February 2009. It sets out aggressive new requirements for the regulation of tailings operations for mineable oil sands. The directive specifies criteria for the reduction of fluid tailings and formation of trafficable deposits. The directive 74 has termed following objective (Alberta Energy Regulator. Feb, 2009):

- To minimize and eventually eliminate the storage of fluid tailings, i.e., tailings ponds, to facilitate progressive reclamation
- To create trafficable landscape soon possible with at least 5 kPa shear strength which has to be 10 kPa in few years
- To reduce contaminants from tailings operations and reduce the affected water storage area
- To maximize the water recycling efficiency and reduce freshwater consumption
- To ensure that liability is managed by oil sands operators by ensuring the progressive reclamation of the tailings ponds

Thus, AER will have a stringent supervision over all mining operations and plans which require them to eliminate growth of tailings ponds. Companies will reduce tailings and provide target dates for pond closure and report reclamation progress. To proactively work on the tailings problem as well as keeping in mind that government regulations are getting stringent day-by-day; 7 major oil sands operators namely Total E&P Canada, Imperial Oil, Shell Canada, Syncrude Canada, Teck Resources, Suncor Energy, Canadian Natural Resources Limited formed 'Oil Sands Tailings Consortium' (OSTC) in December 2010. OSTC's main aim is to work with universities, government and research institutes and consultant companies to find innovative solutions for tailings issue. OSTC promises for financial commitment and sharing knowledge, experience and expertise amongst each other. Similarly, in March 2012 another alliance of 12 oil sands producers known as Canada's Oil Sands Innovation Alliance (COSIA) was formed to improve work done in areas such as tailings, land, air and greenhouse gases (GHGs).

2.6 Tailings Treatment Technologies

Current tailings treatment technologies can be roughly divided into 5 sections. They are:

i. Physical/Mechanical treatment
ii. Natural/Biological treatment
iii. Chemical treatment
iv. Mixtures/co-disposal treatment
v. Permanent storage

A brief description for these 5 sections is below (Guo. 2012, BGC Engineering. July 2010):

I. Physical/Mechanical treatment

Filtration is one of the basic solid-liquid separation technologies. Filtration can take place in both vacuums as well as in pressure vessels. The high recovery of process water has been shown with this technology but it's limited due to very large volumes of tailings and high costs associated with of filters, dry tailings transportation. With high energy and excess process equipment requirement, this process finds little to no practical implementation.

Cross flow filtration is another technique where tailings flow tangentially along the filter surfaces. This one is also an effective technique for higher dewatering but is limited by excessive operations costs associated with the maintenance of filter surfaces. Centrifugation also suffers from similar higher costs and higher maintenance issues.

Thermal drying of Mature Fine Tailings (MFT) over conventional ovens and kilns to reduce the moisture content is very fast but limited due to very high energy demands. The electrical treatment, often termed as 'emerging technique' uses application of direct current, DC electric field for electrokinetic dewatering tailings slurries. It has not been implemented till now because of higher energy demands. However, this in turn gives us an idea from this work's point of view, that solving energy efficiency and cost effectiveness problems are keys for practicality.

II. Natural/Biological treatment

Sedimentation followed by consolidation through own weight is a technology used for decades. The understanding the inter-particle forces for tailings clays has not been very well known. This technique also requires vast areas for sedimentation to take place under self-weight or any sort of external capping.

'Freeze-thaw technology' allows multiple thin tailings slabs to freeze naturally in Alberta's winter and these frozen slabs then thaw in following summer. The solids content of the MFT was reported to rise from 36% to 56% when 5 cm to 15 cm slabs were tested (BGC Engineering. July 2010). Though the capital costs involved for the technique are low, it is very labor intensive and requires large areas for extended period of time, a key problem in tailings treatment.

Dewatering tailings by biological means such as through plant evapotranspiration is a biological treatment method. Some plants can grow on tailings by removing the water by roots from the pond and transpirating the same by leaves. Due to dependence on vegetation, the technique is subject to weather conditions.

III. Chemical treatment

Coagulants and flocculants are widely used for chemical treatment of tailings. Coagulants like Gypsum introduce +ve Calcium cations and reduce the –ve charge on clay particle faces, thus bringing them together. In paste technology, flocculating polymers such as anionic polyacrylamides are added for dewatering Mature Fine Tailings (MFT) and for required shear strength. The coagulants technology faces challenges of being slow and may take many years. The paste technology using flocculants is proving to be one of the better solutions for tailings problem. Still it treats only certain tailings portion and not entire fine tailings portion.

The technology proposed in this work treats fine tailings as well as Mature Fine Tailings (MFT) that is produced subsequently after high voltage treatment. The paste technology using polymeric flocculants may one day go hand-in-hand with electrical NRAT accelerated dewatering system if operating costs are optimized.

IV. Mixtures/Co-disposal treatment

Sand is added to mature tailings to produce 'Composite or Consolidated Tailings' (CT) in different Sand to Fines Ratio (SFR). Gypsum is also added along to 4:1 sand MFT mixture to form non-segregating slurry. This gives the required trafficable shear strength, up to 60% solid content has been obtained. Thus Suncor and Syncrude have both used this technology in 90's (BGC Engineering. July 2010). The industry is moving forward and trying to find a better technology with faster reclamation results as the land and sand requirement can be too much for CT process.

V. Permanent storage

Mature Fine Tailings (MFT) can also be pumped into mined out pits to minimize the land usage. They are also covered with water to form 'end pit lakes'. The idea here is that, eventually this lake will inhibit the properties that of a natural water body. Thus this technique believes in permanent storage of tailings. The problem with the technique is that it is a very long process and as of now industry experts and regulators are unsure whether the desired results will be obtained or not. It has been widely debated that these pit lakes do not provide natural water habitat. Furthermore being carcinogenic, are extremely dangerous to aqueous and wildlife (World Wildlife Fund (WWF) Canada. October 2010). Thus, these permanent storage lakes are neither fast nor sustainable ways to dispose tailings.

2.7 Characteristics of an ideal technique

- The ideal technique should provide complete solution to the whole tailings problem in shortest possible amount of time, possibly few days compared to several years.
- It should be able to treat both Fluid Fine Tailings (FFT) and Mature Fine Tailings (MFT). Most techniques today treat only mature tailings and not fine tailings portion. It should be able to treat newly produced as well as legacy tailings.
- The technique should be able to solidify tailings to a minimum trafficable shear strength required by the government. It should be able to meet stringent government regulations set to meet environmental directives.
- The risks and hazards associated with the operation of the technique should be minimized.
- Most importantly, from oil sands operators' point-of-view; the technique must be economical to run. The technique should be cost effective in terms of capital and operating budget.

2.8 Current Challenges and Opportunities

To this point, it is very clear that treating tailings is quite a challenge. The thicker portion of the tailings, Mature Fine Tailings, is polymer treated in Suncor's Tailings Reduction Operations (TRO) and dried naturally in Dedicated Disposal Areas (DDAs). This gives the dried tailings required trafficable shear strength of 5 kPa and subsequently 10 kPa. However, this process has limited duration due to limited drying months in Alberta's harsh weather conditions. But, with these challenges comes opportunities for engineers.

Some of the current challenges have motivated this work. We wanted to find ways that could accelerate the drying in DDAs, but at the same time works with current infrastructure. Any solution requiring large capital costs as well as any technique that scraps current infrastructure is hard to be accepted by operators. We wanted to investigate a technique that will not only work in DDAs but also with the rest vast amount of fine tailings. These fine tailings take 2-3 years or more to reach to a level where they are considered 'mature' and acceptable for polymer treatment. Thus, in short we wanted to develop a technique that provides end-to-end solution to tailings problem. It should not only treat Mature Fine Tailings (MFT) but also fine tailings and help in drying so as to provide required trafficable shear strength. The method should be able to treat new as well as legacy tailings. The technique developed, observations, results and conclusions are reported in this work.

Similar to Suncor's TRO (Tailings Reduction Operations) which uses binders for MFT; Shell's composite tailings (CT) technology for dewatering and thickening tailings; Syncrude's accelerated dewatering technology using cyclones and CNRL's CO_2 introduction for silts in the tailings are some of the main technologies that are deployed these days in field. All of these are briefly described with advantages and disadvantages in Table 2-1.

Company	Tailings treatment technologies currently used	Brief description	Advantages	Disadvantages
1) Suncor	• TRO™ (Tailings Reduction Operations) • Composite tails	• MFT is mixed with flocculent, anionic polyacrylamide polymer which helps in release of water from clays. This mixture is placed over large sloped areas so that water can run-off and the tailings dried with natural evaporation with the help of Sun.	• Faster reclamation than previously used Composite Tailings (CT) technology which used coarse sand and Gypsum • TRO has less disturbed land area footprint than CT process • 3 times faster reclamation claimed • Cost effective	• Lot of dependence on natural factors such as natural evaporation from Sun in harsh weather of northern Alberta • Cost effective but not fast which in turn increases environmental liability for future capacity increase
2) Shell	• Atmospheric fines drying (AFD) • Thickened tailings – TT (exclusive) • Non-Segregated Tailings (NST) • Composite tailings	• AFD: addition of flocculants followed by layer by layer dewatering and atmospheric drying • TT technology uses thickening plant before tailings are sent to ponds and thereafter	• Cost effective addition of flocculants for dewatering • Exclusive thickened tailings technology for better hot water recycling	• Atmospheric drying limiting factor • Capital and operating costs associated with thickening plant

		to dedicated disposal areas		
3) Syncrude	• Water capping • Composite tails • Centrifuged tails • Rim ditching /accelerated dewatering	• Capping the tailings lake with fresh water • Centrifuging tailings slurry to separate water out	• Claims of natural ponds formation with time • Centrifuging is seen as an costly but highly effective technique	• Refuted by WWF for not forming natural water habitat as claimed • Higher operational costs associated with centrifuges
4) CNRL	• Non-Segregated Tailings (NST) • CO_2 addition to tailings	• Gypsum and coarse sand addition to MFT • CO_2 is added to the tailings stream to get accelerated coagulation of suspended fine clays	• Claimed as the most effective technique by CNRL	• Costs associated with CO_2 capture and its sequestration in tailings
5) Imperial Oil	• Thickened tailings	• New player in tailings management (starting with Kearl project in 2018)	• Will be same as other operators	• Will be same as other operators

Table 2-1 Current industrial tailings treatment techniques

3. Electrical Resonant Auto-Transformer

3.1 Introduction

The idea is to use electrical system power to speed up the dewatering and complete drying treatment of oil sands tailings. Although electrokinetic - DC voltage treatment (Guo. 2012, Fourie. 2006) and Electrocoagulation by AC voltage (EC/AC) application (Ifill. 2010) has been studied previously, there are no known studies on tailings treatment with extremely high voltage application at higher AC frequency. This is probably due to the fact that conventional transformer systems are costly, has a low q-factor (ratio energy stored to energy dissipated per unit cycle) and will consume a lot of power to produce such high voltages. We at NIME group may have found an efficient way to produce high electric field with minimal power using a novel device, i.e., Near-field (Non-radiative) Resonant Auto-Transformer (NRAT) coil.

3.2 Non-field Resonant Auto-Transformer (NRAT)

A Resonant Auto-Transformer is a non-radiating electrical system developed at Nano-Interface and Molecular Engineering (NIME) group, Department of Chemical and Materials Engineering at University of Alberta. The Near-field Resonant Auto-Transformer (NRAT) or synonymously also called helical resonator is a highly modified version of Tesla coil and can produce very high electric field, of order 10^6 V/m, with only small power input (around 250 watts). The Resonant Auto-Transformer uses AC power signal that drives it at a particular frequency with its inductance and capacitance and produces standing quarter waves of voltage (V) and current (I) quarter waves resonating maximum to minimum in sinusoidal fashion. The energy inputted to NRAT system through power amplifier is designed to be confined within the system by suppressing the electromagnetic radiation. This suppression allows the near-field parameters of the system, voltage and current, to resonantly build with each input cycle within few milliseconds.

The system consists of 2 coils, primary and secondary, that are inductively coupled to each other. The cylindrical core of the primary coil has 30 cm radius and is spun by about 450 meters of insulated copper wire of 6 American Wire gauges (AWG) (0.1620 inches or 4.115 mm diameter). The primary has about 260 turns. The secondary coil is a combination of 5 parallel coils arranged in circle with each having 25 turns. The secondary coil base seats about 23 cm above ground. The schematics and experimental setup of NRAT coil is shown in Figure 3-1 and Figure 3-2 respectively.

The NRAT system is a near-field non-radiating system with 5-10 watts output. The tapping electrodes are connected to different locations along this helical coil. A small amount of real electrical power is also dissipated within the system and the unused power is stored back within the system in the form of resonating quarter current and voltage waves. This electric field applied to dielectric medium will polarize the material based on its inherent properties.

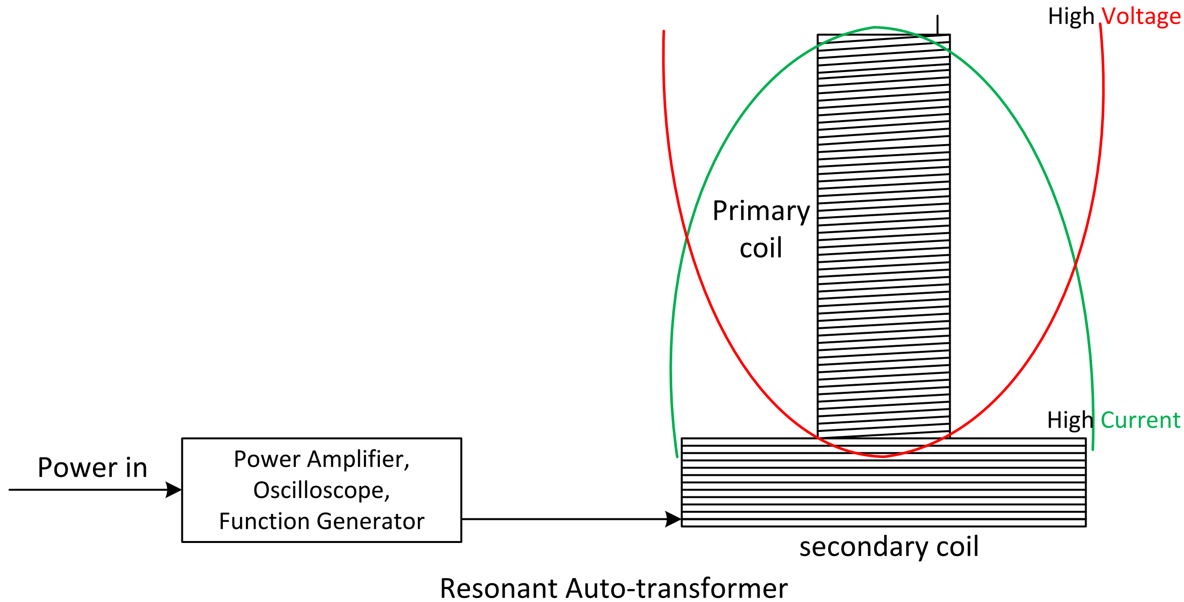


Figure 3-1 Near-field Resonant Auto-Transformer (NRAT)

Figure 3-2 Near-field Resonant Auto-Transformer (NRAT) encased in Faraday's safety cage

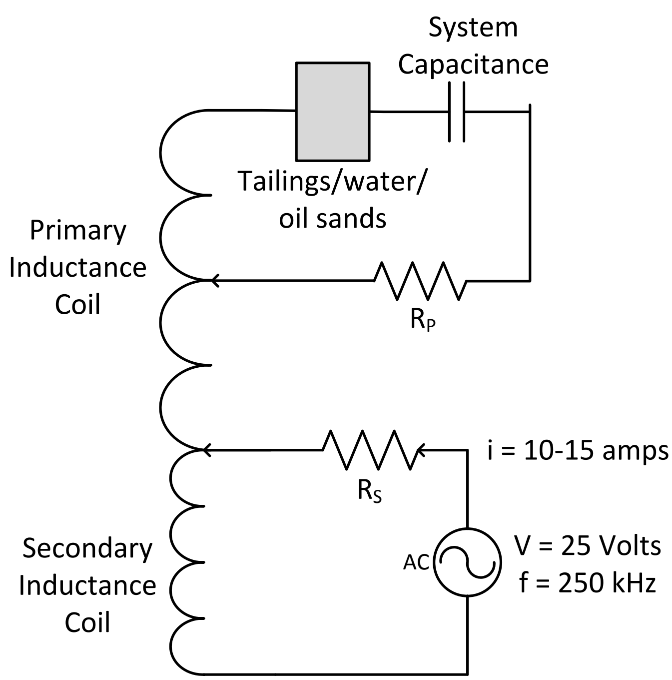


Figure 3-3 Circuit diagram for Resonant Auto-Transformer setup

The voltage and current profile for each turn of coil found out with the help of modeling is shown in Figure 3-4 (Van Neste et al. 2014). It was calculated assuming 25 Volts r.m.s (root mean square) AC input operating at 250 kHz frequency (Figure 3-3). The value of the current for which the system shows the dielectric breakdown of air is 17 amps r.m.s.. The system has been observed to run up to 95.5% efficiency if only primary coil is connected to power supply. It undermines the power amplifiers capacity to put more power in the system as resonance starts to push the power back in power amplifier.

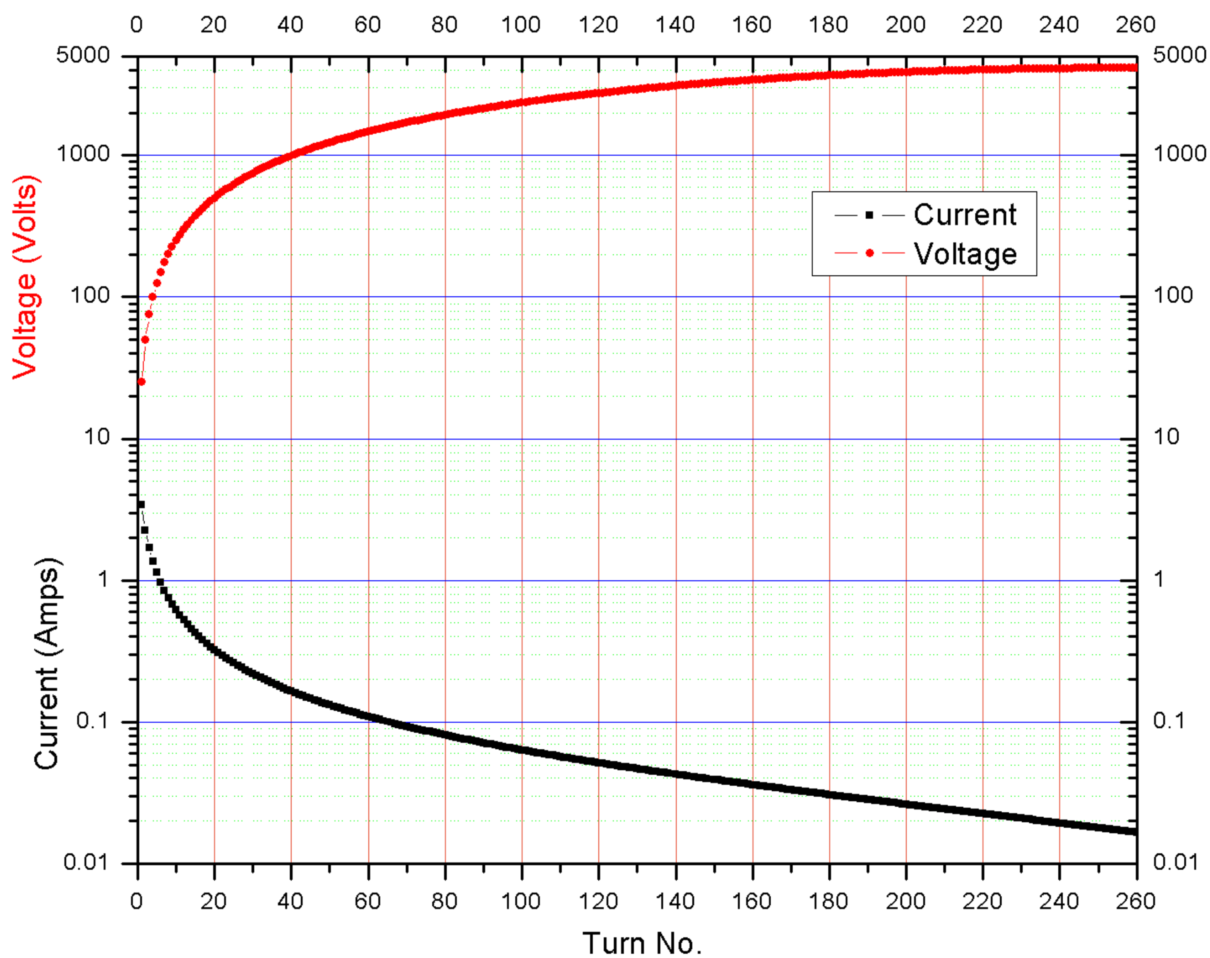


Figure 3-4 Voltage and Current values for each turn of the coil

3.3 Role of Electric Field and Field Gradient

The NRAT system is able to produce alternating high electric voltages across a narrow electrode distance. This in turn produces very high electric fields and field gradients across the electrodes. The application of high-voltage can separate dielectric electrolyte systems by exerting electrophoretic and dielectrophoretic (DEP) forces on them collectively termed as 'Electrokinetic forces'. Electrophoretic forces are induced by interaction of field with charged particles while dielectrophoretic (DEP) forces are induced by interaction of electrical diffuse double layer in a non-uniform electric field.

The conventional expression for DEP force ***F*** acting on a spherical particle of radius 'a' and dielectric permittivity ε_p in a medium of dielectric permittivity ε_m is given as (WASHIZU and JONES. 1994):

$$\boldsymbol{F} = (\boldsymbol{p}.\,\nabla)\boldsymbol{E} = 2\pi\varepsilon_m a^3 \frac{(\varepsilon_p - \varepsilon_m)}{(\varepsilon_p + 2\varepsilon_m)}\ \nabla\boldsymbol{E}^2$$

$\boldsymbol{F}$: DEP force vector

$\boldsymbol{p}$: effective induced dipole moment vector

$\boldsymbol{E}$: Electric field vector

a: radius of spherical particle

ε_p: dielectric permittivity of the particle

ε_m: dielectric permittivity of the medium

The $\frac{(\varepsilon_p - \varepsilon_m)}{(\varepsilon_p + 2\varepsilon_m)}$ factor is further known as Clausius-Mossotti (CM) factor. The higher order compact tensor formulation of the DEP forces can be summarized as follows (Jones and Washizu. 1996):

$$\boldsymbol{F}^{(\boldsymbol{n})} = \frac{\overline{\boldsymbol{p}}^{(n)}\,[.]^n(\nabla)^n\mathbf{E}}{n!}$$

n : force order (n=1 for dipole, n=2 for quadrapole etc.)

$\boldsymbol{F}$: DEP force vector

$\overline{\boldsymbol{p}}^{(n)}$: multipolar induced-moment tensor

$[.]^n$: n dot products

$(\nabla)^n$: n gradient operation

An electrorotational (ROT) torque ($\boldsymbol{T}$) is also acted upon on a dipole/quadrapole etc. is generalized as cross product of dipole moment ($\boldsymbol{p}$) and electric field ($\boldsymbol{E}$) follows:

$$\boldsymbol{T} = \boldsymbol{p} \times \boldsymbol{E}$$

The higher order compact tensor formulation of the ROT torque can be summarized as follows (Jones and Washizu. 1996):

$$\boldsymbol{T}^{(n)} = \frac{\left[\overline{\boldsymbol{p}}^{(n)}\, [.]^{n-1} (\nabla)^{n-1}\right] \times \mathbf{E}}{(n-1)!}$$

n: force order (n=1 for dipole, n=2 for quadrapole etc.)

$\boldsymbol{T}$**:** ROT torque vector

$\overline{\boldsymbol{p}}^{(n)}$: multipolar induced-moment tensor

$[.]^{n-1}$: n-1 dot products

$(\nabla)^{n-1}$: n-1 gradient operation

The simplified dielectrophoretic (DEP) force per unit area can be written as (Shang and Dunlap. 1996):

$$\frac{\partial F}{\partial A} \propto f(\varepsilon)\, \nabla E^2$$

$\partial F / \partial A$: force exerted on charged particles per unit area [N/m^2]

ε : electrical permittivity [F/m or C^2/N.m^2]

∇E : gradient of electric field [V/m or N/C]

Also, the dielectric power dissipated per unit volume within the tailings or any capacitive is given by Poynting factor as follows (Zhang and Marra. 2010):

$$\frac{\partial P}{\partial V} = 2\pi f \varepsilon_0\, \varepsilon_r{}' \tan\delta\, E^2$$

$\partial P / \partial V$: power dissipated within the capacitive medium per unit volume

f : frequency [Hz]

ε_0 : vacuum permittivity, 8.854×10^{-12} [F/m]

ε_r : electrical permittivity (ε = ε’ – jε”) [F/m]

$\tan\delta$: loss tangent (ε”/ ε’)

E : electric field [V/m]

For a higher electric (E) field, being proportional to square of the electric field term force per unit area and power per unit volume are significantly higher. Hence with higher non-uniform electric field, more pressure is applied on charged fines in the tailings. The more this unbalanced force is, the more are the chances of fines colliding and coagulating with each other. Since dielectric power is also dissipated, we are able to raise the temperature of the system through dielectric heating. This dielectric heating imparts convective water currents in the tailings medium and increasing the chances of collision, brings the particle within the attraction region in their Brownian motion (Merkus. 2009).

3.4 Safety

Safety should be the foremost aspect of any industrial technique. Providing a technique which is safe to operate is one of our main objectives. A technique, if not safe, will be hazardous to operators and probably will not meet stringent government regulations of safe industrial practices. As for any electrical and industrial process, the risks are always involved with the operation, but a safer technique is always about minimizing those inherent risks. The Near-field Resonant Auto-Transformer (NRAT) is an electrical system. As any electric system, the risks of electrical hazards are inherent by nature but that does not mean we stop using electric power, we find a safer way around it. Similarly, a safer way around Resonant Auto-Transformer will make it practical to be used during tailings treatment operation.

Although the NRAT system is designed not to radiate, there may be some leaking electromagnetic fields associated with it. To contain these leaking electromagnetic fields, a Faraday's cage has been put around the NRAT system. Faraday's cage is a simple grounded cage structure which acts as a protective shield around the NRAT. There are no electromagnetic fields coming out of Faraday's cage. The NRAT system also detunes by any external interference such as human bodies which will reduce the damage, say compared to the scenario when system is producing million volts. Thus in an industrial treatment scenario, the NRAT system can be put somewhere safe from the tailings treatment area. This will reduce the electrical hazards significantly making the system safe to operate.

As for the advantage of used NRAT system, it does not affect the environment in any way. Many other treatment methods use external chemical agents which irreversibly damage the environment; the same case is not associated with NRAT treatment system. The system rather helps in accelerated dewatering treatment and drying of tailings in environmentally friendly way. It is very capable of meeting all government regulations set for an industrial electrical system. The energy efficiency and cost effectiveness of the system is discussed in the following chapters.

4. Tailings Treatment Experiments

The motivation for treatment of tailings is now clear from points discussed in Chapter 2. In this chapter the inception of tailings treatment idea, general setup, instruments and experiments for tailings treatment are described. First, few general experiments with basic ideas for tailings treatment are discussed. Later, the use of NRAT coil and the instruments, setup used for those experiments are described followed by the observations.

4.1 Basic evaporation based tailings drying

Currently, tailings spread over dedicated disposal areas are naturally dried by evaporation of water by Sun drying in summer months. To get a rough idea about the rate of drying for such atmospheric conditions, 100 g of tailings was left for drying in fume hood at 26^0C. The setup was weighed number of times over a period of 200 hours. The weight profile with time for drying MFT sample is shown in Figure 4-1.

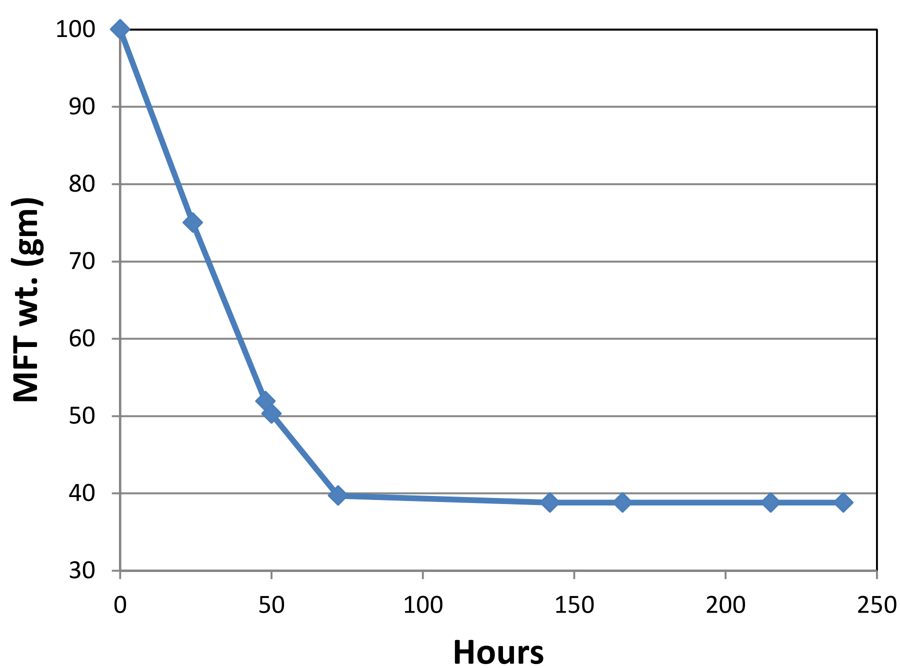


Figure 4-1 Natural drying profile of 100 g MFT sample in fume hood

For this particular 100 g sample of MFT, 61.2 g of water evaporated over the completion of experiment and 38.8 g of solid mass was left by the end. Over initial 72 hours, about 60.3 g of water evaporated. Thus for this initial 72 hours period, we can say the drying rate is approximately 0.8375 g/hour. A 400 ml VWR beaker with 7.5 cm diameter and 10.5 cm height was used in the experiment. The 100 g MFT was about 2 cm in thickness inside the beaker. Though the drying will be dependent on area exposed to the atmosphere for the MFT in beaker and also the height of MFT in beaker, still it can be safely said that the drying rate of say about 1 g/hr is not much and a better solution is required to solve this problem.

4.2 Hot plate drying model and idea of using drying chambers

Using the hot plate to increase the temperature of MFT and evaporate the water might be one of the fastest ways to dry MFT. Based on lab experiment for 100 g MFT, the initial drying rate as high as 5.7 g/hr was observed. The idea of using a heating chamber that evaporates out most of the water from MFT was proposed. The schematic for this idea is shown in Figure 4-2.

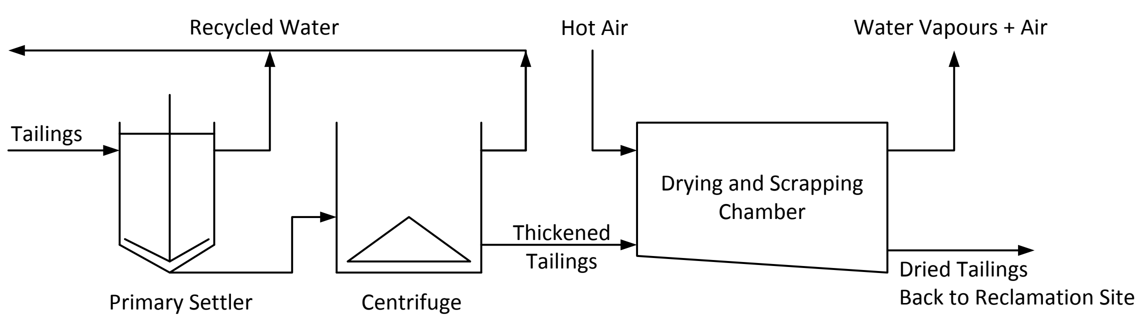


Figure 4-2 Schematics for idea of using centrifuges and drying chambers

The water from primary separator and centrifuge can be recycled and reused for hot water extraction process. The mud coming out of centrifuge can be processed in heating chambers. Currently it’s sprayed all across the land and dried till it loses moisture naturally (which takes a significant amount of time) and then is finally scrapped. With above proposed method we can get dry mass within matter of hours. For the purpose of heating chamber along with incoming hot air, we have few ideas of incorporating electrical heating. One may incorporate a steel plate (on which mud will be evenly distributed) and heat it electrically. Secondly, we can have a steel fence like structure which will be pushed in mud and then electrically heated.

Though theoretically the idea will solve the problem, it has not been used in industry. The MFT components such as water, sand and clays all have high heat capacities. Thus, practically the system will consume too much energy. Based on discussions with industrial partner, it was concluded that the cost, both capital and operating it day-to-day, will be too prohibitive if this system is to be used. This is why the conventional direct solution of heating MFT for the purpose of evaporation is not currently used in industry.

4.3 MFT drying by blowing air

A simple experiment for drying out MFT by blowing both hot air and room temperature air was performed. The schematic for the experiment is shown in Figure 4-3.

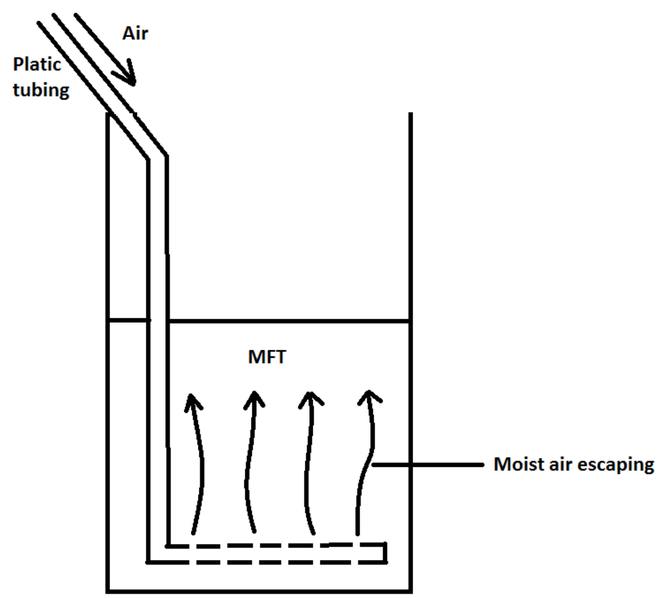


Figure 4-3 MFT drying by blowing hot and cold air

In this experiment, initially air at room temperature was sent through MFT in the beaker. The plastic tubing with multiple orifices at the end was used for sparging the air through MFT. The escaping air stripped MFT of some of the water content it had. The procedure was repeated couple of times. In the second step of this experiment, hot air blower was used over the MFT. After repeating this experiment multiple times excellent drying of MFT was observed (Figure 4-4).

Figure 4-4 Dried MFT by blowing air

The use of hot and cold air combination worked very well. The argument against the method is the capital cost associated with piping/tubing that will have to be installed in dedicated drying areas. Usually MFT is spread in thin layers of 15-20 cm thickness over each other multiple times. Though the technique would work excellent for first few times, after considerable thickness of batches the tubing will be useless. Also, the piping will be lost in disposal areas and of course it is very costly when it comes to piping. The piping/tubing might be unrecoverable after certain time and number of batches. Also the area to be covered remains very vast in DDAs so piping costs will be too prohibitive.

4.4 Tailings microwave treatment

Microwaving the tailings for heating them and evaporating the water has been one of the widely discussed ideas. Although theoretically it will heat the MFT and evaporate water, there are many factors involved that prevent implementation of this technique. The problem with heating the entire tailings is high heat capacities of water, sand and clay, thus the process will take a lot of energy. Rather than heating the tailings right from the start, the drying of densified tailings will take much less energy and cost.

The electromagnetic spectrum of 1 mm – 1 m (λ) wavelength is termed as 'microwave' range. Thus, the frequency for this spectrum comes out to be ($\nu = c/\lambda$; $c=3*10^8$ m/s) 300 MHz to 300 GHz. A typical consumer grade microwave oven uses 2.45 GHz frequency thus has wavelength about 12.2 cm. An industrial or commercial grade microwave can typically operate at about 915 MHz thus having wavelength of 32.8 cm (Litton Industries. 2007). Thus for most microwaves the penetration depth is about 12-33 cm. So with this sort of penetration depth, theoretically thin layers of typical 20 cm thickness will work. But for large batch which mostly has few hundred tonnes tailings, a very vast area will have to be microwaved. Also, the costs associated with microwaves are too high. Of the total input power supplied to microwave electromagnetic (magnetron) coil, only a fraction is used in heating. The unused power is never stored back for microwave ovens unlike NRAT system.

Thus, a capital cost effective tailings treatment system remains to be explored. After thinking over all of the above systems, the NRAT coil was analyzed as a probable candidate for tailings treatment. The instruments, the setup and different NRAT coil experiments are described below.

4.5 Instruments

The instruments used for NRAT coil tailings treatment experiments are as follows:

- High frequency power amplifier (Amp-Line Corp., model Al-1400-HF-A)
- Function generator (Stanford Research Systems, Synthesized function generator, model DS345)
- Oscilloscope (Digital Storage Oscilloscope, TDS2000C)
- Temperature sensing system (Qualitrol® OFX-USB™ Omniflex System)
- Temperature data recording computer
- Novel designed NRAT system

4.6 NRAT coil experimental setup

High frequency power amplifier (Amp-Line Corp., model Al-1400-HF-A) is used to supply power to the NRAT coil while taking its operating input from 120 V wall outlet. The NRAT system is kept in Faraday's cage to prevent leaking electromagnetic field. The function generator (Stanford Research Systems, Synthesized function generator, model DS345) is used to produce sinusoidal waveform for power amplifier. The power amplifier takes this 0-2 V sine wave input and amplifies it with the help of power from wall outlet up to 28 Volts and supplies it to NRAT coil as required. The function generator also helps in tuning the right frequency for the sine waveform so as to set right frequency for resonance. The oscilloscope (Digital Storage Oscilloscope, TDS2000C) helps in the measurement of the current and voltage field (inside Faraday's cage) which indicates the NRAT resonance. At resonance, a sharp rise in peak for both current and voltage field can be observed.

The automated temperature sensing system (Qualitrol® OFX-USB™ Omniflex System) has been procured. The input from optical temperature sensors is send to this system which also displays it on computer monitor screen where it can be recorded. The temperature sensors are carefully placed in the heating medium (water/tailings/MFT/oil sands) when high voltage treatment by NRAT coil is carried out.

4.7 NRAT coil treatment experiments

This section describes briefly into the background of how NRAT system was recognized as the potential technique for complete tailings treatment. It was initially observed that NRAT system can produce high voltages. At first, small 100 ml beaker of water was heated using copper connection chords that are attached to NRAT coil. For a small wattage supplied, the rapid increase in temperature of the water was observed. This rapid increase in temperature is caused due to dielectric heating given by *Poynting factor* ($\delta P/\delta V = 2\pi f*E^2*\varepsilon'*\tan\delta$) for capacitive medium, water in this case. Because the system is considered highly efficient, the similar high voltage treatment and dielectric heating idea was extended to oil sands and tailings. Bitumen extraction by dielectric heating of oil sands and complete remediation of tailings by electrocoagulation followed by complete drying due to dielectric heating were carried out. For the prospect of this thesis, tailings remediation area is focused and bitumen extraction is another separate continuing piece of work from NIME group.

4.7.1 Water heating experiment

The initial experiments with the NRAT system were conducted with small amount of water in glass beaker. The arrangement of introduced electrodes and temperature sensors has been same in most of the experiments as shown in Figure 4-5.

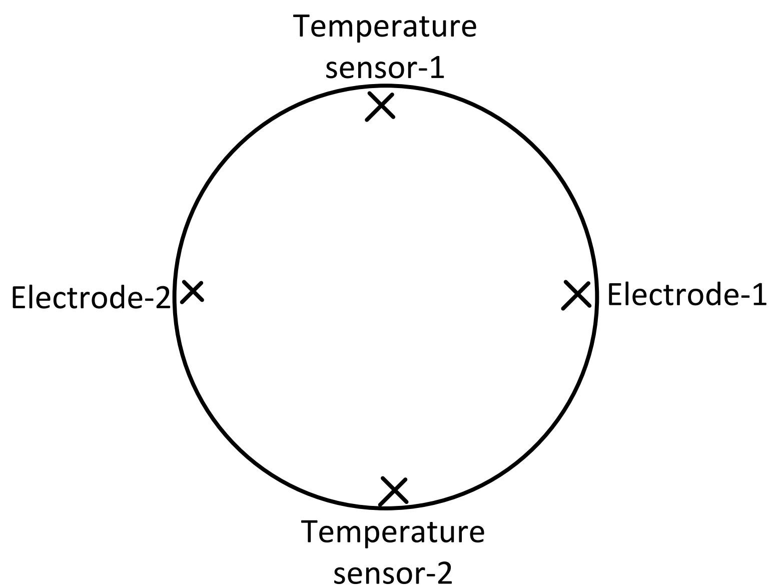


Figure 4-5 Temperature sensor and electrodes configuration for beaker top-view

The top end of the coil, having very high voltage, was connected to electrode 1. The electrode 2 was connected to low end of the coil, tapped to coil itself approximately at the middle. The tapping produces a specific voltage difference between the electrodes which can be changed based on the requirement. Changing tapping is very necessary for maximum power dissipation within the load, as explained in next chapter by principle of load/impedance matching.

The heat was dissipated in water medium by dielectric heating. The temperature data recorded for 100 grams of water system is shown in Figure 4-6.

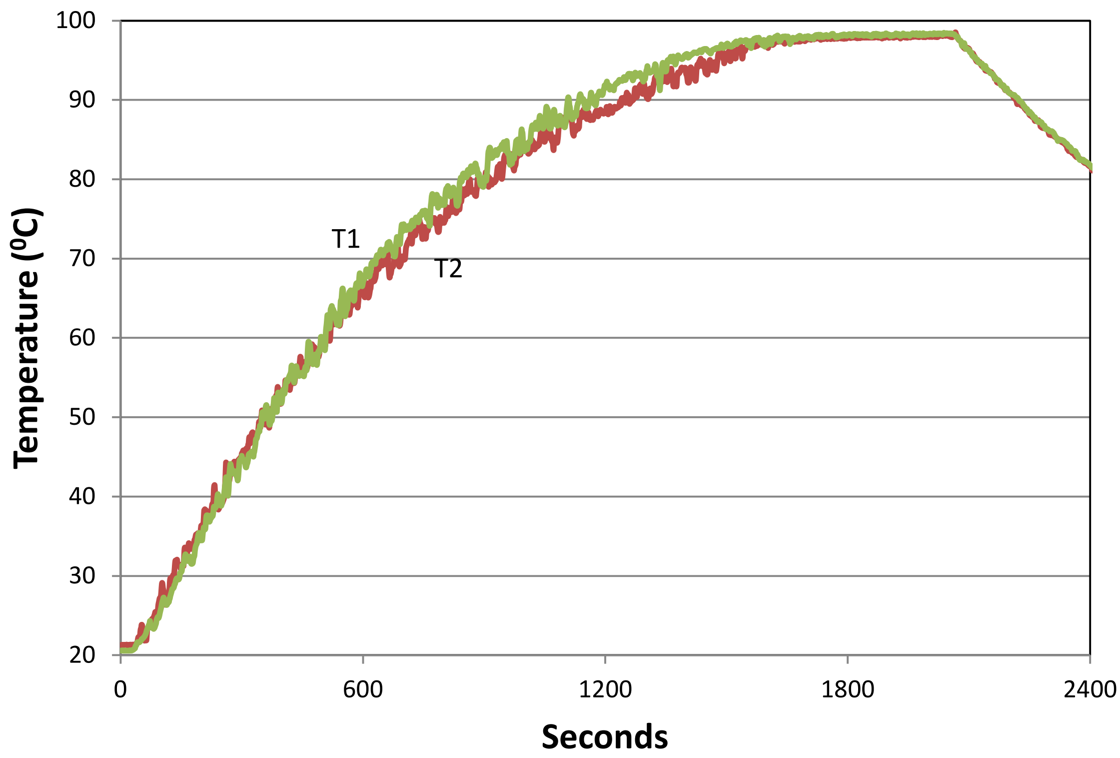


Figure 4-6 100 g water heating graph with NRAT coil with 2 temperature sensors

4.7.2 Oil sands heating experiment

After heating the water with the help of NRAT system, the oil sands sample heating treatment was carried out with system. The conventional in-situ extraction techniques use a large amount of water and energy, that's why a more sustainable and economical way of extractions is needed. The energy efficient NRAT system can very well be used for increasing temperature of the system for bitumen extraction. The preliminary lab-scale experiments have shown promising results. For 500 g oil sands sample, temperature as high as 100^0C have been observed within couple of hours. This temperature rise should be sufficient for viscosity reduction of the bitumen and ways to extract that bitumen from sands are being worked out in a separate project from NIME group.

4.7.3 Mature Fine Tailings (MFT) drying experiment

The treatment of tailings with the help of electrical NRAT system was identified as the most promising application of the system by our industrial partners and work began on understanding the system with MFT initially. In widely used Suncor's Tailings Reduction Operation (TRO™) technique, MFT is treated with polymers and then dried in Dedicated Disposal Areas (DDAs). But, this process has limited time span of Alberta's short summer. Thus, to increase the speed and efficiency of the process any external (electrical) input supplied to the system shall be useful. If an inexpensive but less costly system can be used in this DDAs to shorten the drying cycle of 14 days to a couple of day by increasing the temperature of the batch, thus in turn increasing evaporation from the system; the amount of MFT treated would increase drastically. This will shorten the tailings remediation timespan.

The 800 g sample of MFT was taken in beaker and the setup was heated with help of coil to increase the temperature so that the evaporation increases. The temperature data recorded is given in Figure 4-7.

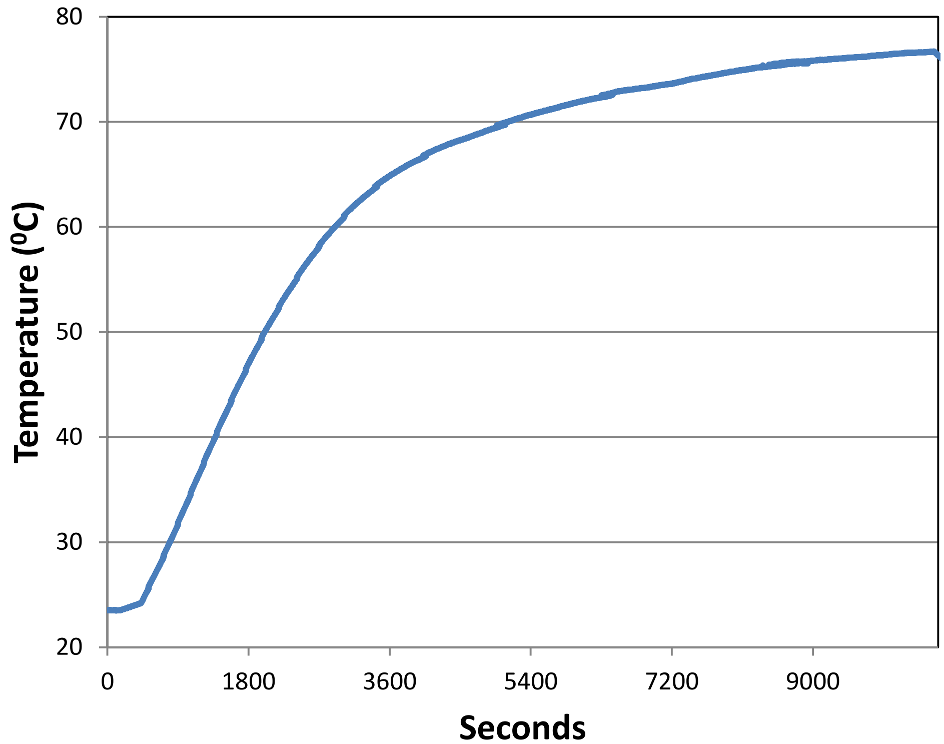


Figure 4-7 Temperature rise for 800 g MFT with NRAT system

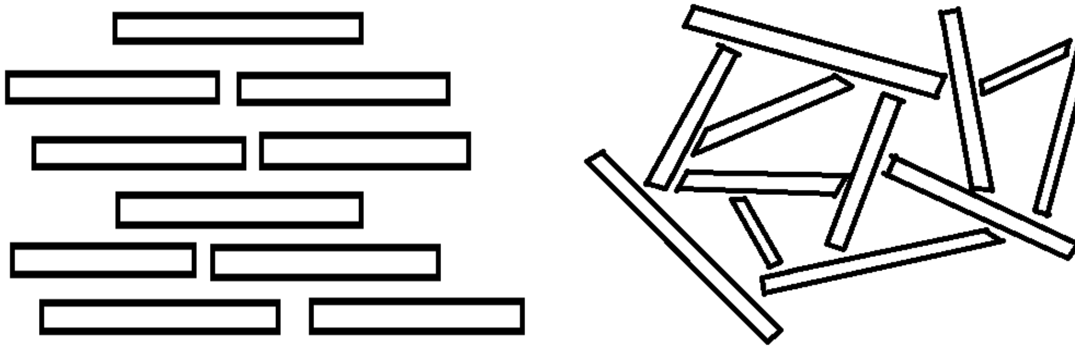
4.7.4 Tailings 'polymer treatment' experiment

The use of polymers has become quite significant in tailings treatment industry. A variety of cationic, non-ionic and anionic polymers are being studied (Wang. 2011). The polymer, mostly partially hydrolyzed anionic polyacrylamide or Magnafloc, is widely used as flocculent for dewatering tailings. It has been significantly researched by (Wang et al. 2010, Long et al. 2006, Wang. 2013). Clays have a negative charge on their face structure and Ca^{2+} ions are strongly adhered to it. The optimum amount of polymer can bind these positively charged Ca^{2+} ions and help with the settling by increasing particle size. It is also worthwhile to mention that this flocculation works only for a certain concentration window and doesn't help if the polymer concentration is too low or too high. With very low concentration, there is not enough binding while with too high concentration, the anionic polymer start its own repulsion with negatively charged clays. The temperature also plays a significant role in the working mechanism of coil-globule transition temperature sensitive polymers (Chan. 2011).

Though use of polymers has been identified as one of the most cost effective present technique, there have been some concerns about quality of recycled water and possible harmful effects on environment by external agent, such as polymers during reclamation process and growth of plants. There might be chances of polymer getting adsorbed in food chain ecosystem when plants are grown over polymer treated reclaimed areas. More work need to be done to prove this concern either way.

4.7.5 Tailings 'acid treatment' experiment

The Canadian Natural Resources Limited Inc. (CNRL) uses CO_2 addition to its tailings for treatment. The sequestration of CO_2 to tailings having significant water content produces Carbonic acid (H_2CO_3). The production of this mild acid, changes the pH of the tailings medium. Clays are very active in cation exchange phenomenon. A negative charge is left when tetravalent Silicon atom is replaced with trivalent aluminum ion having similar morphology. The charges on basal/face plane are considered permanent charges and are independent of pH. For kaolinite clays which are main constituent of tailings, the edge is positively charged in acidic medium and negatively charged in alkaline medium. That's why these clays transform into 'house of cards' structural arrangement in acidic medium from uniformly staggered structure of alkaline medium (Chan. 2011, Masliyah et al. 2011) as shown in Figure 4-8. Thus, 'acid treatment' helps with overall particle size increase of clays but still a significant amount of water is trapped in the voids.



Staggered clays in alkaline medium 'House of cards' clays in acidic medium

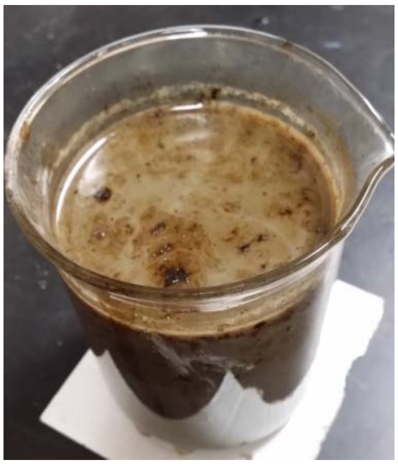
Figure 4-8 A simplified 2-D schematics of clays arrangement in alkaline and acidic medium (Bergaya and Lagaly. 2013)

The lab experiment was carried out to observe such behavior. A weak acid, Levulinic acid, was added to tailings. A visible transformation, coagulation of tailings (like buttermilk initially) to semi-viscous medium (like yogurt) could be instantly observed. No visible dewatering from tailings could be seen.

4.7.6 Fine tailings experiment

As previously discussed, the fine particles in the tailings are composed primarily of highly hydrophilic clays with repulsive negative charges and do not settle under gravity due to their micron and sub-micron sizes. Hydrophobic components in the tailings such as bitumen, attach themselves to the fine particles making their surface heterogeneous. The stability of MFT is a result of competing van-der-Waals and electrostatic repulsion forces. Our experiments show that dielectrophoretic forces produced by NRAT coil can be used for sedimentation of clays.

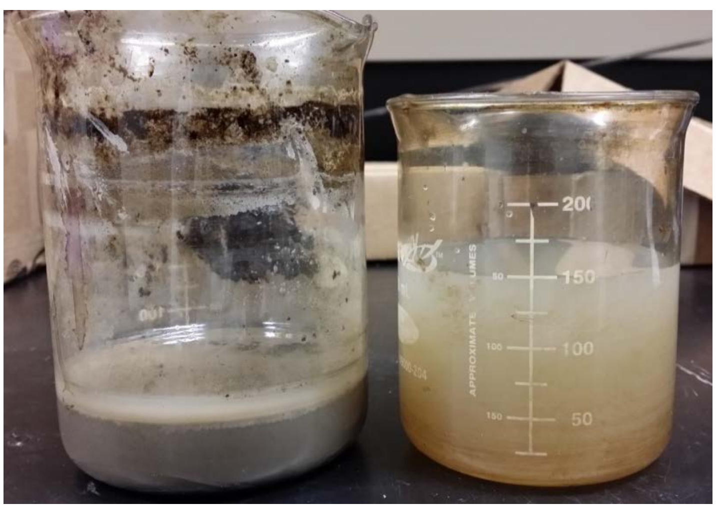
Perhaps the most important and interesting observations were made with fine tailings experiment with NRAT system. When fine tailings were subject to high electric field, within a couple of hours the water cap along with fine bitumen layer was seen on the top of the tailings. The settling of particles initially in colloidal phase was also observed. The images for the above observation for different experiments are shown in Figure 4-9 and Figure 4-10.



Fine tailings (initially)

Tailings separation after Auto-transformer treatment

Different layers formation after Autotransformer treatment

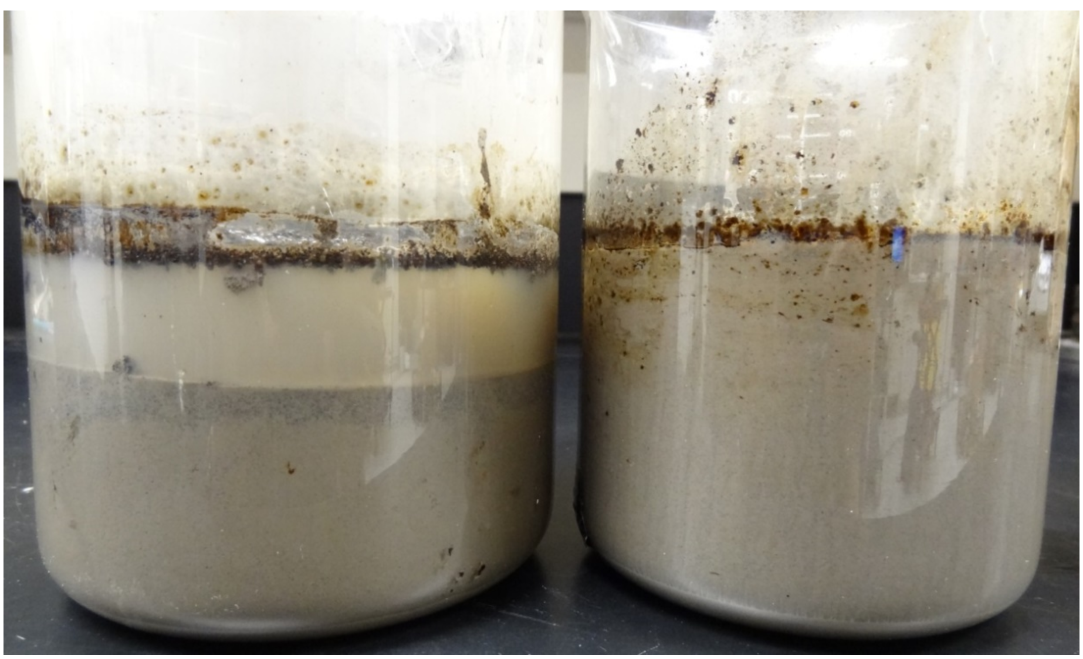


Decanting water out of treated tailings

Bitumen layer on top of treated tailings

Figure 4-9 Fine tailings treatment experiment with NRAT system

Water layer formation on top after autotransformer treatment (exp-2)



Tailings treatment: Auto-transformer treated vs Control (exp-3)

Figure 4-10 Tailings separation observed after NRAT coil treatment

Thus the use of NRAT technology can provide an 'End-to-End' solution to tailings problem which includes:

i. Densification of Fluid Fine Tailings (up to 30wt% solids)
ii. Recycling the decanted water to plant obtained from thickening of fine tailings (residual bitumen (though low in wt%) can also be separated from tailings by this technology)
iii. Drying of thickened tailings

The time of fine tailings settling treatment depends on solid wt% of the sample. Densification to 70 wt% solids or higher along with drying has been observed. Further treatment of thickened tailings (or even polymer treated thickened tailings) can be done in Dedicated Disposal Areas (DDAs), to form a dry solid mass capable of withstanding shear strength of 10 kPa or higher by enhancing the existing Sun evaporation technique. The mechanism responsible for densification from 30% to 70% is localized dielectric heating of MFT layer. Therefore, it is possible to dry the tailings in a layer-by-layer fashion. This can lead to faster evaporation of water in DDAs. A complete cake drying of above settled solids can also be reached by prolonged dielectrically heating with NRAT setup as shown in Figure 4-11.

Figure 4-11 Dry MFT cake

5. Tailings Characterization

The tailings sample for the experiments was purchased from Alberta Innovates Technology Futures (AITF). A pail of MFT from Suncor was previously available and 3 more pails were procured from Syncrude through IOSI program at University of Alberta. Though tailings samples are very heterogeneous and their properties may vary sample to sample, the following characterization experiments were performed to get some idea about the basic properties of the tailings.

5.1 Basic tailings properties

5.1.1 Density of tailings

Though the density of the MFT sample varies with each sample, depending on solid and water wt%; the average density of few samples was calculated as 1.4 g/cc (or 1400 kg/m^3).

5.1.2 pH of tailings

As we have learned previously that in Clark Hot Water Extraction (CHWE) process, oil sands are washed with Caustic Soda, NaOH. Oil sands deposits also naturally contain some metal carbonates deposit. This gives the tailings slurry a slightly alkaline nature. The measured values of pH ranges between 8 - 9. This range also confirms why natural settling is slow in alkaline medium (having staggered clay arrangement) as previously discussed in section 4.7.5.

5.1.3 Heat capacity measurement with DSC

The specific heat capacity of the MFT sample was found out with the help of DSC (Differential Scanning Calorimetry) apparatus. Because the tailings are dielectrically heated with high electric field, it is important to have an idea regarding the heat capacity (C_P) of the tailings. Two different samples were loaded and two runs were carried out for each case. For the first set of experiments, the sample was ground prior to uploading it in the crucible. A total of 81.32 mg was added and this sample in run-1, the tailings were heated from 30°C to 120°C at the rate of 5°C/minute and cooled back to room temperature. Run-2 was carried out on the same sample again to 120°C. The results obtained are shown in Figure 5-1.

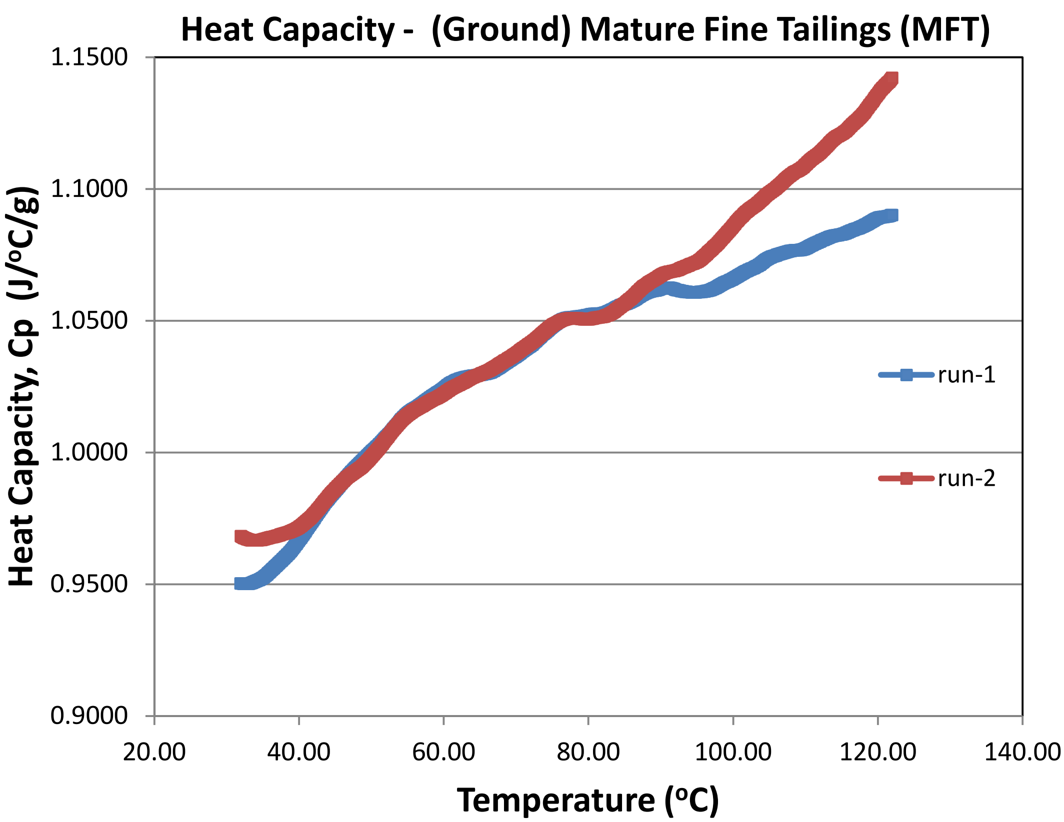


Figure 5-1 DSC heat capacity measurement for ground Mature Fine Tailings (MFT)

The similar experiments were carried for a second set of sample. This time small pieces of solid MFT weighing 110.39 mg was added to crucible. The sample was heated from 30°C to 120°C at the rate of 5°C/minute as previous. The results for the case are shown in Figure 5-2.

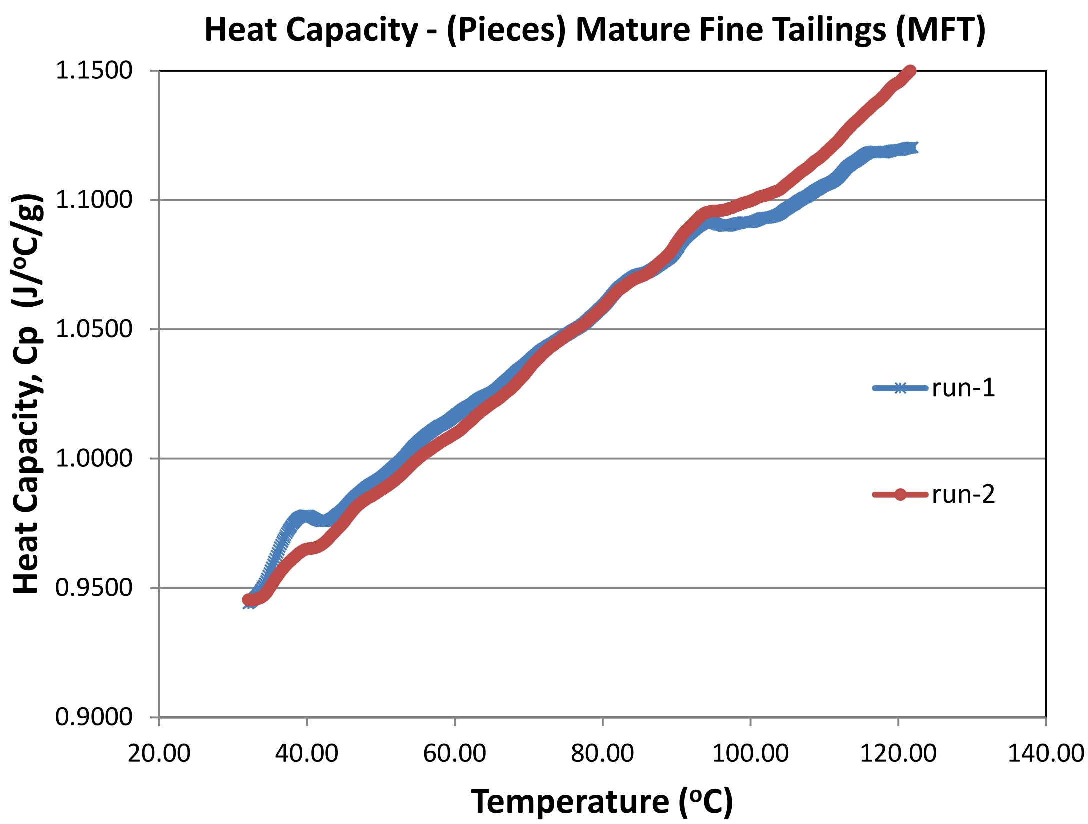


Figure 5-2 DSC heat capacity measurement for milled Mature Fine Tailings (MFT)

The sample-1 was ground to ensure a better distribution in the crucible while sample-2 was milled to pieces. For both the samples 1 and 2, similar deviation in slope of run-1 and run-2 can be observed after about 85^{0}C. The difference in slopes of run-1 and run-2 shows that evaporation of water and irreversible transition (phase change) in MFT components have occurred. This can be attributed to irreversible temperature induced transition of asphaltenes from amorphous to liquid crystalline phase at about 80 – 90 ^{0}C (Mehranfar et al. 2014). For run-1 in both the cases, the energy supplied in terms of temperature is triggering micro-nano-aggregation of asphaltenes. Also the water content is lost from MFT during run-1. Thus in run-2 this energy goes not only for heating evaporation water stripped MFT and temperature increase rather than phase change which has irreversibly occurred in previous run. The Athabasca asphaltenes have been reported for reversible heat capacities from ~27^{0}C (300K) to about 85^{O}C but non-reversing heat capacities thereafter (Tran. 2010).

5.1.4 Centrifugation of tailings

The centrifugation of MFT sample was done and four different layers were observed. The observations are in lines with (Salehi. Fall 2010, Fine Tailings Fundamentals Consortium. 1995). The different fractions are classified as follows and shown in Fig 5-3.

a) A small bitumen layer containing hydrophobic solids (HPS) on the top
b) A region containing water and hydrophilic ultra-fine solids (HUS) and bi-wetted ultra-fine solids (BUS)
c) A dark colored sediments region known as organic rich solids (ORS)
d) A light colored sediment region of coarser residual solids (RS) containing sand particles

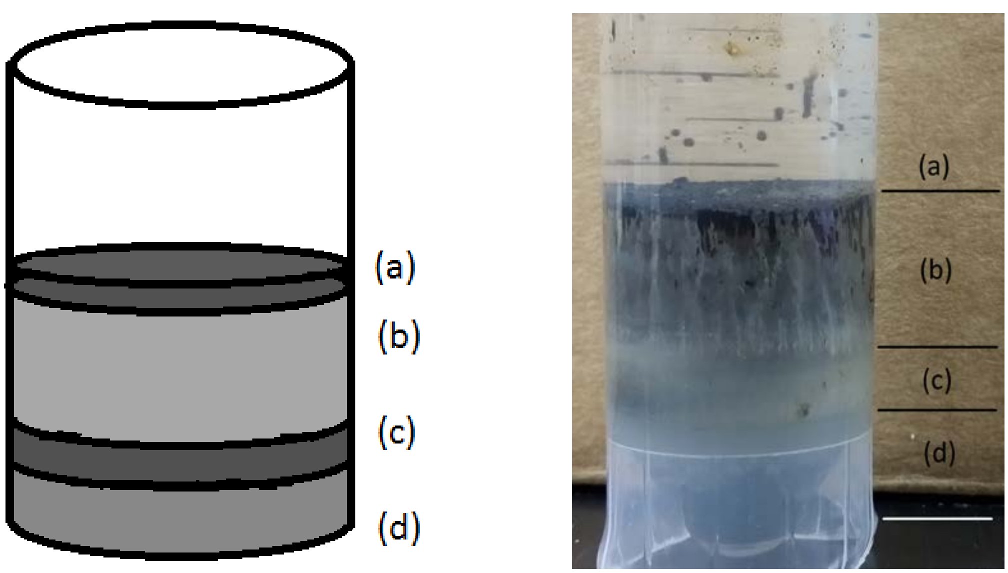


Figure 5-3 Regions of centrifuged tailings sample

5.1.5 Dielectric properties of the tailings

5.1.5.1 Relative permittivity (ε_r)

The absolute electrical permittivity (ε) of any dielectric medium is defined as how electric field affects, and is affected by a dielectric medium. Permittivity is related to electrical susceptibility (χ) which measures how easily a dielectric polarizes in response to electric field. The permittivity ε is defined in Farads per meter as product of ε_r, relative permittivity (unitless) and ε_0 which is vacuum permittivity 8.8542×10^{-12} F/m.

$$\varepsilon = \varepsilon_r . \varepsilon_0 = (1+\chi).\varepsilon_0$$

5.1.5.2 Procedure for measuring relative permittivity

For a parallel plate capacitor setup, the capacitance of an empty cell (with air medium, C_{air}) was measured with the help of '4294A Precision Impedance Network Analyzer by Agilent' over the given frequency ranges. The capacitance of the cell when it was filled with tailings sample was also measured, $C_{tailings}$. With these two values, the relative permittivity of tailings, $\varepsilon_{r,tailings}$, can be easily calculated as below. The relative permittivity of air for all practical purposes is very close to 1. We can get $\varepsilon_{r,tailings}$ as follows:

$$C_{air} = \varepsilon_{air} \cdot \frac{A}{d}$$

$$C_{tailings} = \varepsilon_{tailings} \cdot \frac{A}{d}$$

$$\frac{C_{tailings}}{C_{air}} = \frac{\varepsilon_{tailings}}{\varepsilon_{air}} = \frac{\varepsilon_{r,tailings} \cdot \varepsilon_{vacuum}}{\varepsilon_{r,air} \cdot \varepsilon_{vacuum}}$$

$$As\ \varepsilon_{r,air} \approx 1$$

Hence, $$\varepsilon_{r,tailings} = \frac{C_{tailings}}{C_{air}}$$

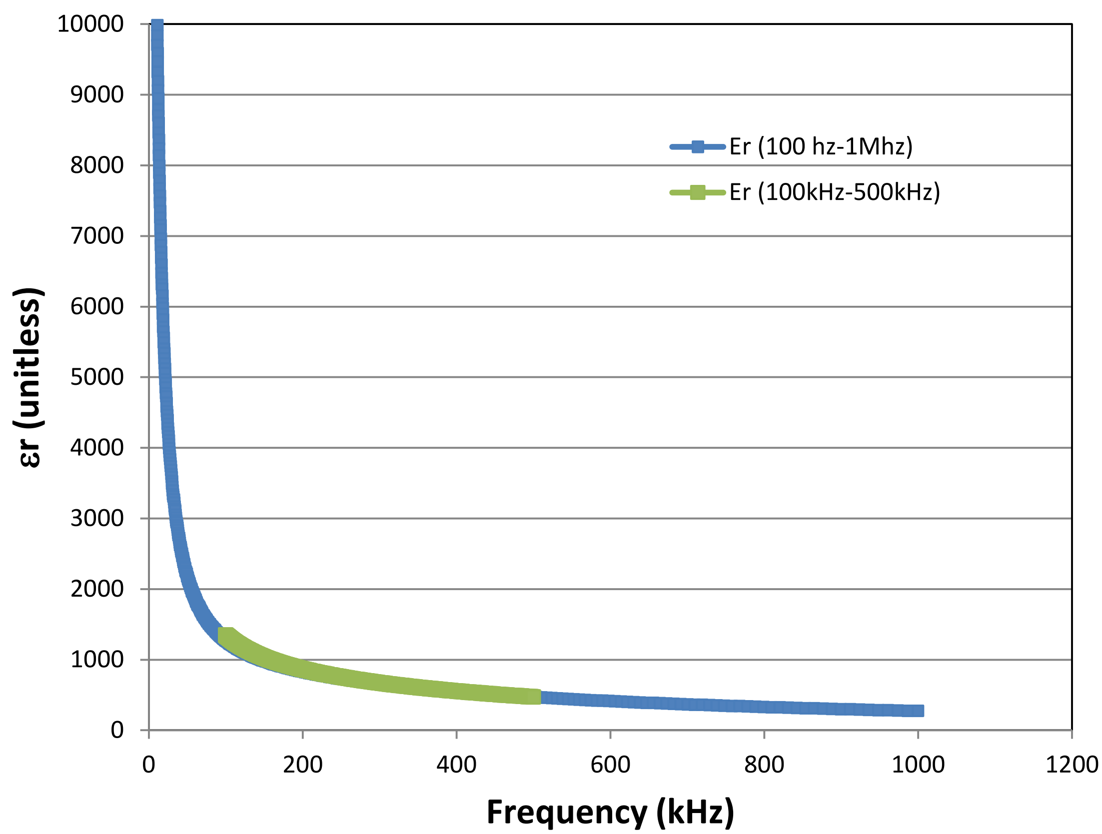


Figure 5-4 Tailings relative permittivity as a function of frequency (100 Hz – 1 MHz)

The graph for a short frequency range 100 kHz – 500 kHz is shown in Figure 5-4. The value of relative permittivity $\varepsilon_{r,tailings}$ was found approximately around 540 at about 250 kHz operating frequency. The values of relative permittivity for a smaller frequency range, 100 kHz – 400 kHz and 100 kHz – 500 kHz is shown in Figure 5-5.

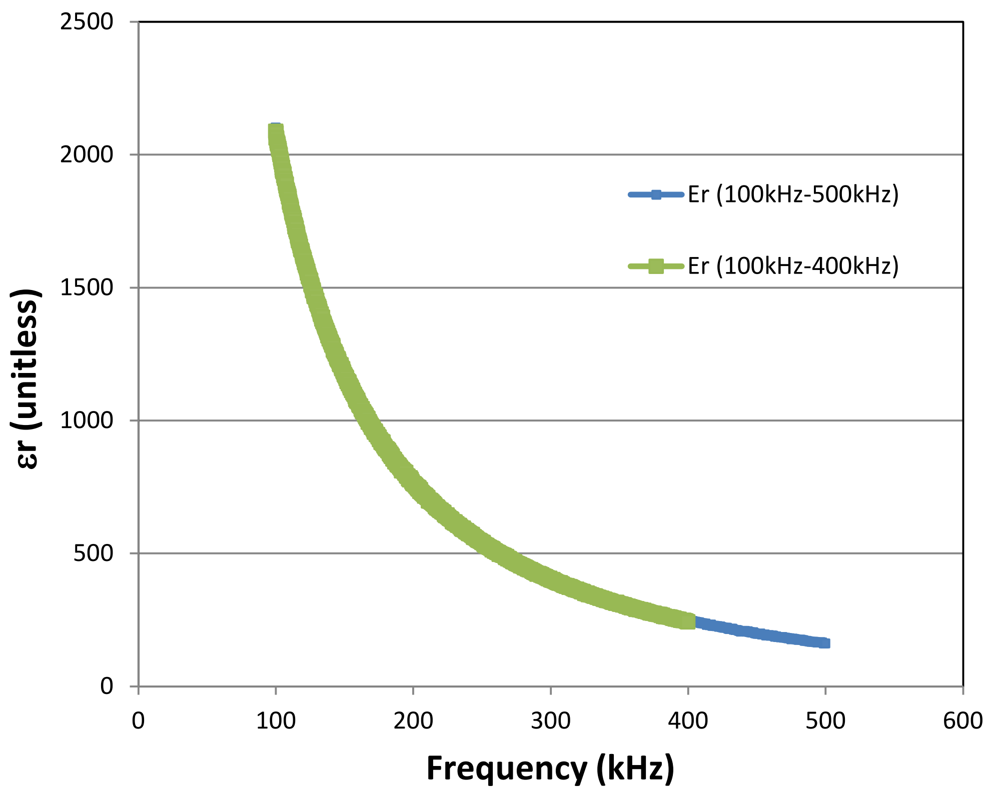


Figure 5-5 Tailings relative permittivity as a function of frequency (100 kHz – 500 kHz)

5.1.5.3 Loss tangent (tanδ)

The absolute complex permittivity for a dielectric medium is defined as $\varepsilon = \varepsilon' - j\varepsilon''$. In general, ε depends on temperature and frequency and to a lesser extent on pressure (Clarke. 2014). The abscissa, ε' is the factor for energy storage in each cycle where the ordinate, ε" is the energy loss factor in the dielectric medium for each cycle. The complex conjugate of ε, ε*(= ε' + *j*ε") is widely used in literature. The dielectric loss happening per unit volume in the medium is given by $\delta P/\delta V = 2\pi f * E^2 * \varepsilon''$. The factor that is usually measured is ε', so it becomes evident to replace ε" with ε'*tanδ. The loss tangent, tanδ is defined as $\tan\delta = \varepsilon''/\varepsilon'$; ratio of energy lost in medium to energy stored in medium per unit cycle. So the energy lost in dielectric medium as per *Poynting* factor becomes (Zhang and Marra. 2010),

$$\frac{\partial P}{\partial V} = 2\pi f.E^2.\varepsilon'.\tan\delta$$

The tanδ values were measured over a frequency range with the help of '4294A Precision Impedance Network Analyzer by Agilent' similar to the capacitance measurement from previous section. The values of loss factor D, tanδ is automatically calculated and presented by the system are shown in Figure 5-6. It must be noted that the tanδ = ε''/ε' also holds true for relative permittivity ε_r values, as ε_0 is fixed constant of value 8.85 * 10^{-12} F/m. At 250 kHz, the tanδ value is about 8.

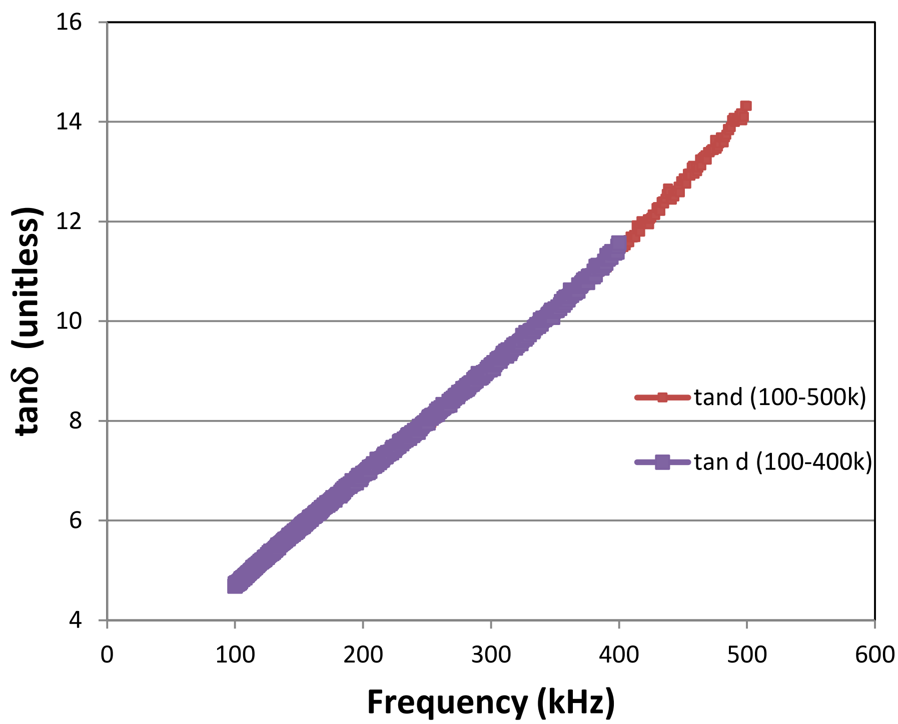


Figure 5-6 Loss tangent (tanδ) as a function of frequency (between 100 kHz - 500 kHz)

5.1.6 Electric conductivity

The electric conductivity is an important parameter for tailings when it comes to dielectric treatment. If the dielectric medium is too conducting between electrodes, instead of building up voltage and current quarter waves; the system will be shorted and alternating current will start to flow depending on voltage and impedance of the system. So, the electrical conductivity G, of tailings was found out with '4294A Precision Impedance Network Analyzer by Agilent' between 1 kHz - 1000 kHz frequency range. The result for the following is shown in Figure 5-7.

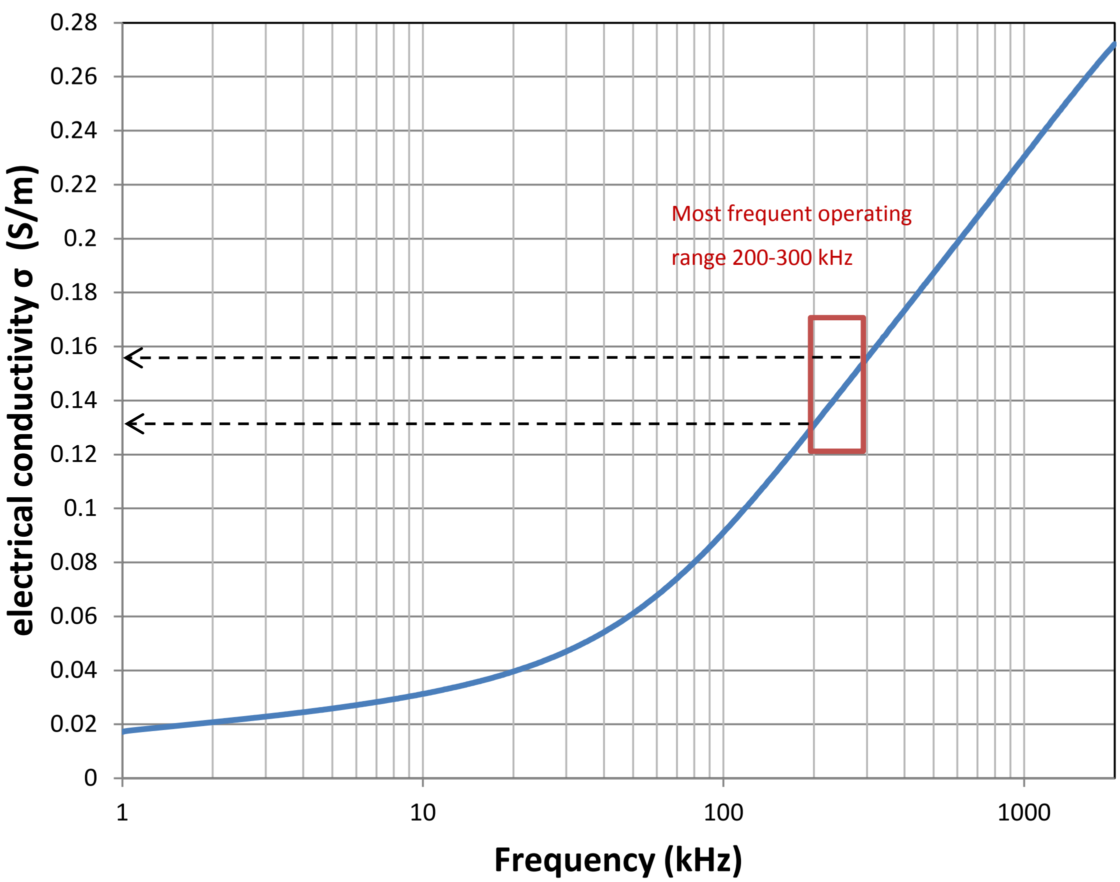


Figure 5-7 Electrical conductivity vs frequency

Thus, the value for 200 kHz – 300 kHz range lies approximately between 0.13 - 0.155 S/m and about 0.14 S/m for 250 kHz.

5.1.7 X-Ray Diffraction (XRD)

X-ray diffraction (XRD) was carried out on dried tailings sample. The procedure was carried out to find major clays and the qualitative mineralogy for the given tailings. The major clay components of the tailings are considered as Kaolinite, Illite, Smectite and Montmorillonite. Only Kaolinite and Illite clays could be observed for the given sample along with silicon dioxide peaks. The result for the XRD analysis is shown in Figure 5-8.

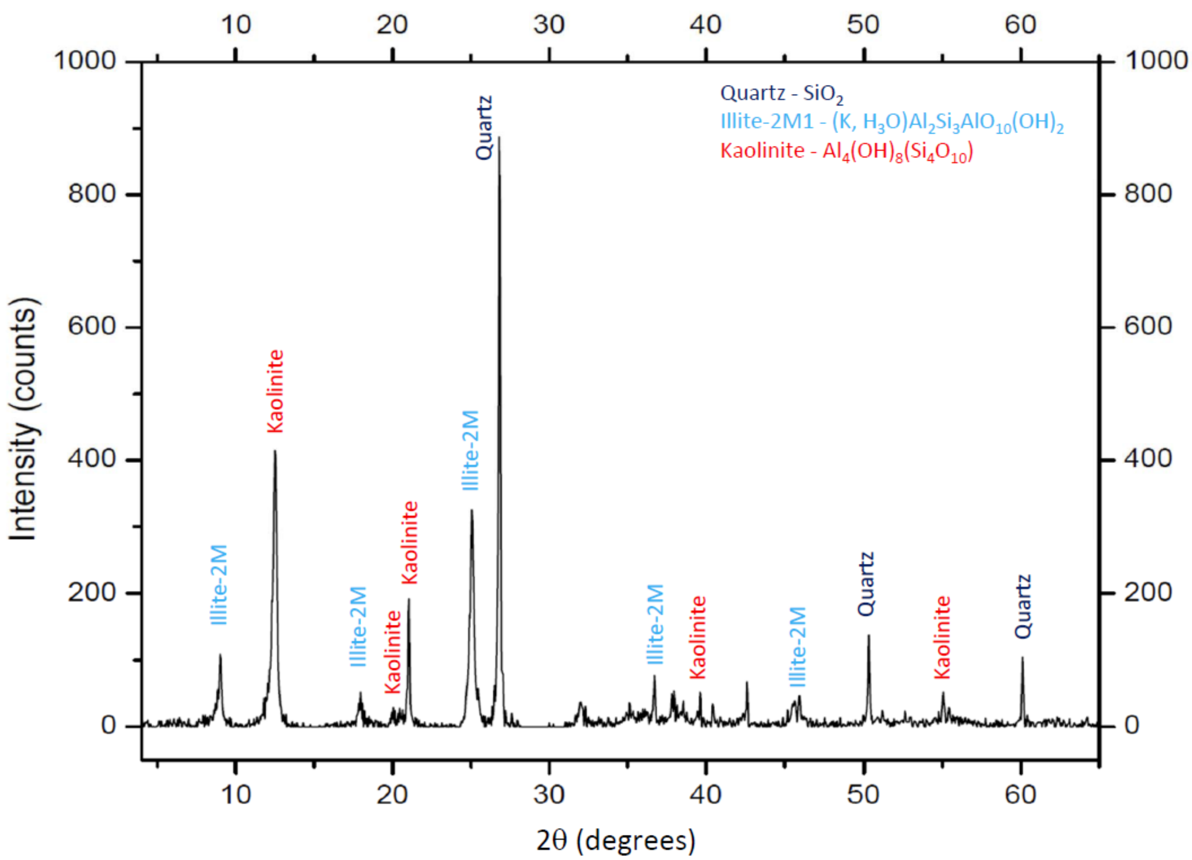


Figure 5-8 XRD analysis of tailings sample

The work of (Gupta. 2011) has also shown with the help of high resolution transmission electron microscopy that the most common clay, kaolinite is composed of silica/alumina bilayers with c-spacing of 7.2 Å.

5.1.8 Turbidity of the decanted water

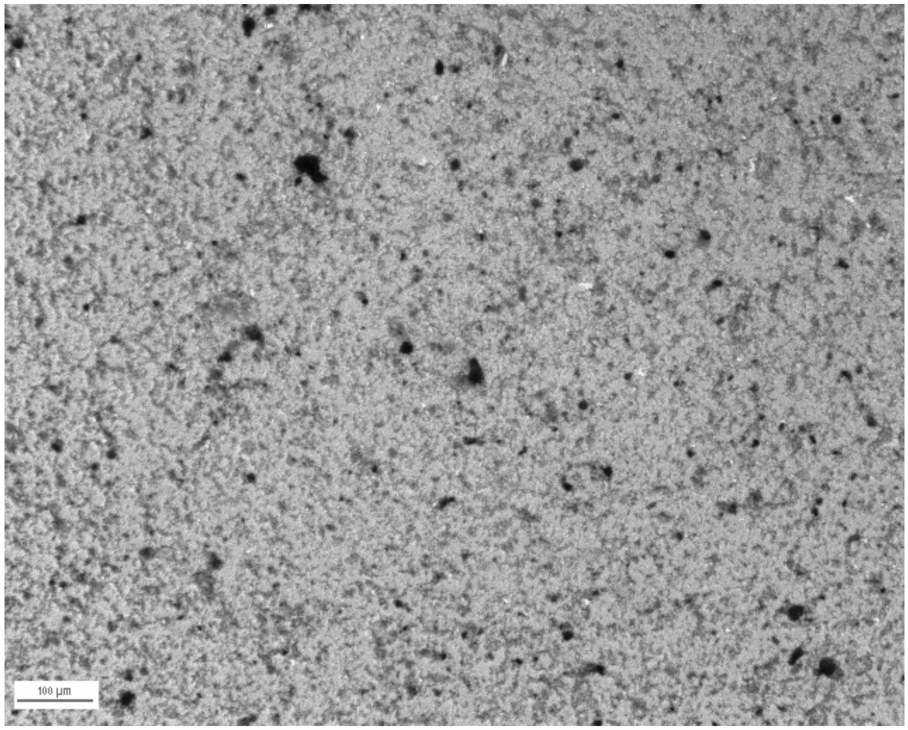
The turbidity of the decanted water was measured with the help of 'HACH – 2100AN Turbidimeter'. For different decanted water samples turbidity was measured ranging from 9 NTU to 386 NTU. This value significantly depends on the solid wt% of the initial sample as well as amount and location of water decanted. When solid wt% of the initial sample was about 5%, turbidity was measured as 9 NTU while for about 15 wt% solids sample it was measured as 386 NTU.

5.1.9 Optical images of tailings sample

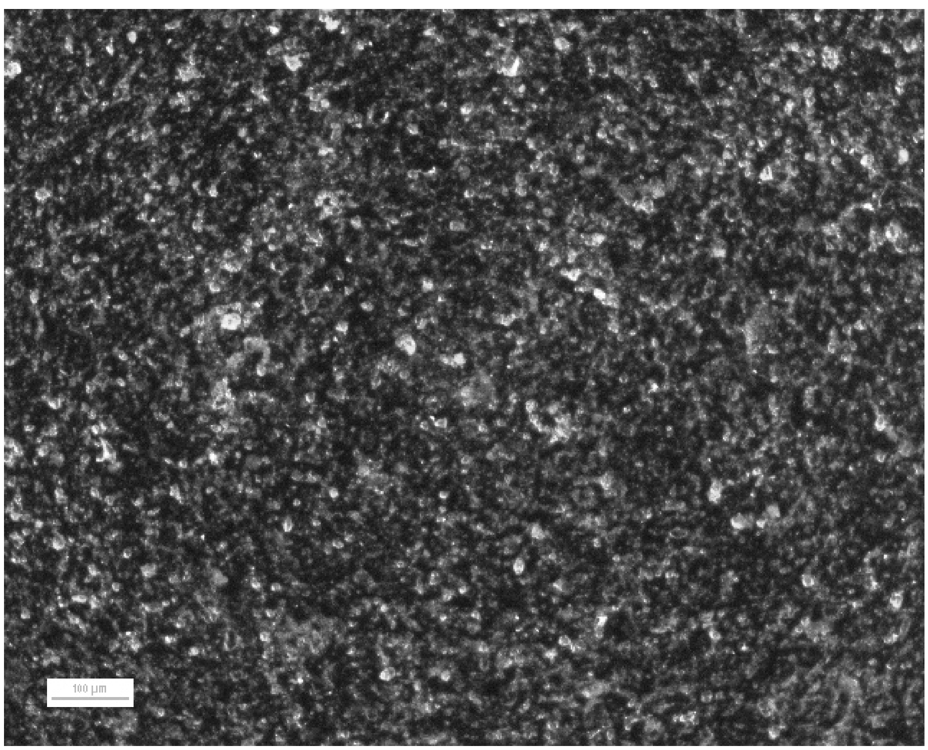
A diluted sample of tailings was studied under Nikon optical microscope (Eclipse Ni-U) to have a better visualization of quartz, sand, clay and fines clusters. A drop of diluted tailings was casted on glass slide and left for atmospheric drying. After the moisture evaporated from the drop, it was studied under given optical microscope for 10x and 20x zoom range. The lighting conditions were differed from dark to bright so that any light absorbing and reflecting material such as silica, bitumen and clays could be observed.

Dark field and bright field reflection optical images are shown in Figure 5-9. In the dark field mode, only particles reflecting light in the ambient conditions would be visible; while in bright field, light is shun from above on the sample. The bright field images show particles like sand, quartz and other minerals which have a tendency to reflect light. The dark field images on the other hand show the presence of light absorbing material like bitumen and clay. The light reflecting part in the images is sand, quartz/SiO_2. The greyish part covering most part of the image is colloidal clay suspension. The dark spots in the image are bitumen droplets. Though for 10x resolution this might not be clearly seen, for 20x resolution the different fractions of tailings can be clearly identified.

10x resolution tailings optical image

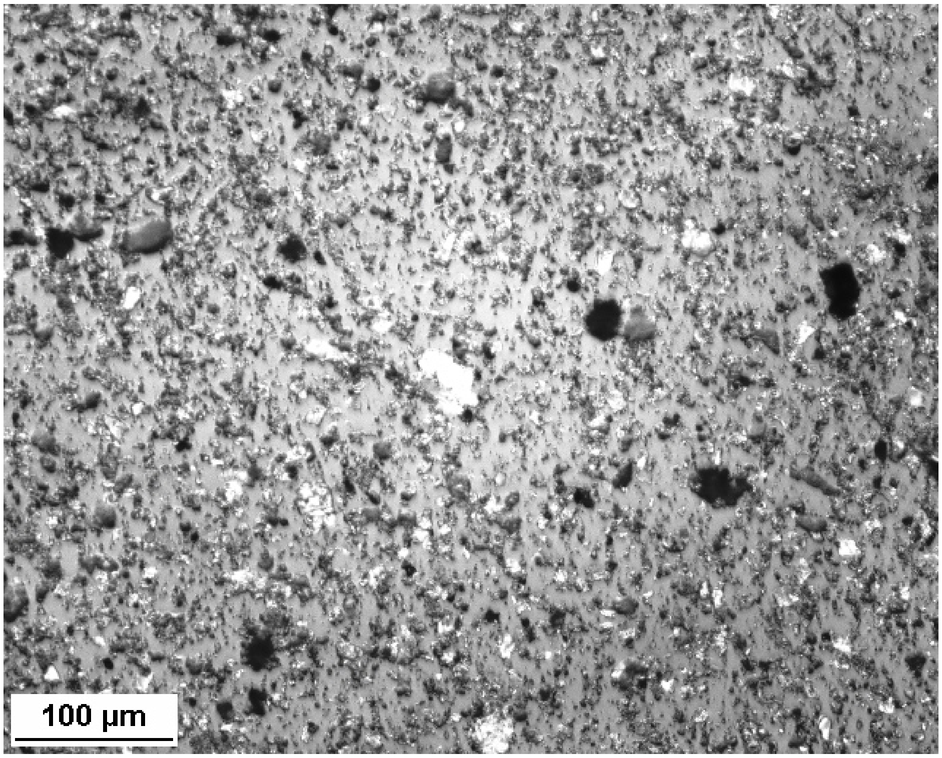


Bright field

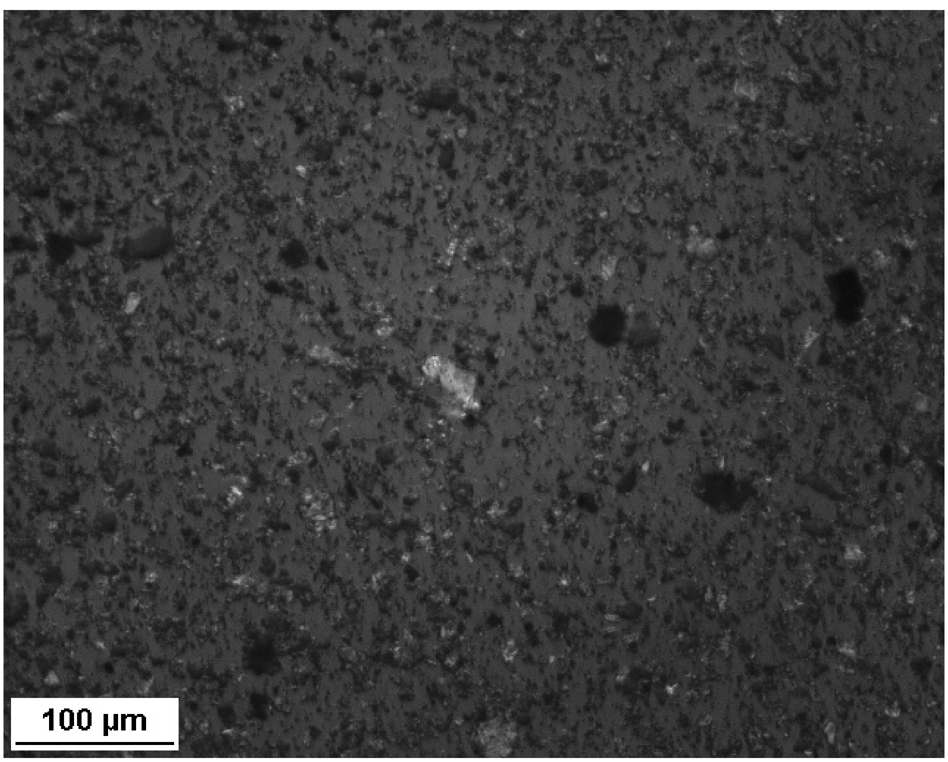


Dark field

20x resolution tailings optical image



Bright field



Dark field

Figure 5-9 Bright and dark field optical images of tailings sample (10x and 20x)

6. Results and Discussion

This chapter discusses the description of scientific and technological principles at work which help with accelerated dewatering and drying treatment of tailings and identify one or more possible working mechanisms.

6.1 Possible mechanisms of effective particle size increase and clays charge reduction

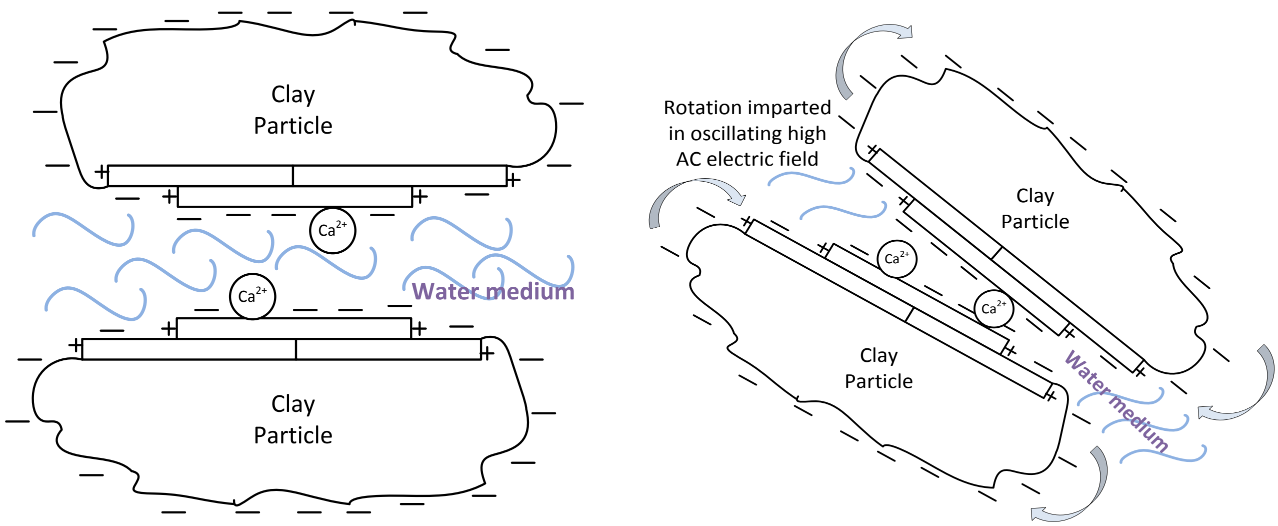
6.1.1 Dielectrophoretic forces on polar molecules

The charged clay particles behave as monopoles (ions), dipole, quadrapoles, octapoles and so on along with polar water molecules. In the very high electric field and field gradient like the one generated by auto-transformer, the dielectrophoretic (DEP) force and electrorotational (ROT) torque are applied on these polar molecules. The water, sand, clay and bitumen all have different dielectric properties which help with the separation. It is proposed that because the AC field is resonating at about 250 kHz, it helps in random collision of the clay particles helping them fuse together. The larger particle size helps with differential settling and increased settling velocity. The denser portion of the tailings settles at the bottom with water and bitumen on the top. The alternating high electric field facilitates collisions between the fine particles. The pressure between the particles as a result of the electric field varies as the square of the field strength (Shang and Dunlap. 1996) (The DEP forces and torques also briefly discussed in section 3.3).

$$\frac{\partial \boldsymbol{F}}{\partial A} \propto f(\varepsilon)\, \boldsymbol{\nabla E}^2$$

Depending on the size/radius of the particles, the forces range can vary from nanoNewtons (nN) to picoNewtons (pN). Therefore, the forces between the particles are large enough to overcome the electrostatic repulsions (picoNewtons or higher).

The Ca^{2+} ions are better adsorbed than Mg^{2+} on clays basal planes as Mg^{2+} has tightly bound hydration shell because of its smaller radius (Rytwo et al. 1996). The structure of typical clays and the proposed mechanism for the increase in particle size is shown in Figure 6-1.



Typical structure of oil sands clays

Mechanism for increasing clay particle size

Figure 6-1 Possible clays coagulation mechanism

There is also dielectric heat dissipation in the system caused by oscillating dipoles within the electric field. This in turn increases the temperature of the system and imparts convective water currents, agitates the system and increases the chances for charged particles to collide with each other in their Brownian motion and thereby coagulate (Merkus. 2009). The denser portion can then be heated with the same setup and dried layer-by-layer by the evaporating water from the system. The example of completely dried cake is shown in Figure 6-2. Applying high electric fields with RAT to tailings without passing any significant current through it decreases power consumption.

Figure 6-2 Cakes formed after drying out MFT

The effective radius of the particles increases as a function of collision time. The terminal settling velocity for solids in slurry is given by hindered settling equation (Masliyah et al. 2011). It depends on the square of the radius of the particle and is the ratio of gravitational force to viscous drag force:

$$v_S = \frac{(\rho_S - \rho_l)d^2 g}{18\mu} f(\alpha_s, Re)$$

v_S : terminal settling velocity [m/s]

ρ_S, ρ_l : density of solid and liquid [kg/m^3]

d: diameter of the particle [m]

g: acceleration due to gravity [9.81 m^2/s]

μ : viscosity of the liquid [Pa.s]

α_s : Volume fraction of solids in the suspension

Re : Reynolds number of the particle

The denser portion of the settled tailings at the bottom can be further treated with current coagulants (salts like $CaCl_2$, $MgCl_2$, Aluminum Sulfate, Ferric Chloride or Lime) and flocculants (polymers such as anionic polyacrylamide) as in Tailings Reduction Operation. The decanted/separated water can be recycled back to the plant to be used again in hot water extraction process.

6.1.2 Electrocoagulation

The coagulation that is aided by electrical means is known as electrocoagulation. It is the electromotive force used to drive chemical reactions. The positive ions that are liberating out from electrodes during electrolysis, help in neutralizing the negative charge on clay particles. This way the uncharged or the reduced charge clays can come together and conglomerate. In the AC applied field, both the electrodes behave as cathode and anode vice versa.

Electrocoagulation is more effective in destabilizing the small colloidal particle suspension. Besides destabilizing these particulate suspensions, electrocoagulation is capable of removing petroleum fractions, dissolved organic compounds, heavy metal ions and anions (like fluoride, phosphate, silicate) from water (Ivanishvili et al. 1987, Renk. 1988). The liquid-liquid separation demulsification capability by electrocoagulation is also studied (Parekh et al. 1992). A maximum oil concentration of 5% could be effectively treated by electrocoagulation and also suspensions containing up to 10% solids could be electrocoagulated successfully (Ifill. 2010, Barkley et al. 1993).

Coagulation is the phenomenon in which charged particles in colloidal suspension are neutralized by mutual collision with counter ions, complemented by diffusion layer compression and agglomerated followed by sedimentation. Coagulation mechanism as summed by (Ifill. 2010) is as follows:

i. Electrical diffuse layer compression
ii. Surface charge neutralization
iii. Inter-particle bridging thus increase in particle size and
iv. Floc formation

6.1.3 Creation of ions (H_3O^+ OH^-) by electrolysis of water

The very high electric field is able to split water molecules present near the sharp contact of high voltage electrode and produce H^+ and OH^- ions. The clay particles being negatively charged and positive H^+ ion being a good diffusor is able to minimize the negative charges. Once the electrostatic repulsion is reduced, the particles can come together due to van-der-Waals forces. This helps clays in coming close to each other which otherwise are repelled by –ve charges.

A similar technique is used in industry by CNRL which bubbles CO_2 gas in the tailings. The CO_2 then combines with water to form Carbonic acid (H_2CO_3) which effectively changes charge distribution and pH of the solution. This in turn effects the electrokinetic or zeta potential of clays and makes the clays colloidal suspension unstable, thus helping with the settling. The arrangement of clays prominently depends on pH of the solution as previously discussed in section 4.7.5.

6.2 Particle size and zeta potential results analysis

6.2.1 Particle size analysis

The spectrum of particle size was analyzed using 'Dispersion Technology Inc. - Acoustic and Electroacoustic Spectrometer (model DT-1202)'. It has a unique acoustic sensor for characterizing particle size distribution by measuring ultrasound attenuation at set frequencies from 1 to 100 MHz along with the speed of sound. This method is known as 'ultrasound scattering'. Ultrasound instead of light helps in characterization of concentrated opaque samples without any dilution. Electroacoustic sensor is capable of measuring zeta-potential thus helping us understand coagulation.

A control sample with 36.48 wt% solids was analyzed for particle size and compared against NRAT coil treated sample with 38.84 wt% solids. The results are shown in Table 6-1.

% size distribution	Control Sample		Experimental Sample	
	reading-1	reading-2	reading-1	reading-2
10%	58.2 nm	54.5 nm	65.0 nm	58.5 nm
16%	74.4 nm	70.4 nm	83.7 nm	76.5 nm
50% (Unimodal)	168.3 nm	165.8 nm	194.0 nm	186.9 nm
84%	391.6 nm	402.4 nm	463.6 nm	470.8 nm
90%	486.3 nm	504.9 nm	519.5 nm	596.3 nm
Mean	**243.8 nm**	**249.4 nm**	**287.8 nm**	**291.0 nm**

Table 6-1 Particle size analysis for tailings sample control vs. experimental

The increase in unimodal (50%) as well as mean particle size distribution after the treatment with NRAT coil can be clearly seen.

6.2.2 Zeta-potential analysis

Zeta potential is electrokinetic potential in colloidal dispersions. For a charged dispersed particle, there is an oppositely charged stationary layer. The potential difference between this layer and dispersion medium is known as zeta potential. The charged particle and the oppositely charged stern layer still carry some net electrical charge which gives rise to inter-particle repulsion and thus offer stability and hinders settling. Zeta potential values which are typically measured in mV gives an idea about the colloidal stability as shown in Table 6-2 (Deming. 2012).

Zeta potential [mV]	Colloidal stability
0 to ± 5	Rapid coagulation or flocculation
± 10 to ± 30	Instability region
± 30 to ± 40	Moderate stability
± 40 to ± 60	Good stability
More than ± 60	Excellent stability

Table 6-2 Colloidal stability vs. Zeta potential

Zeta potential was also measured by DT-1200 unit. The piezo-crystal inside the probe generates sound pulse of certain frequency. These pulses propagate through the sample via gold central electrode. Ultrasound moves particles relative to the liquid, which displaces double layers and generates electric field. This field, in turn, changes the electric potential of the gold electrodes. The electric potential of steel cylinder remains zero because it is outside electric field. The system measures AC current flowing between gold and steel. This colloidal vibration current predicted by *Debye* (1933) is proportional to electrophoretic mobility which in turn is proportional to the Zeta-potential. DT-1200 takes into account both particle-particle hydrodynamic and electro-dynamic interactions when calculating zeta-potential from the measured electroacoustic signal. The zeta potential measurement values for control and experimental sample are reported in Table 6-3. A slight change in the values can be observed from the table below. A control sample had 36.48 wt% solids while the NRAT coil treated sample had 38.84 wt% solids. This might be the reason for slight decrease in zeta potential values for experimental sample.

	Control Sample		**Experimental Sample**	
	reading-1	**reading-2**	**reading-1**	**reading-2**
Zeta potential [mV]	-10.83	-10.46	-11.54	-12.06

Table 6-3 Zeta potential analysis for tailings sample control vs. experimental

6.3 Impedance (load) matching principle

The ‘load matching principle’ explains the condition for maximum power within the load. Accordingly in any circuit, the maximum power is dissipated within the load when impedance of the load matches to that of internal impedance of the circuit. A simple proof of concept is derived below for circuit shown in Figure 6-3.

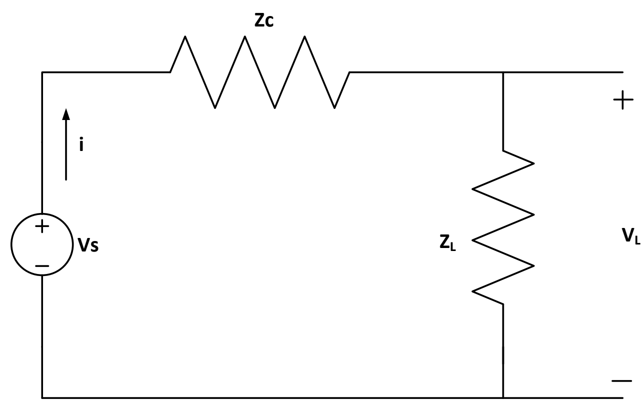


Figure 6-3 A simplified circuit diagram

V_S : source voltage [V]

i : current through the circuit [Amp]

Z_C : impedance of the circuit [ohm]

Z_L : impedance of the load [ohm]

V_L : voltage across the load [V]

In the above circuit,

$$V_S = i.(Z_C + Z_L)$$

$$i = \frac{V_S}{(Z_C + Z_L)}$$

Power dissipated across load Z_L, $P_{ZL} = i^2.Z_L$

Substituting $i = \frac{V_S}{(Z_C + Z_L)}$ in above equation, $P_{ZL} = {V_S}^2.\frac{Z_L}{(Z_C + Z_L)^2}$

For maximizing P_{ZL} for a given value of Z_L,

$$\frac{\partial \mathrm{P_{ZL}}}{\partial \mathrm{Z_L}} = 0 = \frac{{V_S}^2}{(Z_C + Z_L)^2} - \frac{2.{V_S}^2.Z_L}{(Z_C + Z_L)^3}$$

By simplifying this we get,

$$Z_C + Z_L = 2.Z_L$$

i.e., $Z_C = Z_L$

Hence, for maximum power transfer to load, the impedance of the load should be equal to impedance of circuit. Keeping this in mind, for a given system coil was tapped at 3 different locations. First tap was at about $1/3^{rd}$ of total coil length, 2^{nd} tapping was at about halfway of coil length and 3^{rd} tapping was at about 3-quarters of total length from the top. The maximum power transfer was observed for the first tap (or about $1/3^{rd}$ of total coil length); this is probably where impedance matching occurred.

6.4 Treating with coil only at the surface to minimize energy requirements

The total energy requirement can be minimized by placing the electrodes only in the top portion of the beakers. Smaller the dielectric mass in contact with high voltage electrodes, lesser amount of material (tailings, water) will be dielectrically heated. This in turn can help in limiting the temperature rise for the entire system and saving energy costs.

6.4.1 Water heating experiment

About 1000 ml water was heated in beaker with electrodes from NRAT coil only placed at the top. The temperature was recorded at 3 points; top, middle and bottom portion within the beaker. The schematic for the experiment is shown in Figure 6-4. The temperature profile for three temperature sensors (T_t, T_m, T_b) is shown in Figure 6-5.

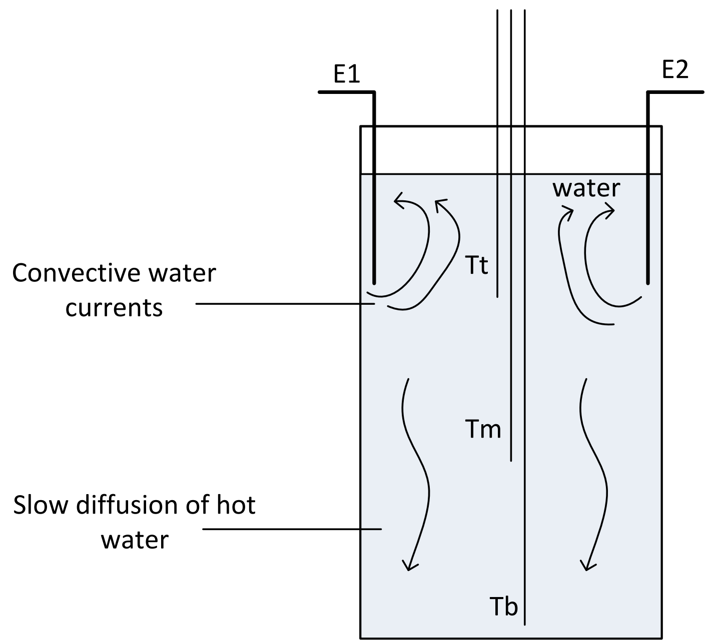


Figure 6-4 Schematics of water heating with electrodes at the top

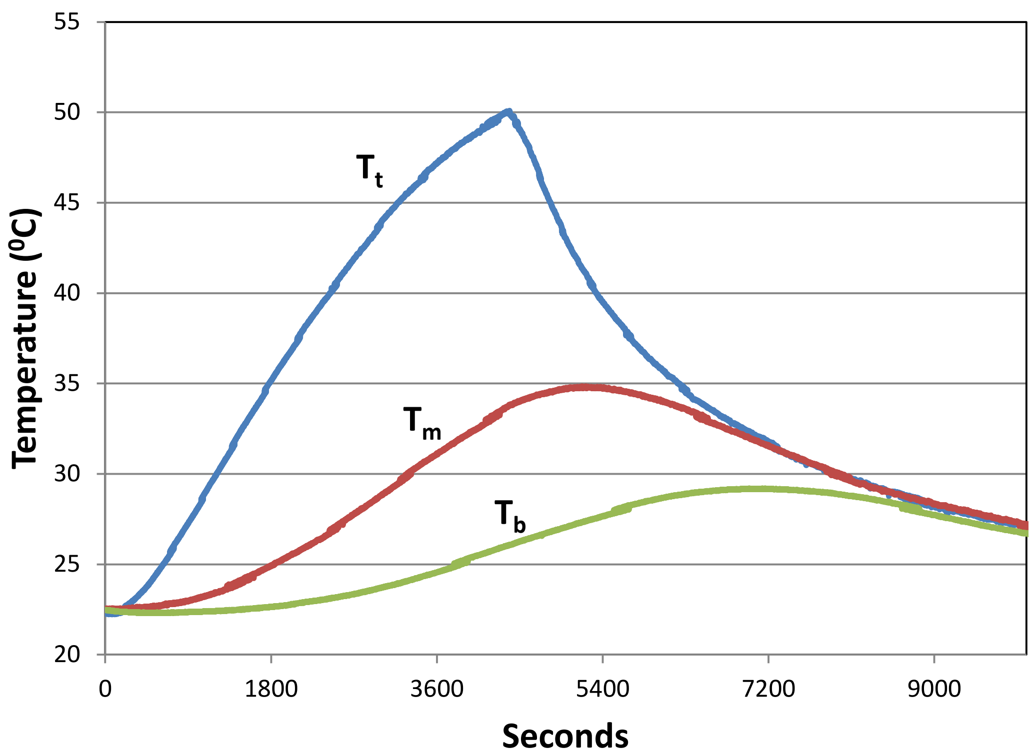


Figure 6-5 Temperature profile for 1000 ml water treated at the top with NRAT coil

It can be clearly seen that temperature at the top, near the electrode is highest and continues to be so. The dielectric heating due to electrodes can be clearly seen at the top. The temperature at the bottom is almost unchanged except a slight increase due to diffusion of hot water molecules. The temperature in the middle is somewhere in between top and bottom. The idea can be extended to layer-by-layer drying of MFT slabs in field.

6.5 Use of Aluminum electrodes

Electrical grade Aluminum wires were used as electrodes with NRAT coil. The ionic species such as Al^{3+} are released in to the solution at anode whereas hydrogen is liberated at cathode. The typical reactions are as follows (Ifill. 2010):

Anode: $Al(s)$ ---------------> $Al^{3+} + 3e^-$

$2H_2O(l)$ -----------> $4H^+ + O_2(g) + 4e^-$

Cathode: $2H^+ + 2e^-$ --------> $H_2(g)$

The Al^{3+} ions having high positive charges help in neutralization of clay charges. Al^{3+} also forms a range of hydroxoaluminium species depending on pH of the solution. These species range from simple Aluminium Hydroxide ions to multiple (10 to 32) Al-cores species (Hunt. 1965, Stol et al. 1976). The aluminum electrodes thus apart from being used in NRAT treatment can also help with chemical coagulation of tailings clays by forming Al^{3+} and its complexes. Similarly, the Al-PAM (Magnafloc 1011) polymer flocculent also helps with the process by release of Al^{3+} ions.

6.6 Different electrode geometries

As the NRAT coil is capable of producing extremely high voltages, a slightest sharpness in electrodes can produce highly localized electrical field which is capable of ionizing air and produce plasma. Therefore, it is very important that any undesired sharpness in electrodes to be avoided completely. But it is also desired to have a highly concentrated non-uniform field, rather than producing less intense field which can be obtained by connecting electrodes to uniform parallel plates. Thus a number of electrode configurations were worked on to see which one gives better tailings treatment. The description of these electrodes configuration is as follows (Figure 6-5):

i. Parallel plate electrodes
ii. Multiple copper wires serving as one electrode (2, 6, 9 contact points)
iii. A wired mesh prepared from copper wires with alternating +/- ends (24, 48 contact points)
iv. A fishhook style electrode made from copper wires
v. A noose knot type electrodes to avoid sharp point at the end

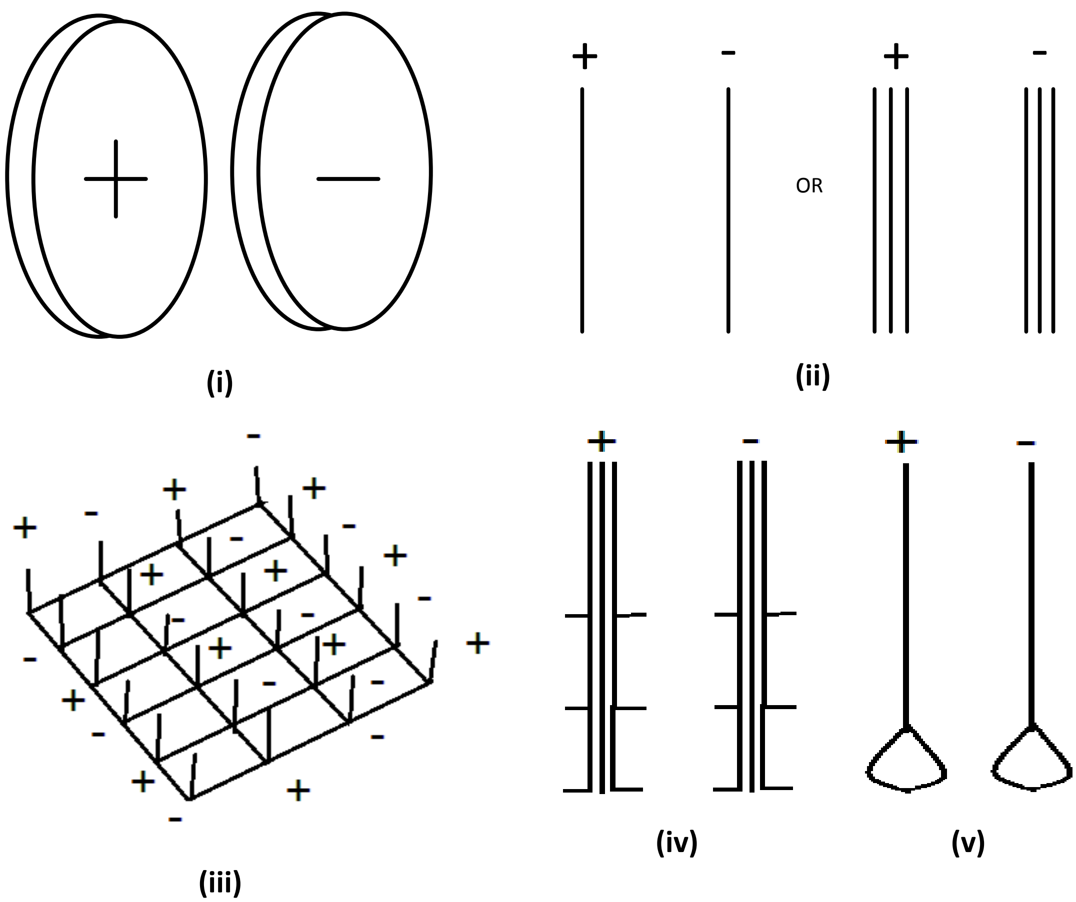


Figure 6-5 Different electrode geometries

The parallel plate electrodes can produce relatively uniform field but the charge being distributed over a larger area, the electric field intensity would be quite low. As previously discussed, high electric field and field gradients are quite necessary for tailings treatment; thus no observations with tailings were made by using parallel plate electrodes. However, these are being used for dielectric heating of oil sands where uniform heating will be required.

Using multiple (2, 6 or 9) copper or aluminum electrodes showed most successful tailings treatment. The configuration would also be most practical if the NRAT technology is used at pilot scale. The wired mesh having 24 or 48 +/- ends was also tested and is an extension of 2, 6 or 9 electrodes that will be used for larger areas.

The shape of electrodes can itself be varied according to requirements. The fishhook style electrodes helped with better evaporation of water by quick release of water vapors along the electrodes. However, for high solid wt% mature fine tailings; this could result in localized drying, corona discharge and detuning of the system. A noose knot type electrodes that do not have any sharp points seemed to help with this problem. A combination of above ideas might be required when implementing NRAT technology to large scale operations.

6.7 Energy and cost calculations

The main setback with the implementation of electrical system for tailings treatment is the energy cost associated with the operation. Keeping this in mind, we are making efforts to address these issues. The design of the NRAT coil is different from conventional transformer systems that use winding across magnetic cores to get voltage rectification. These core losses bring down the quality factor (ratio of energy stored to energy lost per unit cycle) of the conventional transformer to about 20. With NRAT coil technology, though there are many factors involved such as standing wave phenomenon, contact loss resistance etc., the quality factor is still expected to be as high as 150. Thus using NRAT technology compared to conventional high voltage producing transformers would be more efficient.

An estimate is often requested for electricity cost associated with technique, thus a simplified cost calculation is presented in Table 6-4 for an un-optimized NRAT system. By calculating the cost for a small tailings setup of 300 grams and extrapolating it for a tonne, the cost was calculated as 5.53 CAD/tonne. The value is just for the purpose of estimate, while scaling to large systems, the 'economies of scale' would come into play and this number would slide down significantly. One of the main focuses of the future studies based on NRAT treatment of tailings will be to work on optimizing the system and minimizing this cost.

Description	**Values [units]**
Energy output of the coil at the present	5 – 9 [watt or W]
Assuming mean output to the tailings	7 [W]
Maximum observed efficiency	95.5 %
Minimum input power required (assuming 95% efficiency)	7.37 [W] or 7.37×10^{-3} [kW]
Amount of tailings treated	300 [g] or 0.3 [kg]
Time for tailings treatment	9000 [sec] or 2.5 [hr]
Input energy required in kW.hr/kg of tailings	61.42×10^{-3} [kW.hr/kg] or 61.42 [kW.hr/tonne]
Price of industrial electricity in Alberta (approx. average)	9 [cents/kW.hr]
Cost estimate for treatment per tonne of tailings	5.53 [CAD/tonne]

Table 6-4 Cost estimate for NRAT tailings treatment

7. Conclusions and Future Work

7.1 Conclusions

The goal of NRAT technology is to provide an 'end-to-end' solution to tailings problem. Based on the experimental observations made for the treatment of tailings, the following can be summarized:

1) Dielectrophoretic (DEP) forces and electro-rotational torques (ROT) exerted on charged tailings clay particles due to high electric field and field gradients might hold a key to sediment and treat tailings. The dielectric heating from the same technology can be further used for accelerating the evaporation of water for drying out tailings.
2) Densification of fluid fine tailings has been observed and can be performed within hours with NRAT coil which otherwise naturally takes 2-3 years. Conventionally used polymers used for this purpose won't be required.
3) Additional decanted water obtained after this densification may be recycled back to the plant to be reused in CHWE process. This will help in reducing environmental footprint of the process by more recycle and less discharge of affected water to the environment.
4) Residual bitumen from the tailings stream (though as low as about 1-2 wt%) can also be separated with the NRAT technology. The author is not aware of any existing published technique that is able to do the same.
5) Complete drying of tailings to cake formation has been observed. The treatment of thickened tailings obtained from NRAT technique (or even polymer treated thickened tailings) can be done in dedicated disposal areas, to form a dry solid mass capable of withstanding required shear strength of 10 kPa or higher by enhancing the existing Sun drying technique. It will be possible to dry the tailings in a layer-by-layer fashion. This can lead to faster evaporation of water in Dedicated Disposal Areas (DDAs).
6) The NRAT technology can be used for treating both fine and mature fine tailings. Being more efficient than conventional systems, once optimized for large scale

operating energy costs; it might hold a key to scalability to large volumes without using any chemicals or harming the environment in any way.

7.2 Envisioned Use

The challenge with implementation of new technology is huge volume and area of Dedicated Disposal Areas (DDAs) associated with tailings. Typically major players of oil sands surface mining industry deal with about 2.5 million tonnes of tailings per year. With tailings treatment facilities in operation for about 100 days in a year (3.5 months), the average for daily operation deals about 25000 tonnes/day while it could peak to about 30000 tonnes/day on specific days. A DDA is a vast field containing hundreds of individual cells. A drying cell can be typically 70-100 m in length, 25-30 m wide and poured height of MFT ranges typically 15-20 cm. A typical DDA field can cover over 3.5 km^2 apart from tailings pond which also covers significant land area.

The NRAT system capable of outputting high electric field can be used for field scale treatment of tailings. The high output voltage can be distributed over the target area using reusable and inexpensive wired flocculation mesh. The main electrical unit, NRAT coil, will be kept away isolated within Faraday's cage from any human interaction to minimize hazards. The aim of this flocculation mesh is to work with existing DDAs technology without any need of shutdown or complete overhaul of current infrastructure. The large scale-up of this cheap and easy to operate technique should be simple. The idea is to use a fence like wire meshing that can be easily rolled in-out for treatment over DDA. The envisioned use of NRAT with accompanying tailings treatment mesh is illustrated in Figure 7-1.

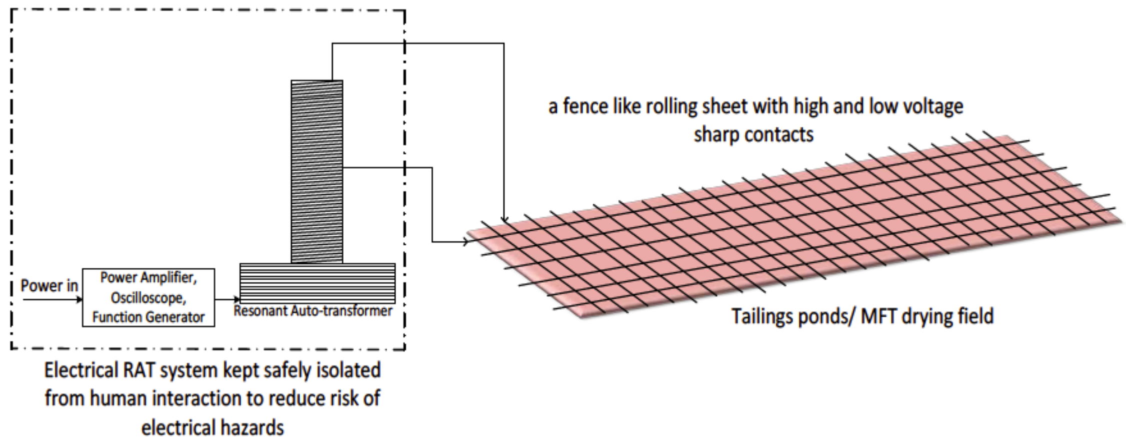


Figure 7-1 Illustration of NRAT tailings treatment system

7.3 Future work

1) We would like to design an optimized NRAT system by decreasing resistive losses from contact resistance, wire resistance as well as inductive and stray capacitive losses of the system. The complete understanding of quarter standing waves and its modeling needs to be considered.
2) The system could be further tuned for enhanced effects and introducing saw-tooth or triangular wave pulses. The additional effect of acoustic waves on tailings settling can also be incorporated.
3) The energy efficiency, capital and operating cost calculations are extremely essential for any system to be tried and tested as a pilot project in the field. Though cost calculations are inherently complicated by nature, best attempt can be made to get estimates regarding pilot-scale costing.
4) The effect of NRAT technique for separation of water, bitumen and clays emulsions obtained from in-situ SAGD process will be further studied. The technology may hold a key for breaking in-situ produced SAGD emulsions containing water, bitumen and clays.
5) Electro-responsive or Electroactive polymers (EAP) can be studied for the electric field, thermal stability and ability to work in conjunction with NRAT system. It has

been studied that strong piezoelectric effects can be observed with commercial synthetic polymers such as Polyvinylidene fluoride (PVDF or PVF_2) and PVDF co-polymers. Ionic polymers whose response depends on mobility or diffusion also form a separate group of EAP (Vinogradov et al. 2005).

6) The degradation of Naphthenic Acids (NAs) due to high electric field can be studied. The toxicity and health effects of NAs have been studied by (Kindzierski et al. 2012). The natural biodegradation rate of NAs is very slow and it is extremely difficult to bring their concentrations below 19 mg/L (Quagraine et al. 2005,Wang. 2011).

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