SOLVENT ASSISTED AND SOLVENT-BASED EXTRACTION FOR SURFACE MINED OIL SANDS: WORKSHOP 2

SOLVENT LEADERSHIP SERIES
July 13, 2017
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WORKSHOP 2

Candice Paton | July 13 2017
Director, Recovery Technologies
Solvent Leadership Series

WORKSHOP 2: SOLVENT ASSISTED AND SOLVENT-BASED EXTRACTION FOR SURFACE MINED OIL SANDS

July 13 2017, Alberta Innovates
Riverview Room, Floor 26, 801 6 Ave SW, Calgary, Alberta

AGENDA

1. Welcome remarks - John Zhou, VP, Clean Energy and Candice Paton, Director, Recovery technologies
   9:00 to 9:15 a.m.

2. Key Presenter: Zhenghe Xu – NSERC Industry Research Chair in Oil Sands Engineering; Canada Research Chair in Mineral Processing.
   9:15 to 10:15 a.m.

3. Key Presenter: Yuming Xu – Senior Research Scientist, CanmetENERGY, NRCan; Scale up and piloting of solvent processes.
   10:15 to 11:15 a.m.

Coffee Break
11:15 to 11:30 a.m.

4. Key Presenter: Qi Liu – Professor and Scientific Director of IOSI. From research outcomes to opportunities for field pilots in solvent technologies.
   11:30 to 12:30 p.m.

5. “Fireside Chat” Interviews and Discussion with presenters
   12:30 to 1:00 p.m.

Networking Lunch and Closing Remarks
1:00 p.m.
Alberta’s Research and Innovation System
Working together – Cross-Ministry & Cross-Sector
Recovery Technologies (AB’s oil: cost & carbon competitive)

Projected Timeline for Commercial Deployment

0 SAGD: Steam assisted gravity drainage; CHWP: Clark hot water process; 1Efficient H2O treatment, heat recovery, infills, etc.; 2Various solvent-assisted SAGD processes, and eMSAGP; 3Enhanced modified VAPour EXtraction (AER 2016); 4Pure solvent processes: N-Solv, CSP, etc.; 5Enhanced Solvent Extraction Incorporating Electromagnetic Heating; 6HBEP = Hybrid bitumen extraction process (surface mining); 7SAGD with carbon capture and utilization; 8Small modular nuclear reactors
Recovery Technologies: SOLVENTS

R & D * Illustrative for Selected Technologies
Piloting
Demonstration
Commercial

SOLVENTS
Cyclic Solvent Process
ESIEH
ESEIEH
HBEPE

ES-SAGD
SA-SAGD

Imperial
cenovus
eMVAPLEX
nsolv
devon
nexen
SUNCOR
HARRIS

AACI
UNIVERSITY OF CALGARY
ALBERTA INNOVATES

Leadership in comnovation
Emissions Reduction Alberta
Progress of Hybrid Extraction of Bitumen at Ambient Temperature from Alberta Mineable Oil Sands

Dr Zhenghe Xu, Yeling (Yale) Zhu, Derek Russell, Qingxia (Chad) Liu, Jacob Masliyah
Liberals provide details of plan for national carbon tax

Proposed federal rules will only apply in provinces without their own carbon tax

By Susan Lunn and Margo McDermid, CBC News  Posted: May 17, 2017

The 26-page document released today outlines in detail how a federal carbon tax would be implemented, including how the levy would be applied to fossil fuels, such as gasoline, diesel and natural gas, starting in 2018.

Ottawa has set a starting price of $10 a tonne on carbon dioxide emissions in 2018, increasing to $50 a tonne by 2022.

So, for example, a tax of $10 a tonne on gasoline would require an extra 2.33 cents per litre added at the pumps. That rises to 11.63 cents per litre by 2022. Some provinces already have a carbon tax on gasoline that meets the federal requirement.

The levy on emissions from industrial facilities will not start before Jan. 2, 2019, and will only apply to facilities that emit more than 50 kilotonnes
Alberta mineable oil sands (OS)...

- ~1 million bbl/d production of bitumen; ~40 % of total OS bitumen production in Alberta.
- Only CHWE (Clark’s hot water extraction) technology used in current industry.

Total Primary Energy Production in Alberta (AER-2017)

Year

REFERENCE
CHWE Process

Typical OS ores
- 10 wt.% bitumen
- 3 wt.% water
- 75 wt.% rocks/sands
- 12 wt.% fines

Fresh water
Processing aids (caustic)
Air

Extraction plant
Processing Water

Tailings slurry
Recycled water

Froth treatment
FTT
Tailings pond

Processing Water

Bitumen froth
Naphthenic/paraffinic solvent

Diluted bitumen

Atmospheric distillation (by upgraders)

Make-up solvent

At 95 % recovery

REFERENCE
Challenges with CHWE

Energy intensity and GHG emission

- High operation temperature (40-45 °C)

**EROEI of different energy sources**

<table>
<thead>
<tr>
<th>Source</th>
<th>EROEI value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro-elect</td>
<td>11 – 267</td>
</tr>
<tr>
<td>Conventional oil</td>
<td>19 – 100</td>
</tr>
<tr>
<td>Coal</td>
<td>50</td>
</tr>
<tr>
<td>Wind</td>
<td>18</td>
</tr>
<tr>
<td>Mineable OS (NFT)</td>
<td>14</td>
</tr>
<tr>
<td>Mineable OS (PFT)</td>
<td>8.5</td>
</tr>
<tr>
<td>In-situ OS (SAGD)</td>
<td>5.5</td>
</tr>
</tbody>
</table>

What could we achieve for **every 1 °C** reduction in operation temperature?

~0.0147 CDN$/bbl bitumen incentive in energy use

Another ~0.0169 CDN$/bbl bitumen incentive in carbon tax by 2022

If temperature drops from 45 °C to 25 °C, cost for 1 million bbl/day bitumen will reduce by:

~294,000 CDN$/day in energy use

~338,000 CDN$/day in carbon tax

~632,000 CDN$/day

REFERENCE


Challenges with CHWE

Poor processability of poor-quality ores

• Reduced bitumen recovery.
• Increased unwanted contents (water/solids) in bitumen froth.
• Large impurities (electrolyte/fine clay) contamination in diluted bitumen product, especially in naphthenic froth treatment (NFT).

REFERENCE
[3] Jianjun Liu, Zhenghe Xu, and Jacob Masliyah DOI: 10.1021/ef050091r
Challenges with CHWE

Fresh water usage
• ~2.8 bbl fresh water are required for 1 bbl bitumen production.

Tailings management
• ~2 bbl MFT are produced for 1 bbl bitumen production.
• Diluent loss, water pollution, land reclamation and safety concern.

REFERENCE
What we want?

- Ambient temperature extraction (reduced energy intensity)
- Improved bitumen recovery
- Robust approach capable of dealing with variability of ores
- Low fresh water intake
- Producing dry stackable tailings
Hybrid Extraction Process
Definition: both solvent and water are used in extraction process.

- Mainly two types
  - **Early “hybrid” process**
    - Oil sands processed with solvent and water.
    - E.g. OHWE, LEE, USO’s Grande Pairie Pilot.
  - **True hybrid process**
    - Oil sands pretreated with solvent (viscosity reduction), followed by water extraction process.

REFERENCE
Effect of Solvent on Viscosity of Distillation Feed Bitumen

- Solvent sufficiently dilutes bitumen to the level of 1-10 Pa.s (or 10-100 poise) at 10-20 wt.% case
Typical OS ores
10 wt.% bitumen
3 wt.% water
75 wt.% rocks/sands
12 wt.% fines

Fresh water
Processing aids (caustic)
Air

Extraction plant
Processing Water

Tailings slurry

Q

Recycled water

Make-up solvent

Naphthenic/paraffinic solvent

Bitumen froth

Froth treatment

FTT

Tailings pond
Water treatment

Atmospheric distillation (by upgraders)

Diluted bitumen

At 95% recovery

Bitumen

REFERENCE
Hybrid Extraction: Features

- **Ambient temperature (25 °C) processing**
- **Solvent addition at low dosage**
  - Common solvent: Diesel; Kerosene; Biodiesel.
  - Common dosage: 10-20 wt% of bitumen, or 1-2 wt% of total oil sands.
- **No caustic addition**
- **Minimum change to CHWE**

**Concept approved in lab-scale test at U of A**

**REFERENCE**


Fundamental Study

(All experiments conducted at 25 °C)
Three Solvents on Two Ore Samples

<table>
<thead>
<tr>
<th>Source</th>
<th>Composition (wt. %)</th>
<th>Bitumen</th>
<th>Water</th>
<th>Solids</th>
<th>Fines*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor processing ore P</td>
<td></td>
<td>9.2</td>
<td>2.6</td>
<td>88.2</td>
<td>35.6</td>
</tr>
<tr>
<td>Medium-grade ore M</td>
<td></td>
<td>11.4</td>
<td>2.3</td>
<td>86.3</td>
<td>8.2</td>
</tr>
</tbody>
</table>

* Fraction of fines (defined as mineral solids less than 44 μm) in solids.

- 0, 5, 10, and 20 wt.% biodiesel, diesel or kerosene with respect to bitumen content as key parameters used in experiments
## Petroleum Diesel on Three Ore Samples

<table>
<thead>
<tr>
<th>Oil Sands Ores</th>
<th>Bitumen (wt.%)</th>
<th>Water (wt.%)*</th>
<th>Solids (wt.%)*</th>
<th>Fines (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AK (2015)</td>
<td>9.20</td>
<td>5.25</td>
<td>85.51</td>
<td>43</td>
</tr>
<tr>
<td>AD (2015)</td>
<td>10.00</td>
<td>4.21</td>
<td>85.80</td>
<td>21</td>
</tr>
<tr>
<td>AC (2016)</td>
<td>11.40</td>
<td>3.23**</td>
<td>84.86**</td>
<td>22</td>
</tr>
</tbody>
</table>

* Determined experimentally using Dean Stark extraction method
** Averaged values based on two samples

- 0, 5, 10, and 20 wt.% petroleum diesel with respect to bitumen content as key parameters used in experiments
- Dodecane for comparison (tailings analysis)
### Composition of AURORA Process Water

<table>
<thead>
<tr>
<th>Ions</th>
<th>Concentration (ppm)</th>
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<tr>
<td>Na⁺</td>
<td>691</td>
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<tr>
<td>K⁺</td>
<td>21</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>19</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>83</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>444</td>
</tr>
</tbody>
</table>

- The temperature and the pH of the Aurora process water were set at 25 ± 0.5 °C and 7.52 ± 0.05, respectively.

Thanks to Jie Ru and Yi Lu for preparing sample and conducting ion chromatography experiment.
Liberation Visualization Technique

REFERENCE
S. Rajagopalan: Study of Bitumen Liberation from Oil Sands Ore
Still Images of Bitumen Liberation

REFERENCE
S. Rajagopalan: Study of Bitumen Liberation from Oil Sands Ore
Effect of Solvent on Bitumen Liberation

REFERENCE
S. Rajagopalan: Study of Bitumen Liberation from Oil Sands Ore

Sample: ore P
Effect of Solvent on Bitumen Aeration

REFERENCE
Effect of Solvent on Bitumen Aeration

REFERENCE

Sample: ore P
Lab Extraction Test
Step 1: Ore Pretreatment with Specified Solvents

- Solvent spread on 500 g oil sands by spray bottle/atomizer.
- Soaking for 20 min.
Step 2: Slurry conditioning

- Agitation rate 800 rpm; air inlet: 150 ml/min.
- Slurry conditioning lasts 10 min.

Modified batch extraction unit (M-BEU)

Impeller (with air nozzle)

Circulating water (25 ± 0.5 °C)

Pretreated oil sands

250 ml process water (pH=7.52 ± 0.05)
**Step 3: Primary flotation**

- Agitation rate 600 rpm; no air inlet.
- Primary flotation lasts 10 min.

Primary froth (to be collected)

800 ml process water (pH=7.52 ± 0.05)

25 ± 0.5 °C
Lab-Based Tests: Procedure

**Step 3: Secondary flotation**

- Agitation rate 800 rpm; air inlet: 150 ml/min.
- Secondary flotation lasts 10 min.
Primary Flotation (first ~60 seconds out of 10 min)

- Blank
- 10 wt% Diesel
- 10 wt% Dodecane
Secondary Flotation (first ~60 seconds out of 10 min)

Blank        10 wt% Diesel      10 wt% Dodecane
Froth Quality (Primary Froth)

Blank

10 wt% Diesel

or

10 wt% Dodecane
Froth Quality (Secondary Froth)

Blank

10 wt% Diesel
or
10 wt% Dodecane
Solvent addition generally improves bitumen extraction regardless of the types of ores.
Effect of Solvent Types on Froth Quality (3 Key Solvent Cases)

<table>
<thead>
<tr>
<th>Name</th>
<th>Bitumen (wt.%)</th>
<th>Fines (wt.% of Solids)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore P</td>
<td>9.2</td>
<td>35.6</td>
</tr>
<tr>
<td>Ore M</td>
<td>11.4</td>
<td>8.2</td>
</tr>
</tbody>
</table>

- Total extraction process time of 30 min.
- Marginal difference in froth quality at 20 wt.% solvent case between three solvents for both ores.
Effect of Petroleum Diesel: Recovery

- Marginal improvement in hydrocarbon recovery at 20 wt.% petroleum diesel compared to 10 wt.% dosage for high grade ores.

<table>
<thead>
<tr>
<th>Name</th>
<th>Bitumen (wt.%)</th>
<th>Fines (wt.% of Solids)</th>
</tr>
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<tr>
<td>AK (2015)</td>
<td>9.20</td>
<td>43</td>
</tr>
<tr>
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</tr>
<tr>
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<td>11.4</td>
<td>22</td>
</tr>
</tbody>
</table>
Effect of Petroleum Diesel: Froth Quality

<table>
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<tr>
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<td>21</td>
</tr>
<tr>
<td>AC (2016)</td>
<td>11.4</td>
<td>22</td>
</tr>
</tbody>
</table>
Key Findings on Extraction Experiments

- Increasing solvent dosage increases overall organics recovery, the level depending on ore characteristics
- Increasing solvent dosage improves froth quality for all the ores
- Petroleum diesel and kerosene perform better than biodiesel for extracting bitumen from ores at ambient temperature and neutral pH conditions
Impact on Tailings Settling
Tailings management

- ~2 bbl MFT are produced for 1 bbl bitumen production.
- Diluent loss, water pollution, land reclamation and safety concern.

Total area of tailings ponds of Alberta mineable oil sands industry

<table>
<thead>
<tr>
<th>Year</th>
<th>2008</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (km²)</td>
<td>130</td>
<td>176</td>
</tr>
</tbody>
</table>

35.3 %

REFERENCE
Lab Tests: Tailings Settling

- Experimental data fits with hyperbola fitting (lines) for 20 wt.% solvent case using poor processing ore, Ore P
- Solvents improve tailings consolidation and enhance compactness of final sediments
• Experimental data fit with linear in double logarithmic scale for 20 wt.% solvent case using poor processing ore, Ore P
Solvent Partition / Loss to Tailings
### Summary of Dodecane Loss to tailings in MBEU-Based Extraction

<table>
<thead>
<tr>
<th></th>
<th>Bitumen (g)</th>
<th>Dodecane (g)</th>
<th>Dodecane / Bitumen Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial State</td>
<td><del>57 (</del>/500 g OS)</td>
<td>5.70</td>
<td>~10 %</td>
</tr>
<tr>
<td>Primary Froth</td>
<td>41.8119</td>
<td>4.4781</td>
<td>10.71%</td>
</tr>
<tr>
<td>Secondary Froth</td>
<td>5.9794</td>
<td>0.5206</td>
<td>8.71%</td>
</tr>
<tr>
<td>Total Froths</td>
<td>47.7913</td>
<td>4.9987</td>
<td>10.46 %</td>
</tr>
<tr>
<td>Final Tailings</td>
<td>~9.2714</td>
<td>0.7013</td>
<td>~7.62%</td>
</tr>
</tbody>
</table>

- Collected froth underwent Dean-Stark apparatus to remove impurities (solid and water).
- Dodecane / bitumen ratio in total froths is higher than that of initial state, suggesting dodecane preferentially stays with bitumen, rather than solid or water.
- With 84% bitumen recovery, solvent recovery is 88%.
Step 1: Jar-Based Hybrid Extraction Demo

- Weigh 50 g oil sands into glass jar; disperse 10 wt% (of bitumen) atomized solvent onto sample for 20 min pretreatment.

- Adding 100 ml processing water; sealed and homogenized by commercial shaker for 3 hrs at ambient temperature (25°C).
Step 2: Froth Collection

• Froth was directly collected and named as “Froth- 25°C”, which mainly contains floated bitumen.

• Continue homogenizing the leftover for another 1 hr at an increased temperature of 70 °C. Extra froth generated and collected as “Froth- 70°C”.

![Diagram showing the steps of Froth Collection, including Froth- 25°C, Leftover, Shaking (1 hr, 70 °C), Final tailings, and Froth- 70°C.]
Step 3: Froth Cleaning

• “Froth- 25°C” and “Froth- 70°C” were treated with cyclo-pentane to reject water/solid impurities; sediment further soaked with adequate amount (not reaching deasphalting threshold) of cyclo-pentane several times to accumulate all bitumen and solvent.
Step 4: Solvent Content Quantification

- Remove cyclo-pentane from diluted bitumen at ~50 °C (B.P.).
- Quantitative analysis of solvent content in product by proper methodology (e.g. FTIR, TGA).

Diluted Bitumen- 25C or Diluted Bitumen- 70C → Remove cyclo-pentane → Solvent-bitumen mixture → Solvent content test
Summary of Biodiesel Partition in Jar-Based Procedure

• Biodiesel / bitumen ratio in froth is close to that of initial state, suggesting biodiesel preferentially stays with bitumen, rather than solid or water.

• Reduced biodiesel concentration (out of bitumen) in froth was observed with increased difficulty in bitumen recovery.

Details of data processing at Page. 61 & 62
Conclusions

Promoted extraction performance
• Improved overall bitumen recovery (up to 80 % for poor processing ore).
• Improved froth quality.

Feasibility of ambient temperature operation verified
• Reduced energy intensity/GHG emissions.

Improved tailings densification
• Faster tailings densification as compared with CHWE.

Ease of commercialization
• High similarity to the current process.
• Full use of current CHWE facilities.

REFERENCE
Alternative solvents: an ideal solvent for hybrid extraction

Improving bitumen recovery (tailings solvent recovery)

Use of process aids

Enhanced tailings dewatering: dry stackable tailings

- Polymer flocculants, i.e. EO-PO, EC derivatives, etc.
- Advanced polymer flocculant under development in UofA.

REFERENCE
Requirement for An Ideal Solvent

◆ Good extraction performance, i.e. high recovery, high product quality, etc.

◆ Easy and economic removal/recovery of solvent from tailings.

◆ Less (negative) environmental impacts, i.e., land, water, air, animals, etc.

◆ Guaranteed operation safety, i.e., flammability, volatility, toxicity, etc.

◆ Readily available on site, such as petroleum diesel.
## Comparison of Extraction Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Medium</th>
<th>Processing Temperature</th>
<th>PROS</th>
<th>CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHWE</td>
<td>Water only with caustic</td>
<td>40-45 °C</td>
<td>• Satisfactory recovery from good/medium grade ore</td>
<td>• High energy intensity&lt;br&gt;• Reduced recovery for poor grade ore&lt;br&gt;• MFT generation; poor tailings dewatering; fresh water intake</td>
</tr>
<tr>
<td>Hybrid Extraction</td>
<td>Solvent (O/S: ~1:0.02) with Water similar to CHWE</td>
<td>R.T. or higher</td>
<td>• Enhanced recovery&lt;br&gt;• Enhanced tailings condensation&lt;br&gt;• Good operation safety.&lt;br&gt;• Ease of application</td>
<td>• Solvent loss to tailings.</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>Solvent only (O/S: 1:1-1:2, commonly) No/little water</td>
<td>R.T. or higher</td>
<td>• Enhanced recovery&lt;br&gt;• Water-induced problems alleviated</td>
<td>• Energy intensive solvent recovery from tailings&lt;br&gt;• Solvent-induced hazards&lt;br&gt;• Safety concerns&lt;br&gt;• Hard to choose proper solvent</td>
</tr>
</tbody>
</table>
## Comparison of Extraction Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Medium</th>
<th>Processing Temperature</th>
<th>OPEX Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHWE</td>
<td>Water with caustic</td>
<td>40-45 °C</td>
<td>• Baseline</td>
</tr>
</tbody>
</table>
| Hybrid Extraction        | Conventional solvent (O/S: ~1:0.02) Water similar as CHWE              | R.T. or higher         | • **0.294 CDN$ / bbl bitumen** saving in energy use & carbon tax; **But** incentive would gradually increase to **0.632 CDN$ / bbl bitumen** by 2022.  
  • Solvent loss could be minimized by increased recovery of bitumen. |
| Solvent Extraction       | Conventional solvent (O/S: 1:1-1:2, commonly) No/little water         | R.T. or higher         | Set SESA Project as example  
  • **CAPEX: 4 times higher than CHWE**  
  • **OPEX: twice as high**                                                              |

### Reference
• Members of Oil Sands Research Group
• Jim Skwarok and Jie Ru
• Lisa Carreiro and Carl Corbett
• NSERC-IRC in Oil Sands Engineering
• Alberta Innovates – Energy & Environmental Solutions
• Industrial Sponsors
On the Move

Welcome to visit Shenzhen

“Shenzhen is the city that most resembles the Silicon Valley.”
--- Business Week (2014)
An overview of Continuous/Pilot-Scale Hybrid Bitumen Extraction Process

Feng Lin and Yuming Xu
Natural Resources Canada, CanmetENERGY - Devon

Presentation at Solvent Leadership workshop, Calgary, Alberta, July 13 2017
Outline of Presentation

- Overview of pilot facilities
- Pilot hybrid bitumen extraction (HBE)
- Solvent losses to the tailings
- Tailings dewatering properties
- Non aqueous extraction
Nonaqueous Extraction of Oil Sands
Research at the Institute for Oil Sands Innovation

Alberta Innovates Solvent Leadership Series
Workshop 2: Solvent-assisted and Solvent-based Extraction for Surface Mined Oil Sands
July 13, 2017, Alberta Innovates, Calgary, Alberta

Qi Liu
Director, Institute for Oil Sands Innovation
• Institute for Oil Sands Innovation (IOSI)
• Nonaqueous extraction (NAE) flowsheet
• Nonaqueous solvents
• Effect of mineralogy, fines contents, water contents
• Challenges
• Outlook
• Acknowledgements
• An industry-government-university partnership
• Research network extending to 15 universities and government labs
• Annual expenditures of $2-3 million

As of February 2017

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<td>6</td>
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</table>
**Extraction**

Originally “Nonaqueous Bitumen Extraction”, started from 2005. Changed from May 2016 to the current name to include both nonaqueous and water-based extraction.

**Product Cleaning and Partial Upgrading**

Originally “Bitumen Upgrading and Characterization”, started from 2005. Changed from May 2016 to the current name to emphasize bitumen transportation and direct feed to refinery.

**Online Instrumentation for Oil Sands** (started 2014)

**Tailings Fundamentals**

Originally “Tailings Process Fundamentals”, started from 2011. Changed from May 2016 to the current name to include both tailings processes and tailings geotechnics fundamentals.
## Solvent selection and interfacial chemistry

<table>
<thead>
<tr>
<th>Year</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006-01</td>
<td>Design of Solvent Use for Bitumen Extraction by Molecular Modeling and Inverse Gas Chromatography</td>
</tr>
<tr>
<td>2009-06</td>
<td>Unsticking Bitumen from Kaolinite</td>
</tr>
<tr>
<td>2010-01</td>
<td>Interfacial Forces in Solvent Extraction Processes</td>
</tr>
<tr>
<td>2010-08</td>
<td>Non-aqueous Bitumen Extraction: Interfacial Science behind the Process</td>
</tr>
<tr>
<td>2014-03</td>
<td>Cyclohexane-Adjuvant Systems for Improved Non-aqueous Extraction of Bitumen from Oil Sands</td>
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</table>

## Mineralogy

<table>
<thead>
<tr>
<th>Year</th>
<th>Project Description</th>
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<tbody>
<tr>
<td>2006-02</td>
<td>Clay Mineralogy in the Oil Sands</td>
</tr>
<tr>
<td>2009-11</td>
<td>Role of Mineralogy and Solids Surface Condition in Separation of Bitumen from Oil Sands using Solvent Extraction and Solids Agglomeration</td>
</tr>
<tr>
<td>2010-06</td>
<td>Nano- and Micro-size Minerals in Nonaqueous Bitumen Extraction from Oil Sands</td>
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## Fine solids removal

<table>
<thead>
<tr>
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<th>Project Description</th>
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<tr>
<td>2006-05</td>
<td>Attachment and Transport of Particulates at the Oil-Water Interface</td>
</tr>
<tr>
<td>2012-11</td>
<td>Optimization of Solids Removal from Solvent-Recycled Bitumen through Asphaltene Precipitation Kinetics</td>
</tr>
<tr>
<td>2014-02</td>
<td>Behaviour of Bitumen-Coated Fine Solids in Organic Solvents</td>
</tr>
<tr>
<td>2016-03</td>
<td>Surface-functionalized Magnetic Particles for Removal of Suspended Fine Solids from NAE Bitumen</td>
</tr>
<tr>
<td>2016-05</td>
<td>Removal of Hydrophobic Bitumen-coated Fine Solids from NAE Bitumen Using Water Droplets with Modified Interfacial Chemistry and Bio-inspired Polymers</td>
</tr>
</tbody>
</table>

## Solvent recovery / destruction

<table>
<thead>
<tr>
<th>Year</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007-04</td>
<td>Recovery of Residual Oil Using Microemulsions</td>
</tr>
<tr>
<td>2010-04</td>
<td>Kinetics of Solvent Recovery from Extracted Oil Sands Tailings</td>
</tr>
<tr>
<td>2016-04</td>
<td>Biodegradation of Cyclohexane under Different Redox Conditions</td>
</tr>
</tbody>
</table>
Ore A: High grade, low fines content

Ore B: Low grade, high fines content

Need to understand wettability of sand/clay surfaces

Solvent drains out
Clay particles and bitumen layer

Desired outcome

Undesirable outcome
Fine solids stick on sand grains
No fines in bitumen
No wet tailings

250 microns
Extraction

- **Bitumen extraction performance**

<table>
<thead>
<tr>
<th>Solvent</th>
<th>C % in 2nd Tailing</th>
<th>Bitumen recovery, %</th>
<th>C % in centrifuge solids</th>
<th>Weight of centrifuge solids, % of ore</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Toluene</td>
<td>0.79</td>
<td>96.3 ± 1.1</td>
<td>20.1 ± 2.8</td>
<td>0.07 ± 0.03</td>
</tr>
<tr>
<td>70% Toluene/30% n-Heptane</td>
<td>1.04</td>
<td>94.3 ± 2.3</td>
<td>18.1 ± 6.4</td>
<td>0.16 ± 0.10</td>
</tr>
<tr>
<td>50% Toluene/50% n-Heptane</td>
<td>0.85</td>
<td>95.9*</td>
<td>23.6</td>
<td>0.07</td>
</tr>
<tr>
<td>30% Toluene/70% n-Heptane</td>
<td>0.86</td>
<td>95.8 ± 2.5</td>
<td>19.2 ± 6.3</td>
<td>0.63 ± 0.22</td>
</tr>
<tr>
<td>20% Toluene/80% n-Heptane</td>
<td>0.85</td>
<td>95.9</td>
<td>24.4</td>
<td>1.37</td>
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<tr>
<td>10% Toluene/90% n-Heptane</td>
<td>1.27</td>
<td>92.6 ± 3.2</td>
<td>26.9 ± 7.2</td>
<td>2.33 ± 0.64</td>
</tr>
<tr>
<td>10% Toluene/90% Cyclohexane</td>
<td>1.18</td>
<td>93.2</td>
<td>23.2</td>
<td>0.10</td>
</tr>
<tr>
<td>Methyl Cyclohexane</td>
<td>0.97</td>
<td>94.9</td>
<td>17.0</td>
<td>0.24</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>1.05</td>
<td>94.4 ± 1.7</td>
<td>21.9 ± 1.7</td>
<td>0.11 ± 0.04</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>1.11</td>
<td>93.8</td>
<td>18.6</td>
<td>0.07</td>
</tr>
<tr>
<td>Xylenes</td>
<td>1.16</td>
<td>93.4</td>
<td>20.1</td>
<td>0.08</td>
</tr>
<tr>
<td>Isoprene</td>
<td>1.40</td>
<td>91.4 ± 1.5</td>
<td>20.6 ± 1.7</td>
<td>0.38 ± 0.09</td>
</tr>
<tr>
<td>Limonene</td>
<td>5.87</td>
<td>53.0</td>
<td>22.3</td>
<td>0.11</td>
</tr>
</tbody>
</table>

* No duplicate tests

• **Amount of centrifuge solids**

More fine solids in bitumen when the solvent had a low solubility parameter

Possibly caused by the “filtration” effect on the 45-µm sieve

Not a sedimentation process


Two-stage evaporation process.

The 1st stage was solvent evaporation and it was fast.

The 2nd stage was water evaporation and it was slow.
- **Solvent recovery from the 2\textsuperscript{nd} extraction tailings**

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Vapour pressure at 297 K (kPa)</th>
<th>Residual solvent concentration (mg/kg of tailings)</th>
<th>Total equilibration time (min)</th>
<th>1\textsuperscript{st} evaporation stage equilibration time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% Toluene</td>
<td>3.6</td>
<td>210</td>
<td>118</td>
<td>72</td>
</tr>
<tr>
<td>70% Toluene/30% n-Heptane</td>
<td>4.2</td>
<td>108</td>
<td>120</td>
<td>66</td>
</tr>
<tr>
<td>30% Toluene/70% n-Heptane</td>
<td>5.0</td>
<td>93</td>
<td>70</td>
<td>48</td>
</tr>
<tr>
<td>10% Toluene/90% n-Heptane</td>
<td>5.5</td>
<td>89</td>
<td>69</td>
<td>44</td>
</tr>
<tr>
<td>10% Toluene/90% Cyclohexane</td>
<td>10.5</td>
<td>20</td>
<td>100</td>
<td>30</td>
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<tr>
<td>Methyl Cyclohexane</td>
<td>5.8</td>
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<td>85</td>
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<td>Cyclohexane</td>
<td>11.3</td>
<td>5</td>
<td>61</td>
<td>25</td>
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<tr>
<td>Ethylbenzene</td>
<td>1.2</td>
<td>407</td>
<td>200</td>
<td>123</td>
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<tr>
<td>Xylenes</td>
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<td>150</td>
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<tr>
<td>Isoprene</td>
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<td>130</td>
<td>5.2</td>
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<tr>
<td>Limonene</td>
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<td>1400</td>
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</table>

Solvent evaporation rate is linearly related to its vapor pressure

End members

- **Four petrologic end member samples**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Size fraction (μm)</th>
<th>Quartz</th>
<th>K-feldspar</th>
<th>Calcite</th>
<th>Dolomite</th>
<th>Siderite</th>
<th>TiO₂ minerals</th>
<th>Kaolinite</th>
<th>Total 2:1 clays</th>
<th>Chlorite</th>
<th>Pyrite</th>
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</thead>
<tbody>
<tr>
<td>EC after DS</td>
<td>Bulk</td>
<td>52.3</td>
<td>2.7</td>
<td>0.0</td>
<td>0.3</td>
<td>3.0</td>
<td>0.7</td>
<td>14.4</td>
<td>25.3</td>
<td>1.3</td>
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<td>3.3</td>
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<tr>
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<td>2–45</td>
<td>69.0</td>
<td>3.3</td>
<td>0.0</td>
<td>0.1</td>
<td>0.7</td>
<td>0.8</td>
<td>9.5</td>
<td>14.8</td>
<td>1.8</td>
<td>0.0</td>
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<tr>
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<td>&lt;2</td>
<td>4.2</td>
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<td>0.8</td>
<td>0.3</td>
<td>1.0</td>
<td>0.3</td>
<td>28.9</td>
<td>58.9</td>
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<td>0.2–2</td>
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<td>0.2</td>
<td>0.1</td>
<td>0.3</td>
<td>37.0</td>
<td>52.6</td>
<td>2.3</td>
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<td>0.3</td>
<td>1.1</td>
<td>0.3</td>
<td>21.4</td>
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<td>1.4</td>
<td>0.1</td>
<td>0.3</td>
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<td>7.5</td>
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<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
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<td>2.1</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
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<td>2–45</td>
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<td>4.6</td>
<td>9.5</td>
<td>2.8</td>
<td>0.4</td>
<td>0.1</td>
<td>14.2</td>
<td>10.9</td>
<td>2.3</td>
<td>0.2</td>
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<tr>
<td>MC after DS</td>
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<td>1.2</td>
<td>0.4</td>
<td>0.1</td>
<td>30.4</td>
<td>40.6</td>
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<td>0.2</td>
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<td>0.9</td>
<td>38.4</td>
<td>33.7</td>
<td>1.2</td>
<td>0.0</td>
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<tr>
<td>MC after DS</td>
<td>&lt;0.2</td>
<td>1.9</td>
<td>2.4</td>
<td>7.4</td>
<td>0.7</td>
<td>0.9</td>
<td>0.0</td>
<td>20.9</td>
<td>54.9</td>
<td>10.7</td>
<td>0.2</td>
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<td>Bulk</td>
<td>94.5</td>
<td>3.6</td>
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<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>0.8</td>
<td>0.7</td>
<td>0.2</td>
<td>0.0</td>
</tr>
<tr>
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<td>94.7</td>
<td>4.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
<td>1.1</td>
<td>0.0</td>
<td>0.0</td>
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<td>0.2</td>
<td>0.5</td>
<td>0.0</td>
<td>18.2</td>
<td>7.7</td>
<td>1.3</td>
<td>0.4</td>
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<tr>
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<td>18.7</td>
<td>4.1</td>
<td>7.1</td>
<td>1.8</td>
<td>1.6</td>
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<td>4.1</td>
<td>2.5</td>
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<td>0.2</td>
</tr>
<tr>
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<td>1.4</td>
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<td>0.3</td>
<td>0.2</td>
<td>1.5</td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
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<td>&gt;45</td>
<td>93.0</td>
<td>2.8</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
<td>17.6</td>
<td>10.4</td>
<td>2.4</td>
<td>0.9</td>
</tr>
<tr>
<td>MS after DS</td>
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<td>4.5</td>
<td>2.9</td>
<td>2.2</td>
<td>0.6</td>
<td>0.2</td>
<td>30.9</td>
<td>31.8</td>
<td>3.4</td>
<td>0.6</td>
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<tr>
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<td>18.7</td>
<td>4.1</td>
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<td>1.8</td>
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<td>0.0</td>
<td>4.1</td>
<td>2.5</td>
<td>0.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Total 2:1 clays – the sum of illite and illite-smectite.

DS – Dean Stark extraction.

### Table 4

Chemical composition (in wt%) of the oil sands determined by ICP-MS.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Size fraction (µm)</th>
<th>Al</th>
<th>Ca</th>
<th>Na</th>
<th>Mg</th>
<th>K</th>
<th>Fe</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC after DS</td>
<td>Bulk</td>
<td>6.49</td>
<td>0.22</td>
<td>0.27</td>
<td>0.40</td>
<td>1.44</td>
<td>2.61</td>
<td>0.38</td>
</tr>
<tr>
<td>EC after DS</td>
<td>&gt;45</td>
<td>2.13</td>
<td>0.08</td>
<td>0.10</td>
<td>0.10</td>
<td>0.86</td>
<td>0.89</td>
<td>0.15</td>
</tr>
<tr>
<td>EC after DS</td>
<td>2–45</td>
<td>5.23</td>
<td>0.14</td>
<td>0.12</td>
<td>0.27</td>
<td>1.46</td>
<td>2.95</td>
<td>0.43</td>
</tr>
<tr>
<td>EC after DS</td>
<td>&lt;2</td>
<td>11.54</td>
<td>0.17</td>
<td>1.05</td>
<td>0.68</td>
<td>2.85</td>
<td>7.02</td>
<td>0.71</td>
</tr>
<tr>
<td>EC after DS</td>
<td>0.2–2</td>
<td>10.23</td>
<td>0.26</td>
<td>0.15</td>
<td>0.54</td>
<td>2.70</td>
<td>2.86</td>
<td>0.85</td>
</tr>
<tr>
<td>EC after DS</td>
<td>&lt;0.2</td>
<td>9.76</td>
<td>0.37</td>
<td>1.34</td>
<td>0.64</td>
<td>2.45</td>
<td>3.61</td>
<td>0.52</td>
</tr>
<tr>
<td>MC after DS</td>
<td>Bulk</td>
<td>4.47</td>
<td>4.32</td>
<td>0.17</td>
<td>0.54</td>
<td>0.87</td>
<td>0.64</td>
<td>0.23</td>
</tr>
<tr>
<td>MC after DS</td>
<td>&gt;45</td>
<td>1.46</td>
<td>1.31</td>
<td>0.06</td>
<td>0.13</td>
<td>0.64</td>
<td>0.25</td>
<td>0.14</td>
</tr>
<tr>
<td>MC after DS</td>
<td>2–45</td>
<td>4.35</td>
<td>5.78</td>
<td>0.09</td>
<td>0.62</td>
<td>1.07</td>
<td>0.82</td>
<td>0.34</td>
</tr>
<tr>
<td>MC after DS</td>
<td>&lt;2</td>
<td>7.39</td>
<td>7.71</td>
<td>0.29</td>
<td>0.75</td>
<td>1.35</td>
<td>1.05</td>
<td>0.41</td>
</tr>
<tr>
<td>MC after DS</td>
<td>0.2–2</td>
<td>9.39</td>
<td>4.77</td>
<td>0.06</td>
<td>0.42</td>
<td>1.43</td>
<td>0.94</td>
<td>0.36</td>
</tr>
<tr>
<td>MC after DS</td>
<td>&lt;0.2</td>
<td>9.36</td>
<td>6.86</td>
<td>0.73</td>
<td>0.75</td>
<td>1.65</td>
<td>1.36</td>
<td>0.52</td>
</tr>
<tr>
<td>ES after DS</td>
<td>Bulk</td>
<td>0.60</td>
<td>&lt;0.01</td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>0.47</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>ES after DS</td>
<td>&gt;45</td>
<td>0.77</td>
<td>0.01</td>
<td>0.04</td>
<td>0.01</td>
<td>0.67</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>ES after DS</td>
<td>2–45</td>
<td>5.52</td>
<td>0.04</td>
<td>0.14</td>
<td>0.13</td>
<td>1.85</td>
<td>0.83</td>
<td>0.34</td>
</tr>
<tr>
<td>MS after DS</td>
<td>Bulk</td>
<td>1.46</td>
<td>1.16</td>
<td>0.08</td>
<td>0.20</td>
<td>0.55</td>
<td>0.55</td>
<td>0.09</td>
</tr>
<tr>
<td>MS after DS</td>
<td>&gt;45</td>
<td>1.35</td>
<td>1.30</td>
<td>0.05</td>
<td>0.22</td>
<td>0.70</td>
<td>0.85</td>
<td>0.09</td>
</tr>
<tr>
<td>MS after DS</td>
<td>2–45</td>
<td>3.25</td>
<td>4.69</td>
<td>0.10</td>
<td>0.62</td>
<td>0.99</td>
<td>1.97</td>
<td>0.30</td>
</tr>
</tbody>
</table>

DS – Dean Stark extraction.

End members

Reasonably good correlation between aluminum content and clay mineral content

Correlation of clay minerals to potassium is more scattered

• **Pure clays** (smectite Swy-2, illite-smectite ISCz-1, kaolinite KGa-2, Illite IMt-1, chlorite CCa-2)

To examine their tendencies to retain solvent and bitumen

### Table 2. Cation Exchange Capacity (CEC), Specific Surface Area (SSA), and Elemental (H, N, S, and C) Analysis

<table>
<thead>
<tr>
<th>Sample Description</th>
<th>CEC (meq/100g)</th>
<th>SSA (m²/g)</th>
<th>H (wt %)</th>
<th>N (wt %)</th>
<th>S (wt %)</th>
<th>C (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>starting SWY-2</td>
<td>87.1 ± 1.10</td>
<td>28.3 ± 3.69</td>
<td>0.736 ± 0.04</td>
<td>0.053 ± 0.01</td>
<td>0.009 ± 0.00</td>
<td>0.133 ± 0.02</td>
</tr>
<tr>
<td>starting ISCz-1</td>
<td>37.5 ± 0.28</td>
<td>50.4 ± 1.24</td>
<td>0.687 ± 0.01</td>
<td>0.045 ± 0.01</td>
<td>0.009 ± 0.00</td>
<td>0.100 ± 0.00</td>
</tr>
<tr>
<td>Solvent-Clay Mixtures without Bitumen (Blanks)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWY-2 blank 0% RH</td>
<td>85.6 ± 1.24</td>
<td>13.4</td>
<td>1.010 ± 0.06</td>
<td>0.048 ± 0.02</td>
<td>0.049 ± 0.06</td>
<td>0.888 ± 0.01</td>
</tr>
<tr>
<td>SWY-2 blank 50% RH</td>
<td>87.5 ± 0.31</td>
<td>12.2</td>
<td>1.114 ± 0.01</td>
<td>0.053 ± 0.01</td>
<td>0.006 ± 0.00</td>
<td>0.750 ± 0.00</td>
</tr>
<tr>
<td>SWY-2 blank 95% RH</td>
<td>85.7 ± 1.03</td>
<td>9.3</td>
<td>1.432 ± 0.01</td>
<td>0.120 ± 0.00</td>
<td>0.022 ± 0.00</td>
<td>0.807 ± 0.03</td>
</tr>
<tr>
<td>ISCz-1 blank 0% RH</td>
<td>36.9 ± 0.43</td>
<td>38.6</td>
<td>0.774 ± 0.02</td>
<td>0.060 ± 0.01</td>
<td>0.062 ± 0.01</td>
<td>0.898 ± 0.01</td>
</tr>
<tr>
<td>ISCz-1 blank 50% RH</td>
<td>37.2 ± 0.63</td>
<td>42.4</td>
<td>0.862 ± 0.02</td>
<td>0.047 ± 0.01</td>
<td>0.021 ± 0.00</td>
<td>0.867 ± 0.02</td>
</tr>
<tr>
<td>ISCz-1 blank 95% RH</td>
<td>37.6 ± 0.12</td>
<td>43.9</td>
<td>0.977 ± 0.02</td>
<td>0.120 ± 0.00</td>
<td>0.015 ± 0.00</td>
<td>0.593 ± 0.01</td>
</tr>
<tr>
<td>Bitumen-Clay Mixtures after Cyclohexane Extraction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWY-2 bitumen 0% RH</td>
<td>82.1 ± 0.80</td>
<td>4.7</td>
<td>1.342 ± 0.08</td>
<td>0.123 ± 0.01</td>
<td>0.038 ± 0.01</td>
<td>4.605 ± 0.03</td>
</tr>
<tr>
<td>SWY-2 bitumen 50% RH</td>
<td>79.3 ± 0.14</td>
<td>5.6</td>
<td>1.515 ± 0.01</td>
<td>0.123 ± 0.01</td>
<td>0.536 ± 0.02</td>
<td>5.523 ± 0.19</td>
</tr>
<tr>
<td>SWY-2 bitumen 95% RH</td>
<td>76.9 ± 0.08</td>
<td>6.0</td>
<td>2.173 ± 0.01</td>
<td>0.193 ± 0.01</td>
<td>0.031 ± 0.01</td>
<td>8.153 ± 0.15</td>
</tr>
<tr>
<td>ISCz-1 bitumen 0% RH</td>
<td>32.3 ± 0.03</td>
<td>6.3</td>
<td>1.368 ± 0.08</td>
<td>0.153 ± 0.01</td>
<td>0.048 ± 0.00</td>
<td>7.083 ± 0.04</td>
</tr>
<tr>
<td>ISCz-1 bitumen 50% RH</td>
<td>29.2 ± 0.65</td>
<td>6.3</td>
<td>1.570 ± 0.01</td>
<td>0.160 ± 0.01</td>
<td>0.014 ± 0.00</td>
<td>8.180 ± 0.06</td>
</tr>
<tr>
<td>ISCz-1 bitumen 95% RH</td>
<td>30.2 ± 2.16</td>
<td>5.5</td>
<td>1.693 ± 0.01</td>
<td>0.203 ± 0.01</td>
<td>0.037 ± 0.00</td>
<td>8.047 ± 0.11</td>
</tr>
</tbody>
</table>

Good bitumen recovery seemed to have been achieved after 3rd solvent wash using pure heptane, even for the low grade ore with high fines content.

But this was possibly due to the bitumen-coated fines in the extracted bitumen product.

Paraffinic solvent tended to lead to poor supernatant quality (higher fine solids content)

But the 10/90 (toluene/heptane) was a notable exception

---

- Kaolinite enrichment in supernatant

Kaolinite was enriched in the supernatant relative to illite.

**Effect of water**

- Add solvent (cyclohexane) after water lowered bitumen recovery
- Low water content (2-12 wt%) helped reduce fine solids content in bitumen
- Too much water or no water increased fines solids content in bitumen, and the fine solids had lower carbon content

**Table 5. Mineralogy of Centrifuge Solids**

<table>
<thead>
<tr>
<th>mineral</th>
<th>weight % (normalized)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nonclays</td>
<td>38.6</td>
</tr>
<tr>
<td>quartz</td>
<td>8.0</td>
</tr>
<tr>
<td>potassium feldspar</td>
<td>2.4</td>
</tr>
<tr>
<td>calcite</td>
<td>0.8</td>
</tr>
<tr>
<td>dolomite</td>
<td>3.2</td>
</tr>
<tr>
<td>siderite</td>
<td>0.7</td>
</tr>
<tr>
<td>pyrite</td>
<td>0.2</td>
</tr>
<tr>
<td>hematite</td>
<td>0.2</td>
</tr>
<tr>
<td>anatase</td>
<td></td>
</tr>
<tr>
<td>total nonclays</td>
<td>54.1</td>
</tr>
<tr>
<td>clays</td>
<td></td>
</tr>
<tr>
<td>kaolinite (disordered)</td>
<td>27.2</td>
</tr>
<tr>
<td>illite</td>
<td>16.8</td>
</tr>
<tr>
<td>chlorite</td>
<td>1.8</td>
</tr>
<tr>
<td>total clays</td>
<td>45.9</td>
</tr>
<tr>
<td>total</td>
<td>100.0</td>
</tr>
</tbody>
</table>

*a* Low-fines ore, centrifuged solids after filter washing with toluene.

Two challenges

Fine solids removal from recovered bitumen to meet refinery requirements (less than 300 ppm fine solids) to eliminate the need for upgrader.

Solvent recovery from extraction tailings to meet regulation (4 parts solvent in extraction tailings per thousand part of extracted bitumen)

- works out to be about 260 ppm for rich ore (~13 wt% bitumen)
- low energy intensity in solvent recovery
Two challenges  Solvent recovery

- **Effect of clay surface bitumen coating**

Table 3. Equilibrium data and kinetic rate constants for cyclohexane vapour \((p/p^0 = 0.4)\) and water vapour \((p/p^0 = 0.5)\) on the three samples in the absence and presence of the other vapour at 30 °C

<table>
<thead>
<tr>
<th>Kaolinite</th>
<th>FS</th>
<th>ORFS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sorbed amount</td>
<td>sorbed amount</td>
</tr>
<tr>
<td></td>
<td>mmol/g</td>
<td>g/g</td>
</tr>
<tr>
<td>cyclohexane alone</td>
<td>0.12</td>
<td>0.0101</td>
</tr>
<tr>
<td>cyclohexane after water</td>
<td>0.06</td>
<td>0.005</td>
</tr>
<tr>
<td>water alone</td>
<td>0.88</td>
<td>0.0158</td>
</tr>
<tr>
<td>water after cyclohexane</td>
<td>0.57</td>
<td>0.0103</td>
</tr>
</tbody>
</table>

1 mmol/g: mmol of adsorbate per gram of adsorbent; g/g: mass of adsorbate on adsorbent

Two challenges  Solvent recovery

- **Effect of water content during extraction**

![Graph](image)

Figure 5. Residual cyclohexane content in the gangue after drying in the environmental chamber at 24°C for 40 min as a function of water content.

High water content during extraction kept more cyclohexane in the extraction tailings.

Two challenges

- **Drying chamber tests**

  ![Flowsheet Diagram](image)

  **Figure 4.** Maximum cyclohexane mass flux for high-grade gangue. Curves represent the best fit of data to Equation (3).

- Different modes of cyclohexane transport and evaporation from extraction tailings

Two challenges  Solvent recovery

- Cyclohexane evaporation from re-constituted extraction tailings

Two challenges  Solvent recovery

Two challenges: Solvent recovery and Fines removal. Residual bitumen in the extraction tailings extended the time required to evaporate cyclohexane, mainly due to its gradual accumulation on the particle bed surface.

Two challenges  Solvent recovery  Fines removal

- **Effect of surface bitumen coating, and solvent**

  ![Graph](image1)

  **Fig. 3.** Sedimentation of clean (i.e. untreated) and bitumen-treated silica in hydrocarbon solvents. The solvents were mixtures of n-heptane and toluene at various ratios.

- Pure silica settled fast in heptol
- Bitumen-coated silica settled slower in heptol. The more the toluene, the slower the settling rate
- The settling rate correlated well with attraction force

---

Two challenges

- Solvent recovery
- Fines removal

Fast settling was due to aggregation of bitumen-coated silica in a paraffinic solvent.

100% toluene

50% toluene, 50% heptane

100% heptane

---

Two challenges  
Solvent recovery  
Fines removal

- **Effect of solvent blend**

**Table 1. Properties of Solvents in Descending Order of Solubility Parameter**

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Boiling Point (°C)</th>
<th>Density (g cm⁻³)</th>
<th>Solubility Parameter (MPa¹/²)¹/²</th>
</tr>
</thead>
<tbody>
<tr>
<td>cyclohexane</td>
<td>80.7</td>
<td>0.78</td>
<td>16.8</td>
</tr>
<tr>
<td>cyclopentane</td>
<td>49</td>
<td>0.75</td>
<td>16.6</td>
</tr>
<tr>
<td>methylcyclopentane</td>
<td>71.8</td>
<td>0.75</td>
<td>16.2</td>
</tr>
<tr>
<td>n-heptane</td>
<td>98.4</td>
<td>0.68</td>
<td>15.34</td>
</tr>
<tr>
<td>n-hexane</td>
<td>68.7</td>
<td>0.66</td>
<td>14.93</td>
</tr>
<tr>
<td>n-pentane</td>
<td>36.1</td>
<td>0.63</td>
<td>14.32</td>
</tr>
</tbody>
</table>

**Figure 3. Comparison of bitumen recovery (fines-free basis) for mixtures of cyclopentane and cyclohexane with paraffinic solvents at a constant value of the solubility parameter of 16.45 MPa¹/².**

**Table 2. Performance of Single Solvents for Non-aqueous Extraction of a High Grade Oil Sands Ore Sample**

<table>
<thead>
<tr>
<th>Solvent</th>
<th>Bitumen Recovery (%)</th>
<th>Centrifuged Solid Fines (wt % in bitumen product)</th>
<th>Carbon (wt %)</th>
<th>Bitumen Recovery (fines-free basis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cyclohexane</td>
<td>97.9 ± 0.8</td>
<td>5.8 ± 0.1</td>
<td>8 ± 0.3</td>
<td>97.4 ± 0.8</td>
</tr>
<tr>
<td>cyclopentane</td>
<td>91.6 ± 0.8</td>
<td>5.5 ± 0.8</td>
<td>11.6 ± 1.6</td>
<td>90.8 ± 1.0</td>
</tr>
<tr>
<td>methylcyclopentane</td>
<td>84.8 ± 1.2</td>
<td>8.9 ± 1.2</td>
<td>9.2 ± 0.5</td>
<td>83.9 ± 1.2</td>
</tr>
<tr>
<td>n-heptane</td>
<td>96.0 ± 0.63</td>
<td>32.6 ± 0.3</td>
<td>30.0 ± 0.8</td>
<td>81.5 ± 0.02</td>
</tr>
</tbody>
</table>

*Mass percent of recovered bitumen on a solvent-free basis.*

Two challenges
- Solvent recovery
- Fines removal

Figure 2. Percentage of centrifuged fine solids in the bitumen product using solvent mixtures of cyclohexane and n-heptane. The line shows the trend for mean values of duplicated experiments.

- Some particular combination of cyclohexane/heptane seems to cause lower fine solids content in NAE bitumen
- Higher cycloalkane content caused lower fine solids content
- Shorter chain alkane caused lower fine solids content

Figure 4. Percentage of centrifuged fine solids in extracted bitumen using cyclohexane and cyclopentane in mixtures with different paraffinic solvents. Where indicated, error bars are standard deviations of experiments in triplicate. The lines show linear regression for data of blends of constant solubility parameter.

Two challenges  Solvent recovery  Fines removal

- **Hydrothermal treatment + water venting + hot filtration** (tested on bitumen froth)

![Diagram](image)

**Fig. 2.** Schematics for laboratory-scale hydrothermal bitumen froth cleaning test set up. The schematics show the hydrothermal treatment (a), venting (b) and solids hot filtration (c).

Two challenges  Solvent recovery  Fines removal

Venting at 270°C removed all the emulsified water from bitumen froth.

Without venting, about half of the emulsified water was demulsified and phase-separated out.

Fig. 3. Residual water contents in TBM as a function of temperature for a treatment time of 30 min. The inset figure shows the water contents under different treatment times at 390°C.

Hydrothermal treatment at 390°C significantly improved the filtration removal of fine solids from bitumen froth.

The bitumen froth became filterable whether by room-temperature filtration (after toluene dilution) or hot filtration (200°C) without solvent dilution.

Fig. 5. Effect of treatment temperature on the room-temperature filtration behavior (hydrothermal treatment time 30 min).

Fig. 7. Effect of treatment temperature on the hot filtration behavior (hydrothermal treatment time 30 min). The error bar at 390°C indicates the standard deviation from three repeat tests.

What we know

- Solvent
- Swelling and non-swelling clays
- Bitumen coating on the fine solids and clays
- Water
- Solvent recovery: thermodynamics and kinetics
- Fine solids removal

What we don’t know

- Energy consumption in solvent recovery, GHG emission
- Feasible fine solids removal method(s)
- How to build a NAE plant
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