Webinars

# Role of Nanoparticle Technology in Oil and Gas Industry Application: Small Size, Big Effects

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Calgary, Alberta

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# Agenda

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- Background
- Introduction to nanoscale
- Challenges facing nanoparticle application
- Integration of nanoparticles in processes of:
  - Oil upgrading and recovery
  - Asphaltene
  - Friction reduction
  - Natural gas
  - Produced water treatment
  - Conversion of waste hydrocarbon into valuable products
- Take-home message
- Acknowledgments

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# Proven Oil Reserves Worldwide

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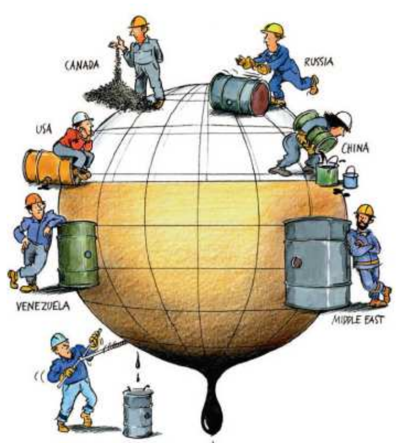


FIGURE 1. DISTRIBUTION OF CANADIAN ENERGY RESOURCES


Source: Courtesy of the Canadian Centre for Energy Information.

SPE International

Image courtesy: Kjell Aleklett, Unconventional Oil & Gas 2012 TaiYuan 2012-09-24

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# Oil and Natural Gas Resources

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- Canada ranks third, in terms of proven global crude oil reserves.
- More than 96% of Canada's oil reserves are in Alberta.
- In 2010, Alberta’s total proven oil reserves were 170.8 billion barrels, or about 12% of total global oil reserves (1,469.6 billion barrels).

- Canada ranks fourth, in terms of proven global NG reserves
- 2020: marketed NG production in Alberta = 8,286.6 Million Cubic Metres
- In August 2021, marketable natural gas production was 9.0 billion cubic metres, up 8.4% from August 2020's production level.

- There are 220 km$^2$ of tailing in Alberta
- 340 billion gallons of toxic sludge
- 27 billion dollars is the estimated amount needed for the cleanup using current implemented technologies
- 150 million metric tons of petroleum coke is stockpiled per annum.

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Dr. Nassar Group
For Nanotechnology Research

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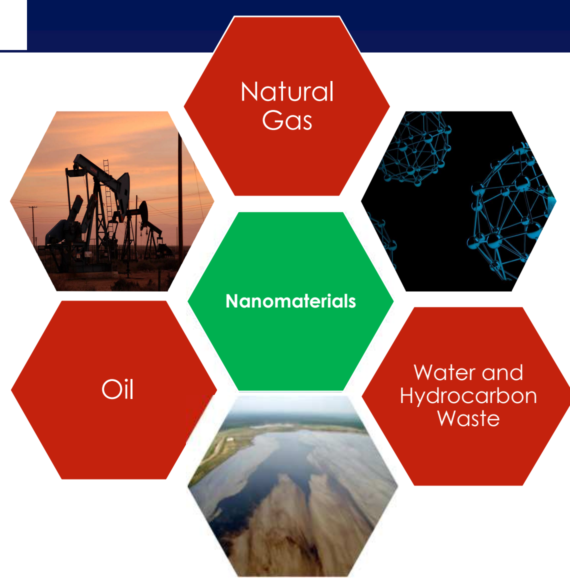


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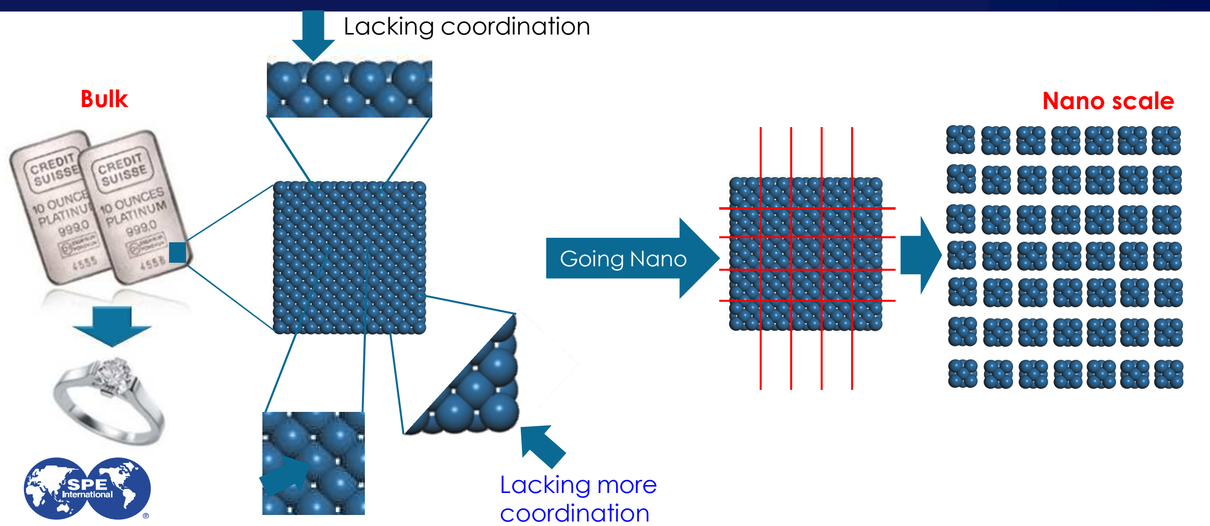
## Why Nanoparticles are different?




Source: Chapter 23: Naturally-derived Pyroxene Nanomaterials -An Ore for Wide Applications in Handbook of Functionalized Nanomaterials for Industrial Applications, Hossein Chaudhery, Ed., Elsevier, pp 731-773.

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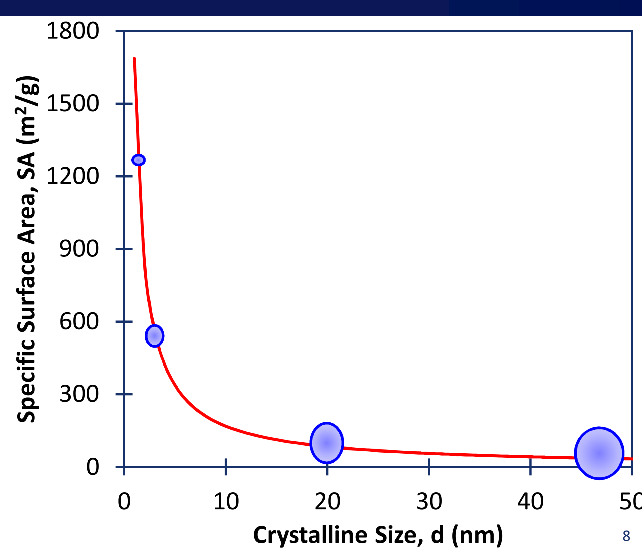
## Why Nanoparticles are different?

$$V = \frac{\pi}{6} d_p^3$$

$$A = \pi d_p^2$$

$$\rho = \frac{m}{V}$$

$$SA = \frac{6}{\rho d_p}$$

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## Why Nanoparticles are different?

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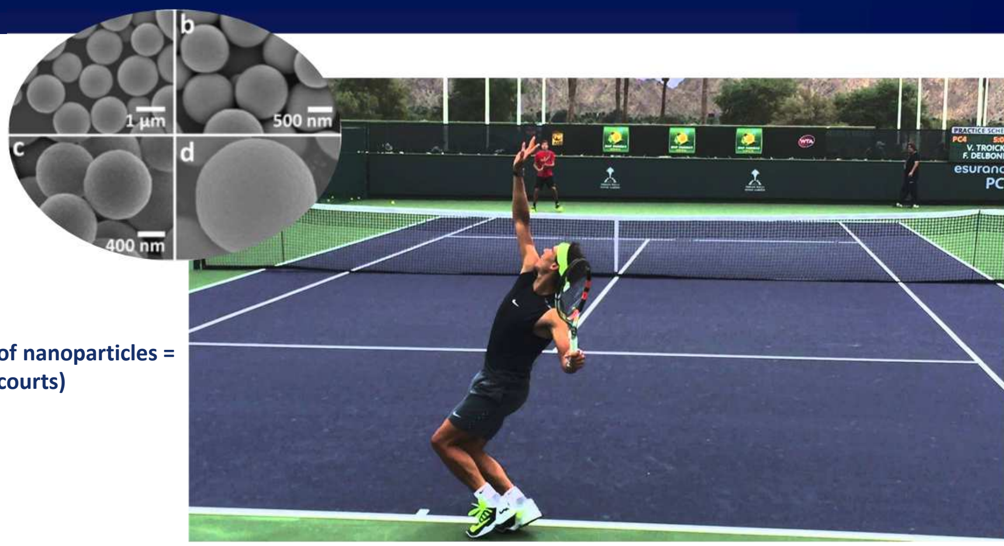


**Area of one gram of nanoparticles = 1000 m$^2$ (4 tennis courts)**

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## Preparation of Nanoparticles?

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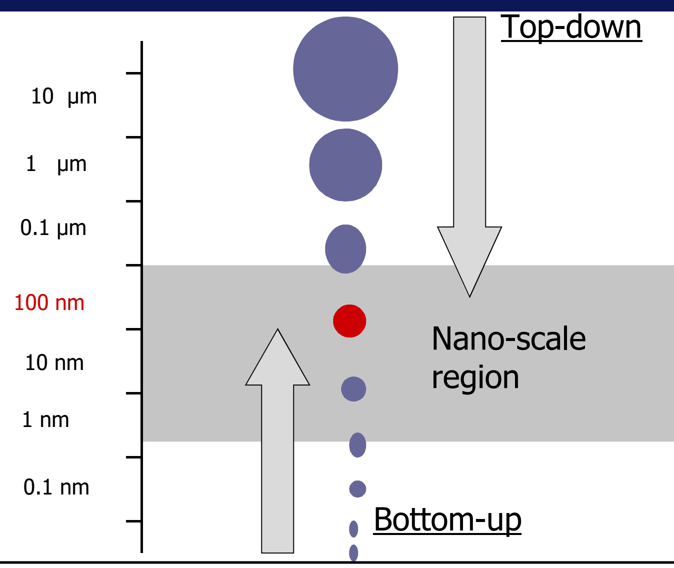


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# Naturally bottom-up built materials

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Source: seashells.com



# Size, Shape, Surface and Structural Modifications

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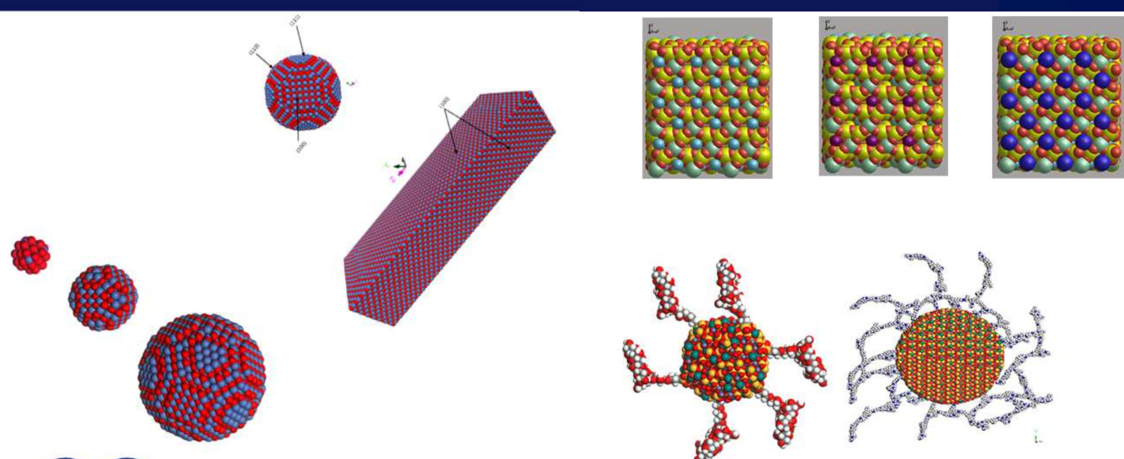

ACS Applied Nano Materials. 3 (2020) 5311–5326
Phys. Chem. Chem. Phys., 2016, 18, 6839
RSC Adv., 2017, 7, 14021
Journal of Colloid and Interface Science, 2016, 461, 396–408

## Nanoparticle Challenges

Scaling up and commercialization

Control over particle size

Applications

Stability

Handling

Quantity

Recovery/ Regeneration

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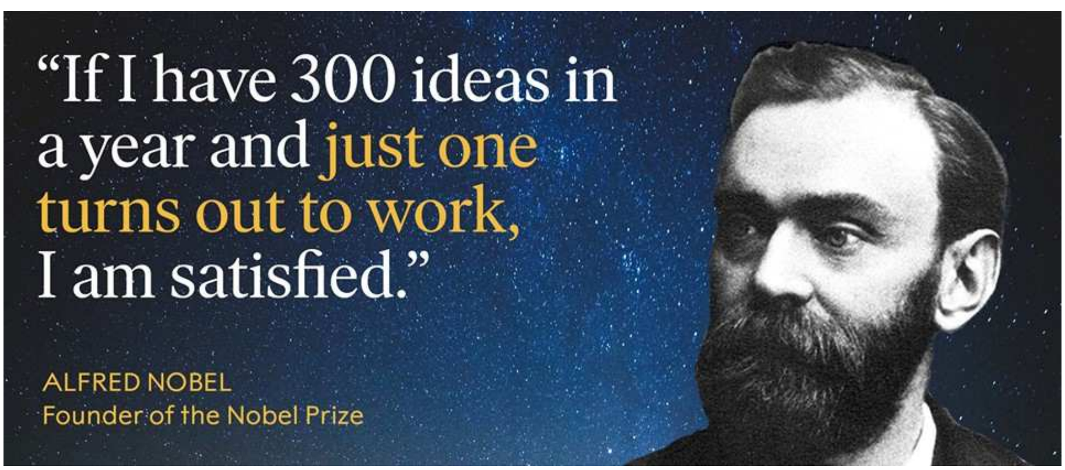


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## Challenge: Nano to real application

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Size, shape, SA, functionality, etc

Purity, efficiency, productions, et

Profitable, $CO_2$ reduction, Sustainability, etc

**Nanoparticles** → Fundamental of Science → **Properties** → Engineering → **Process** → System → **Field testing** → Policy → **Market**

Adsorption affinity, uptake, catalytic activity, interactions, etc

Scale up, cost, integration, environmental impact, etc

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## Materials Toolbox: Naturally-derived Nanomaterials

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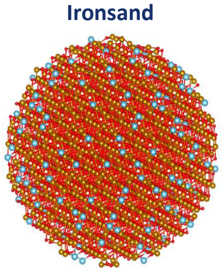
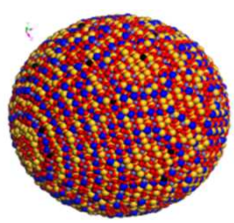
**Ironsand**



($Fe_3$—x$TixO_4$)

**Aegirine**

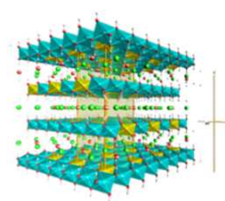


$Na(Ce_x\text{-}Ni_y\text{-}Fe_{(1\text{-}x\text{-}y)})Si_2O_6$

**Metakaolin**

$(Cs_2O\text{-}BaO\text{-}NiO)Al_2Si_2O_7$

**Hydrotalcite**



$Mg_{4.30}Ni_{1.70}CeAl(OH)_{16}.CO_3.4H_2O$

- Naturally-derived nanomaterials
- Prepared at mild conditions
- Tunable surface
- Most abundant elements on earth
- Could be utilized for both in-situ and ex-situ applications.

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USA Patent No. US16/289,218 (pending)
USA Patent No. US63/231,083 (pending)
RSC Adv., 2016, 6, 64482
RSC Adv., 2017, 7, 14021
Journal of Colloid and Interface Science, 2016, 461, 396–408

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## Process toolbox: Oil, gas, water, and solid waste

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### Oil

- Upgrading & recovery
- Asphaltenes
- Formation damage
- TAN
- Friction reduction (fracking)

### Natural Gas

- Purification
- Transportation (LNG)
- Conversion (G2L, DME, $H_2$)

### Wastewater

- SAGD
- MFT
- Oil spill

### Solid waste

- Petroleum coke
- Asphaltenes
- Low-rank coal

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## Combining Efforts

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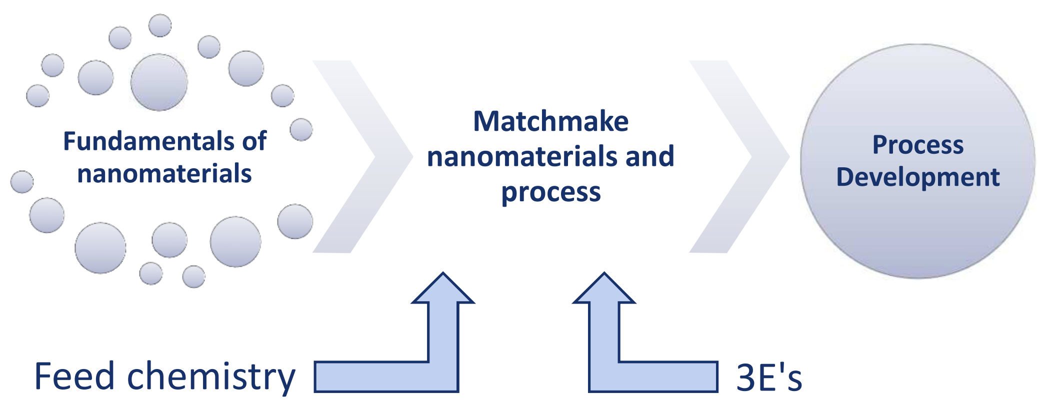


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**Is it a material challenge and/or a process challenge?**

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## Nano-catalysts: Partial upgrading of heavy oil to meet pipeline specifications!

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- Dilbit using NGC
  - Costly
  - High volume capacity (~50%)
  - Not readily available in large quantity
  - Energy intensive
- Upgrading
  - On surface
  - In-situ
- Catalytic upgrading with E-UD nanocatalysts

Applied Energy, 2014, 133, 374–387
Energy Fuels, 2014, 28, 1338–1350
Energy Fuels 2014, 28, 1351–1361

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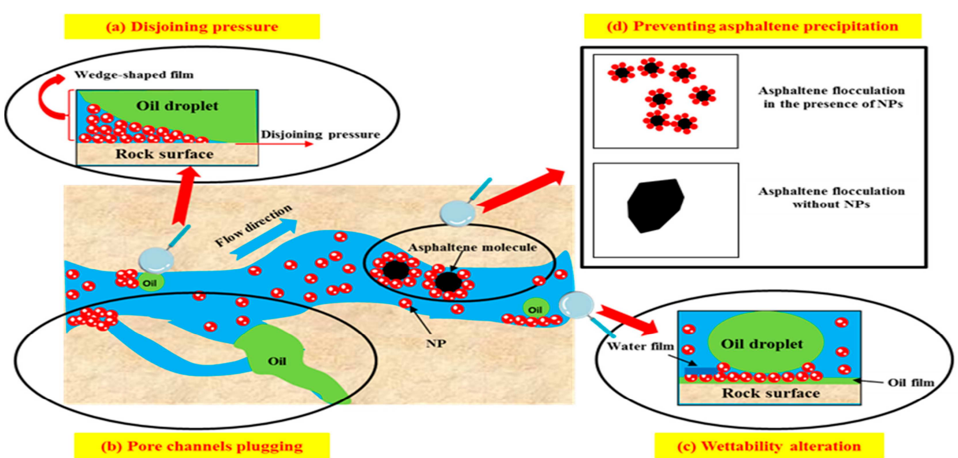
## Integrating Nanoparticles with Water Flooding for EOR

Webinars

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Ind. Eng. Chem. Res. 2016, 55, 6122–6132
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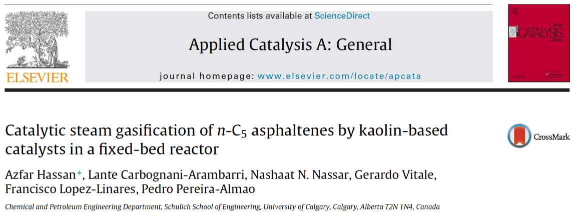

Contents lists available at ScienceDirect

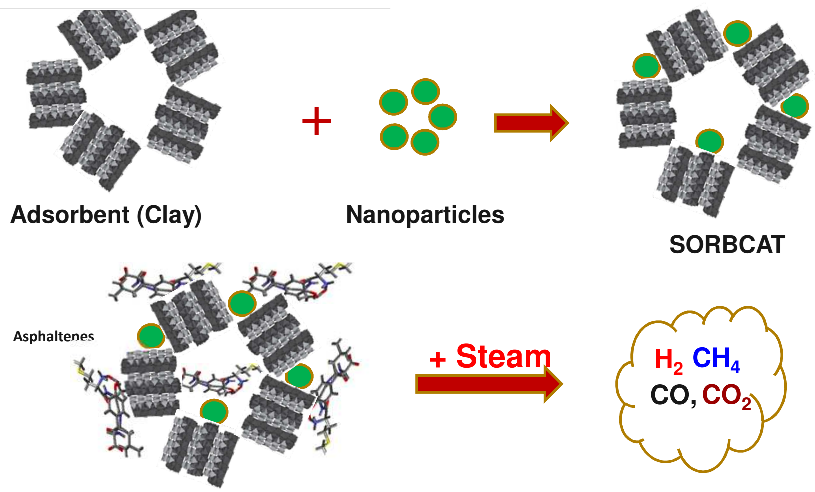
Applied Catalysis A: General

journal homepage: www.elsevier.com/locate/apcata

Catalytic steam gasification of $n$-$C_5$ asphaltenes by kaolin-based catalysts in a fixed-bed reactor

Azfar Hassan*, Lante Carbognani-Arambarri, Nashaat N. Nassar, Gerardo Vitale, Francisco Lopez-Linares, Pedro Pereira-Almao

*Chemical and Petroleum Engineering Department, Schulich School of Engineering, University of Calgary, Calgary, Alberta T2N 1N4, Canada*

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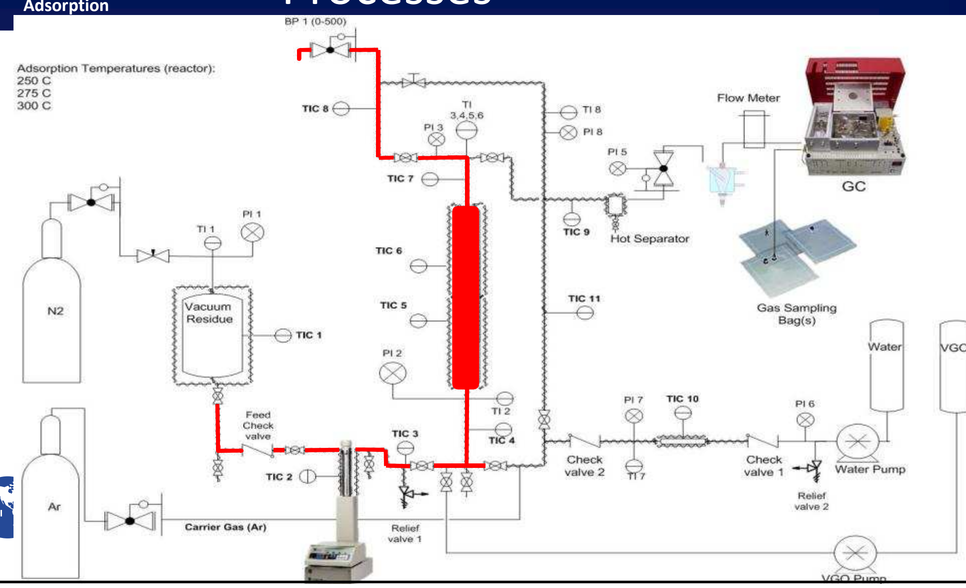
# Getting Real: Adsorption and Gasification Processes

Adsorption

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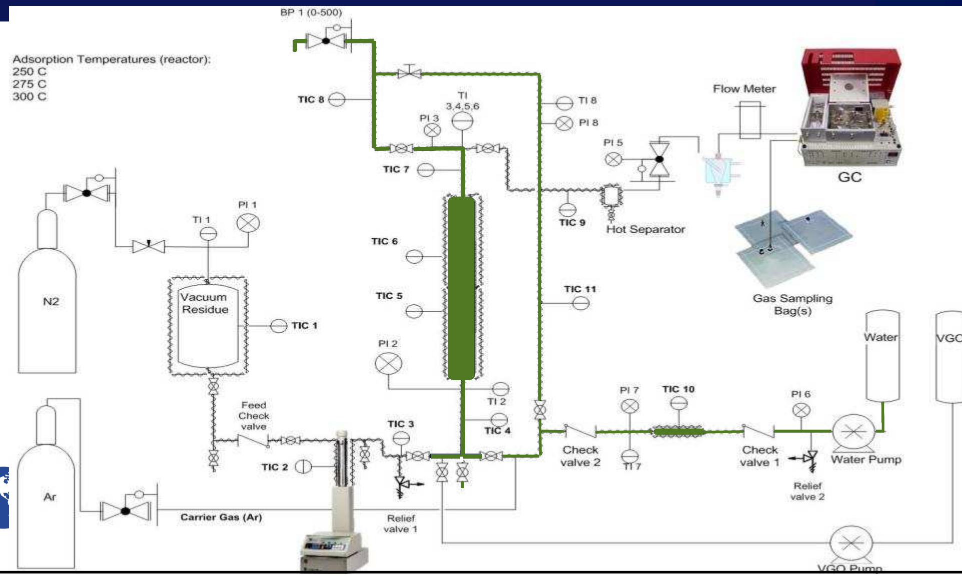
# Getting Real: Adsorption and Gasification Processes

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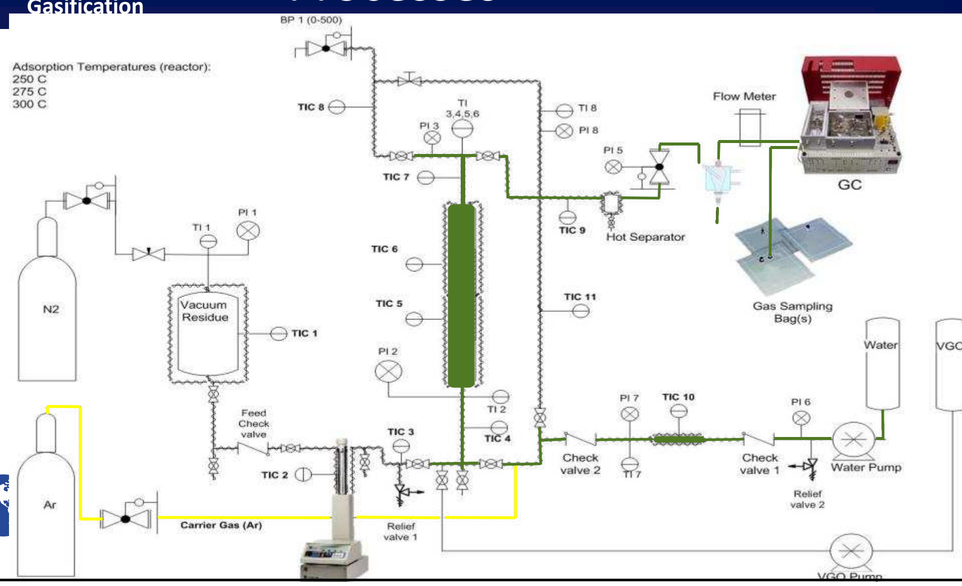
# Getting Real: Adsorption and Gasification Processes

Gasification

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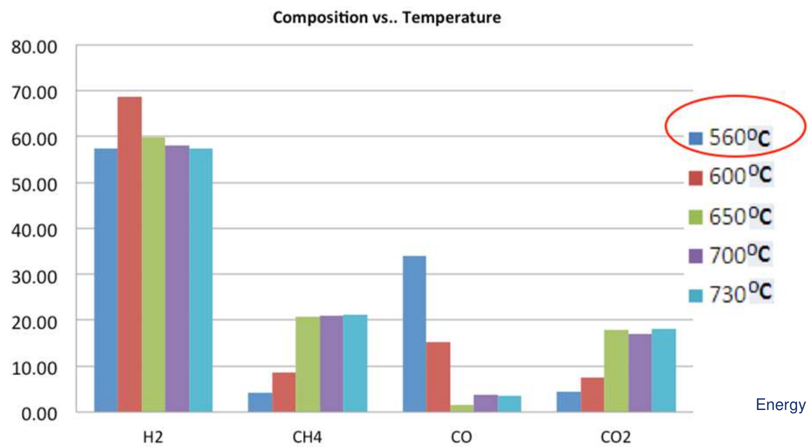
## Preliminary Catalytic Steam Gasification Results

- Feed: Athabasca Vacuum Residue
- Catalyst: 3wt% NiO-Kaoline




Energy & Fuels 31 (2017) 7396–7404



## Nano-inhibitor: prevents asphaltene deposition

energy&fuels ARTICLE

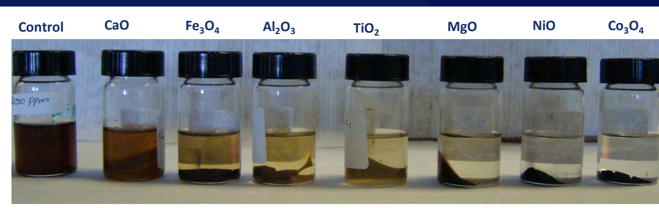
pubs.acs.org/EF

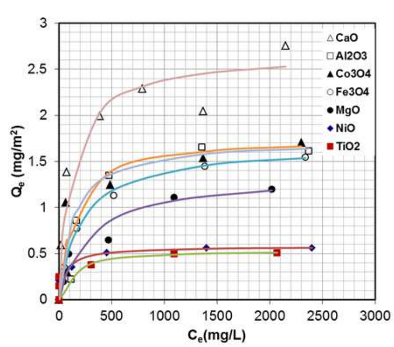
**Metal Oxide Nanoparticles for Asphaltene Adsorption and Oxidation**

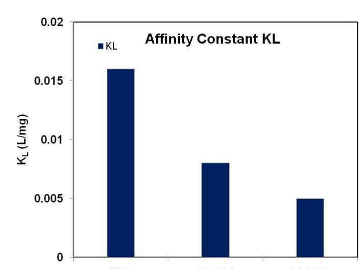
Nashaat N. Nassar,[†,‡] Azfar Hassan,[†,‡] and Pedro Pereira-Almao[*,†,‡]

[†]Alberta Ingenuity Centre for In-Situ Energy, University of Calgary, Calgary, Alberta, Canada

[‡]Department of Chemical & Petroleum Engineering, University of Calgary, Calgary, Alberta, Canada




$$Q_e = Q_m \frac{K_L C_e}{1 + K_L C_e}$$

Energy Fuels 2014, 28, 4963–4975

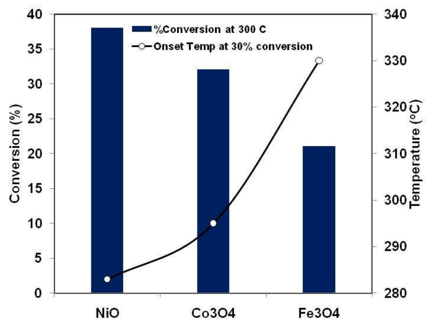


Energy Fuels 2015, 29, 1610–1621

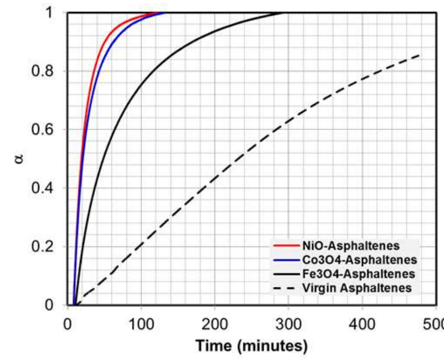
Catalysis Today 207 (2013) 127–132
Contents lists available at SciVerse ScienceDirect
Catalysis Today
journal homepage: www.elsevier.com/locate/cattod

Kinetics of the catalytic thermo-oxidation of asphaltenes at isothermal conditions on different metal oxide nanoparticle surfaces

Nashaat N. Nassar*, Azfar Hassan, German Luna, Pedro Pereira-Almao
Department of Chemical & Petroleum Engineering, Schulich School of Engineering, University of Calgary, Calgary, Alberta T2N 1N4, Canada




Isothermal oxidation (T = 300°C)




- Affinity constant a measure of catalytic conversion?
- Experimentally verified for the first time!
- Similar trends have been found for pyrolysis and gasification.

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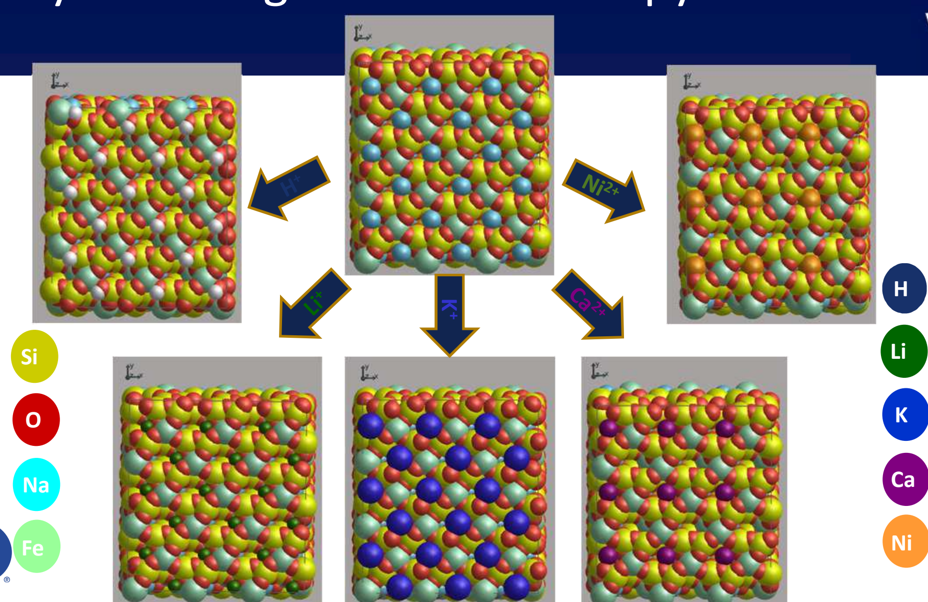
# Naturally occurring materials: Nanopyroxene

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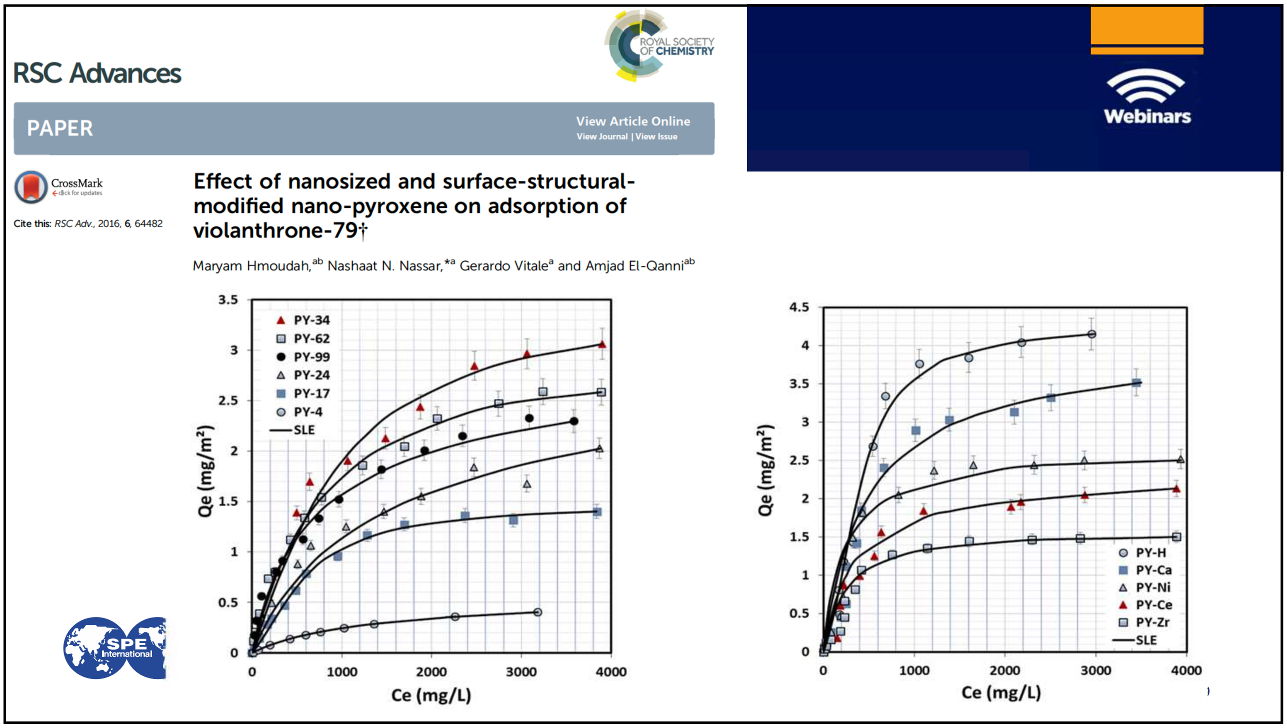
RSC Adv., 2016, 6, 64482


ROYAL SOCIETY OF CHEMISTRY
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Cite this: RSC Adv., 2016, 6, 64482
Effect of nanosized and surface-structural-modified nano-pyroxene on adsorption of violanthrone-79†
Maryam Hmoudah,ab Nashaat N. Nassar,*a Gerardo Vitalea and Amjad El-Qanniab
PY-34
PY-62
PY-99
PY-24
PY-17
PY-4
SLE
Qe (mg/m²)
Ce (mg/L)
PY-H
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PY-Ni
PY-Ce
PY-Zr
SLE
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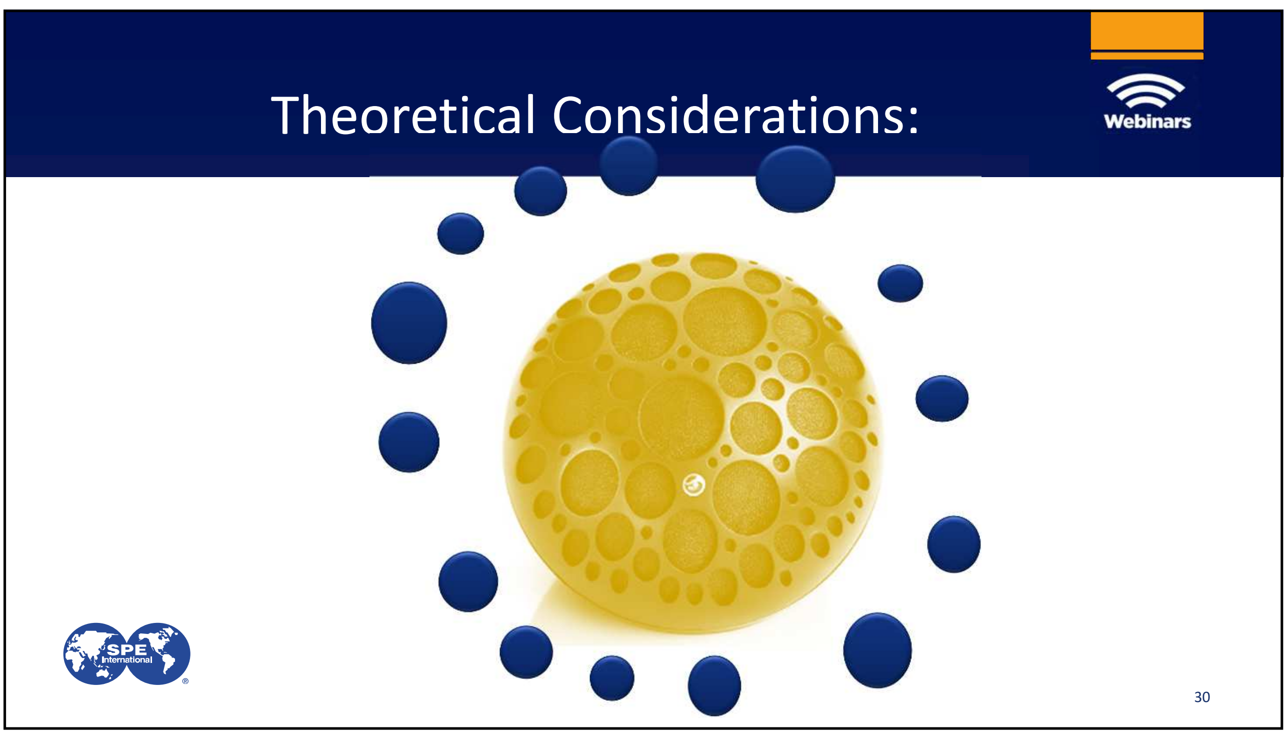
Theoretical Considerations:
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## Theoretical Considerations:

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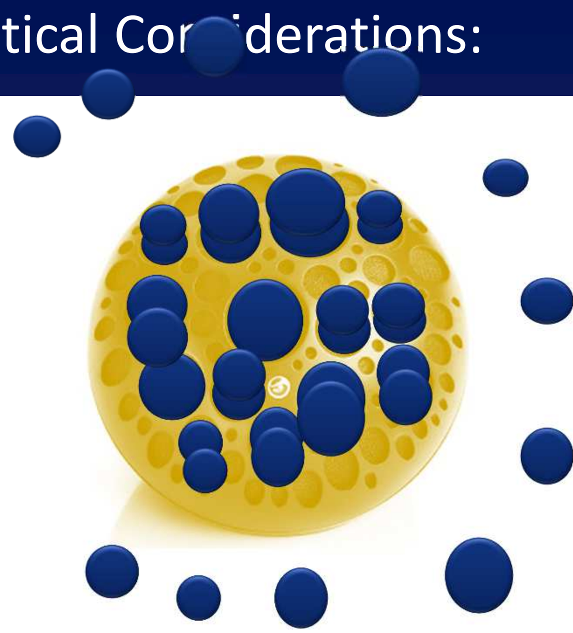
## Theoretical Considerations:



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energy&fuels | Energy Fuels 2014, 28, 4963−4975 Article
pubs.acs.org/EF

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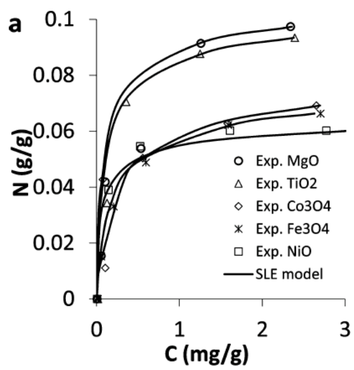
## A Novel Solid−Liquid Equilibrium Model for Describing the Adsorption of Associating Asphaltene Molecules onto Solid Surfaces Based on the "Chemical Theory"

Tatiana Montoya,[†] Diana Coral,[†] Camilo A. Franco,[†] Nashaat N. Nassar,[*,‡] and Farid B. Cortés[*,†]




$$C = \frac{\psi H}{1 + K\psi} \exp\left(\frac{\psi}{N_m}\right) \quad (12)$$

This adsorption isotherm model describes the behavior of asphaltenes onto a solid surface, i.e., solid−liquid equilibrium, which is a temperature-dependent model of three parameters (i.e., $N_m$, $H$, and $K$).[6,70,71] $H$ is the measured Henry's law constant, which is only a function of temperature, and an indicator of the adsorption affinity (i.e., the strength of interactions for adsorption) of asphaltenes onto solid surface. The lower the $H$ value (i.e., higher Henry's constant), the higher the affinity (i.e., the active sites are in locations that are easily accessible by asphaltenes). $K$ is constant and an indicator of rapid association of asphaltenes molecules once the primary sites are occupied. $N_m$ is the maximum adsorption capacity of asphaltenes (g/g). The other parameters are defined as follows:

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energy&fuels Energy Fuels 2015, 29, 4210−4221 Article
pubs.acs.org/EF

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## A New Model for Describing the Adsorption of Asphaltenes on Porous Media at a High Pressure and Temperature under Flow Conditions

Nashaat N. Nassar,[*,†] Tatiana Montoya,[†] Camilo A. Franco,[‡] Farid B. Cortés[*,‡]

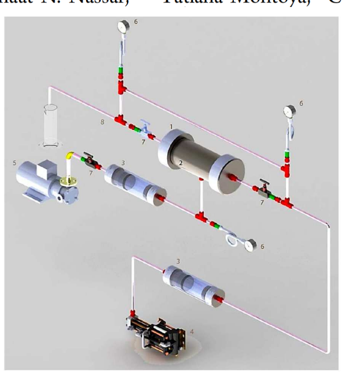


**Figure 2.** Schematic representation of the experimental setup. Legend: (1) the core holder, (2) the sand packed bed, (3) the displacement cylinder, (4) the displacement positive pump, (5) the mineral oil pump, (6) the pressure transducers, (7) the valves, and (8) sample output.

$$C = \frac{\Psi H}{1 + K\Psi} \exp\left(\frac{\psi}{N_m}\right) \exp\left[-\frac{v_{as}}{RT}(\delta_{as} - \delta_T)^2\right] \quad (12)$$

where the definitions of $K$ and $\Psi$ are given by[33]

$$K = \frac{K_T RT}{SA} \quad (13)$$

$$\Psi = \frac{-1 + \sqrt{1 + 4K\xi}}{2K} \quad (14)$$

where $\xi$ is a constant (defined as $\xi = NN_m/(N_m - N)$), $N$ is the amount adsorbed (in units of g/g), $N_m$ is the maximum adsorption capacity, $K_T$ is the reaction constant for dimer formation, SA is the specific surface area of the adsorbent (in units of cm$^2$/g), $v_{as}$ is the asphaltene molar volume (in units of cm (g/g)$^3$/mol), $\delta_{as}$ is the solubility parameter for asphaltenes (in units of MPa$^{1/2}$), and $\delta_T$ is the solubility parameter (in units of MPa$^{1/2}$) for the dissolvent reported in the literature.[65] Equation 12 represents the new adsorption model that considers the effects of the temperature and pressure.

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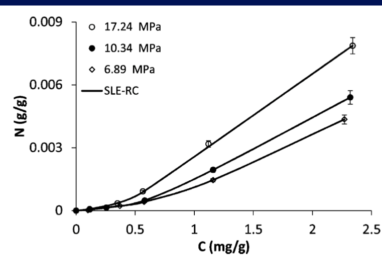


**Figure 4.** Adsorption isotherms of $n$-$C_7$ asphaltenes at different test pressures and temperature of 313 K. The symbols represent the experimental data and the solid curves are from SLE-RC model (see eq 12).

**Table 2. Estimated Parameters of the Solid−Liquid Model under Reservoir Conditions in the SLE-RC Model for Different Test Pressures at 313 K**

| | Value | | |
|---|---|---|---|
| parameter | 6.89 MPa | 10.34 MPa | 17.24 MPa |
| $H$ (mg/g) | 8086.42 | 7030.61 | 3321.65 |
| $K$ (g/g) | 1259.76 | 1440.82 | 1473.52 |
| $N_m$ (g/g) | 0.00668 | 0.00708 | 0.00879 |
| $\delta_{as}$ (MPa$^{1/2}$) | 16.56 | 16.64 | 16.80 |
| $v_{as}$ (cm$^3$/mol) | 1040.4 | 1025.28 | 743.74 |
| RMSE% | 1.70 | 0.04 | 0.63 |

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energy&fuels
*Energy Fuels* 2016, 30, 2052−2059
Article
pubs.acs.org/EF

## Importance of the Adsorption Method Used for Obtaining the Nanoparticle Dosage for Asphaltene-Related Treatments

Juan D. Guzmán,[†] Stefania Betancur,[†] Francisco Carrasco-Marín,[‡] Camilo A. Franco,[†,⊥] Nashaat N. Nassar,[*,§] and Farid B. Cortés[*,†,⊥]

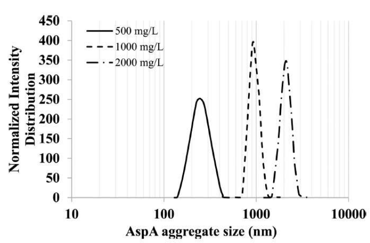


**Figure 2.** AspA aggregate size distribution in Heptol 60 solutions at different asphaltene initial concentrations of 500, 1000, and 2000 mg/L and 298 K.

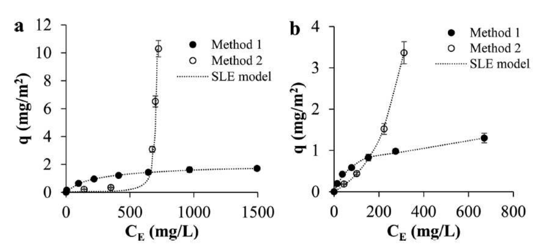


**Figure 6.** Adsorption isotherms for AspB adsorption onto (a) SS and (b) CM nanoparticles constructed through methods 1 ($M$ = 10 g/L) and 2 ($C_i$ = 1000 mg/L) at 298 K.

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I&EC research
Industrial & Engineering Chemistry Research
Ind. Eng. Chem. Res. 2015, 54, 8201−8211
Article
pubs.acs.org/IECR

# Development of a Population Balance Model to Describe the Influence of Shear and Nanoparticles on the Aggregation and Fragmentation of Asphaltene Aggregates

Nashaat N. Nassar,[*,†] Stefania Betancur,[‡] Sócrates Acevedo,[§] Camilo A. Franco,[‡] and Farid B. Cortés[*,‡]

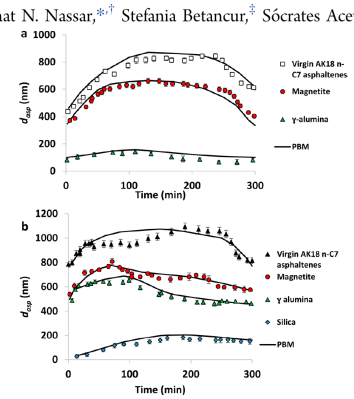



**Figure 5.** Kinetics of asphaltenes aggregation-fragmentation in the presence of nanoparticles for (a) heptol 20 and (b) heptol 40 at 293 K. The symbols are experimental data, and the solid lines are from the PBM model (see eq 3).

$$\frac{dn_i}{dt} = \frac{1}{2}\sum_{j+k=i} \alpha\beta_{jk}(V_j, V_k)n_jn_k - n_i\sum_{k=1}^{n_{max}} \alpha\beta_{ki}(V_k, V_i)n_k - B_in_i + \sum_{j=i+1}^{n_{max}} \gamma_{i,j}B_jn_j - \frac{dq}{dt} \qquad (3)$$

where $n_i$ is the number concentration of aggregates with size $i$ that contains $i$ primary particles and $n_{max}$ is the maximum size of the particles that will form fragments of size $i$ before fragmentation. In eq 3 from right to left, the first term defines the adsorption kinetics on the nanoparticle, the second and fifth terms define the formation of $i$-sized particles, and the third and fourth terms account for the disappearance of particles of size $i$. $\beta_{jk}$ is the collision frequency between particles of volume $V_j$ and $V_k$ due to Brownian motion and fluid shear, as expressed in eq 4:[16,76,77]

$$B_{jk} = \frac{2}{3}\frac{K_BT}{\mu}\left(\frac{d_i - d_j}{d_id_j}\right)^2 + \frac{G}{6}(d_i + d_j)^3 \qquad (4)$$



energy&fuels
Energy Fuels 2013, 27, 2899−2907
Article
pubs.acs.org/EF

# Nanoparticles for Inhibition of Asphaltenes Damage: Adsorption Study and Displacement Test on Porous Media

Camilo A. Franco,[†] Nashaat N. Nassar,[‡,§] Marco A. Ruiz,[†] Pedro Pereira-Almao,[‡] and Farid B. Cortés[*,†]

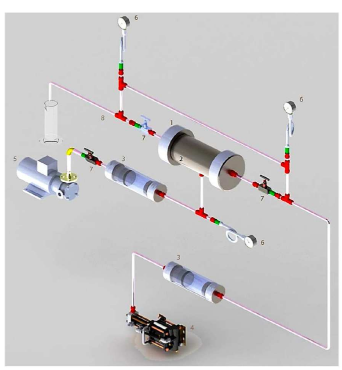


**Figure 2.** Schematic representation of the experimental setup. Legend: (1) the core holder, (2) the sand packed bed, (3) the displacement cylinder, (4) the displacement positive pump, (5) the mineral oil pump, (6) the pressure transducers, (7) the valves, and (8) sample output.

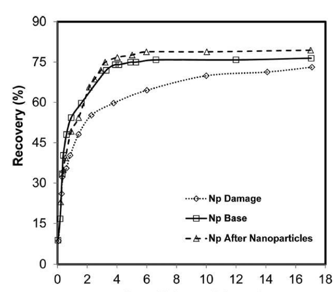
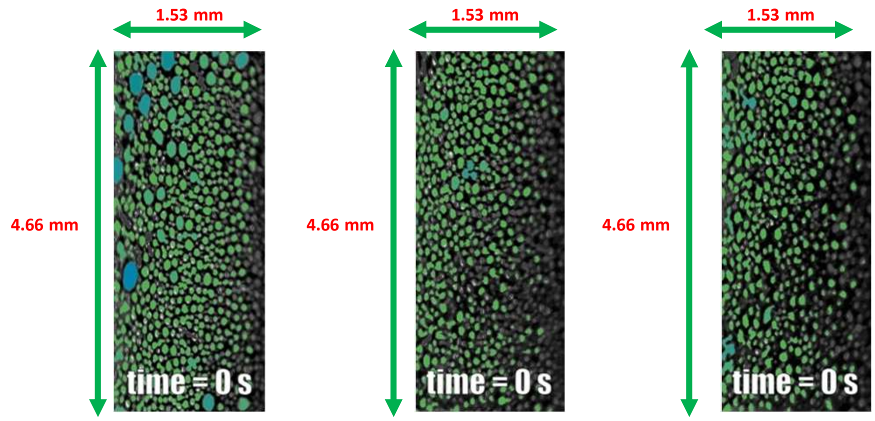



**Figure 5.** Recovery curves for (1) the base system; (2) the system after nanoparticle injection (where 0.5 PV of nanofluids was injected simultaneously with crude oil, followed by injection of 0.5 PV of $n$-heptane); and (3) the damaged system (where 0.5 PV of $n$-heptane was injected without the presence of nanoparticles to generate damage). Other experimental conditions include porosity, 33%; pressure, 6.9 MPa;, and temperature, 323 K.

## Foamability and Foam Stability for $CO_2$-EOR




Surfactant @ 1,500 ppm

Surfactant & nanoparticle @ 1,500, 50 ppm

Surfactant @ 3,000 ppm

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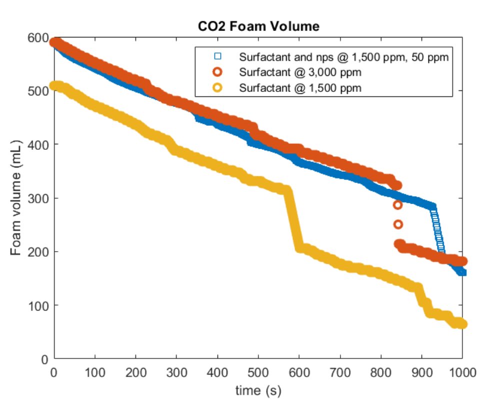
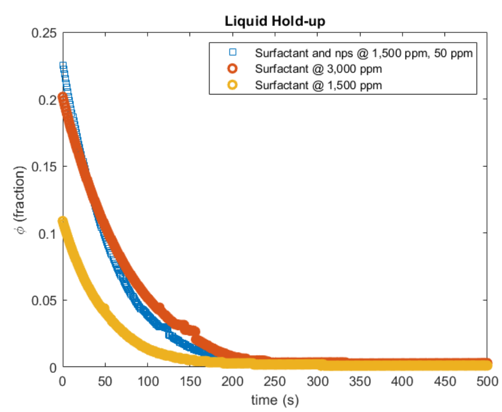
## Foamability and Foam Stability for $CO_2$-EOR




Unpublished work

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# Hydraulic Fracturing

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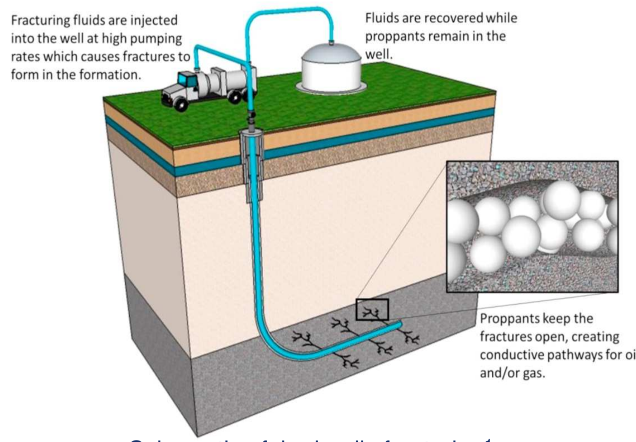
- The high flow rates (>100bbl/min) and high pressure in hydraulic fracturing results in high energy consumption and pumping power
- To mitigate these concerns, dilute concentrations of polymers (friction reducers) reduce the energy consumption, and pumping power in hydraulic fracturing by up to 80%




Schematic of hydraulic fracturing[1]

1 Polymers for proppants used in hydraulic fracturing, Pangilinan et al (2016); copyright © 2016 Elsevier B.V

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# Drag Reduction

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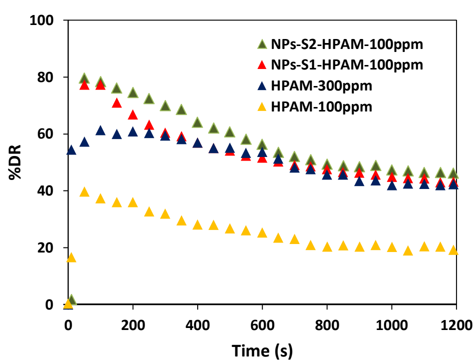
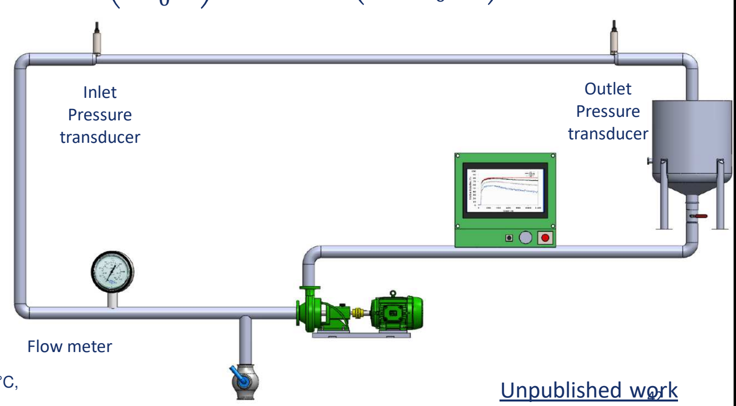



$$FR\% = \left(\frac{f_0 - f_1}{f_0}\right) \times 100 = \left(\frac{\Delta P_0 - \Delta P_1}{\Delta P_0}\right) \times 100$$

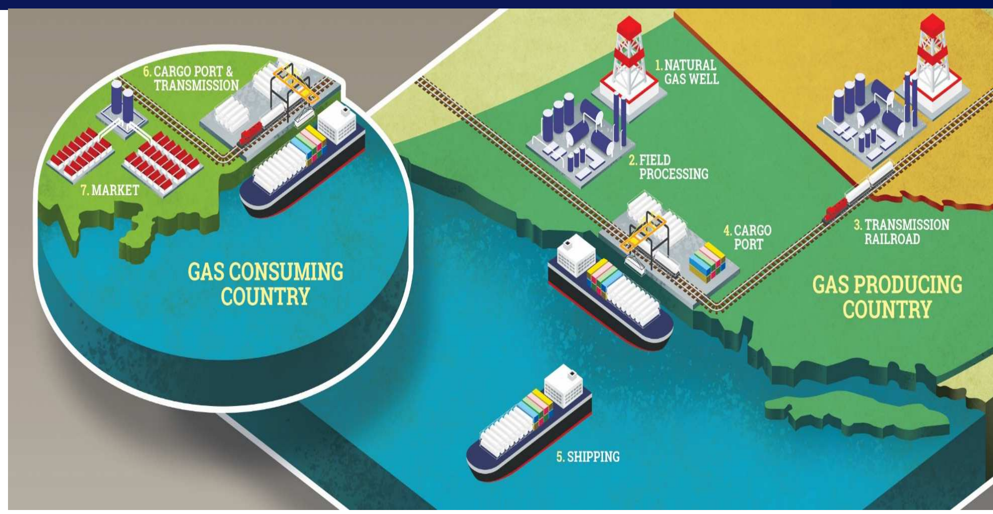



All flow loop experiments were performed at ~25°C, 80L/min (Re=~105538), and a 0.709" ID pipe

Unpublished work

# Small Scale LNG Value Chain

Webinars

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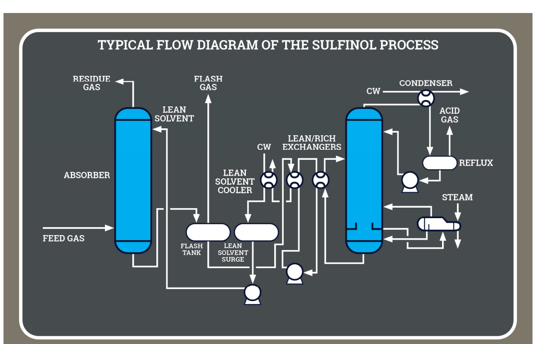
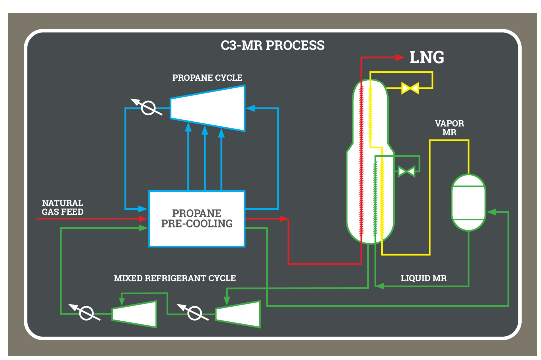
# LNG Production Unit

Webinars

- Any LNG production plant comprised two main sections;
  - Natural Gas Purification
  - Natural Gas Liquefaction

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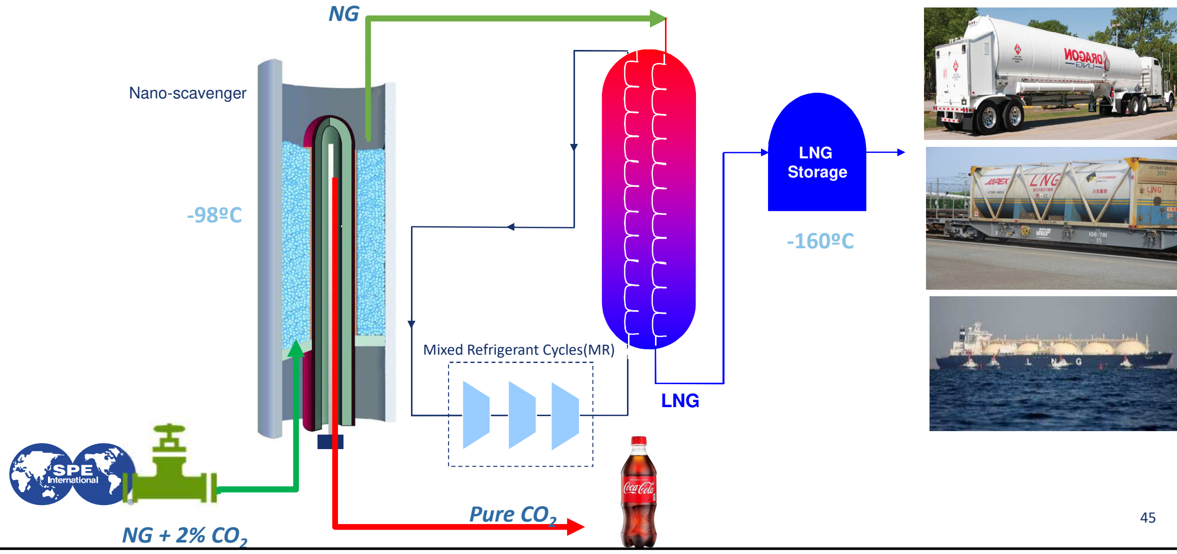
## NG to LNG

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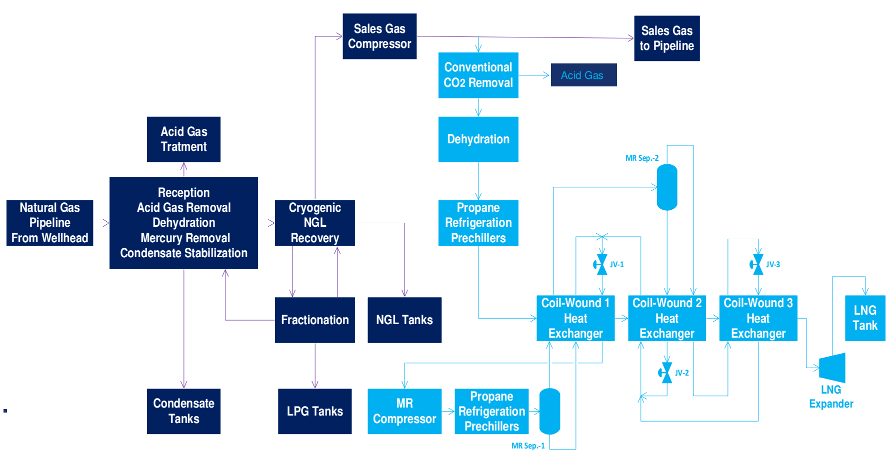
## Conventional Technology – Non-Integrated LNG Production Unit

- The blue process blocks are representation of a conventional LNG production, classical Amine Treating and Dehydration process in purification section and C3-MR process in liquefaction section.

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# Split Flow Integrated LNG Production Unit (SFI-LNG)

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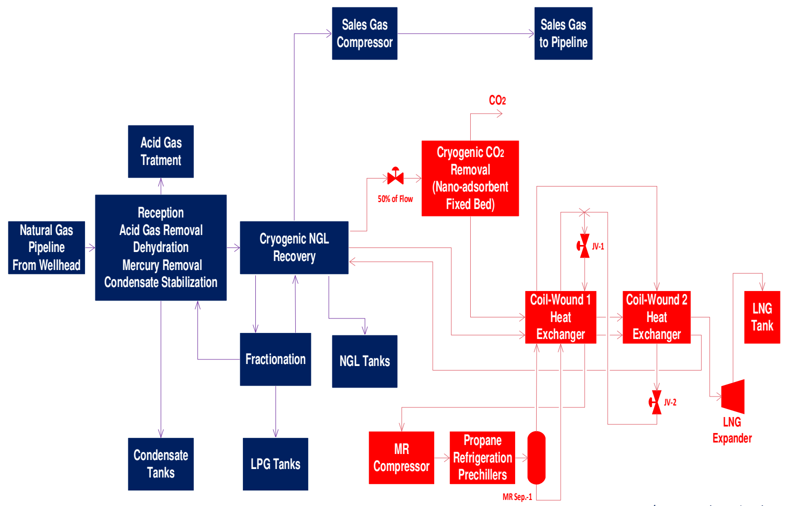
- Red process boxes represent the SFI-LNG process, a new Cryogenic $CO_2$ Removal process in purification section and Semi-C3-MR process in liquefaction section.




USA Patent, No. 62/636,385 (Pending) 7

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# SFI-LNG Cryogenic $CO_2$ Removal

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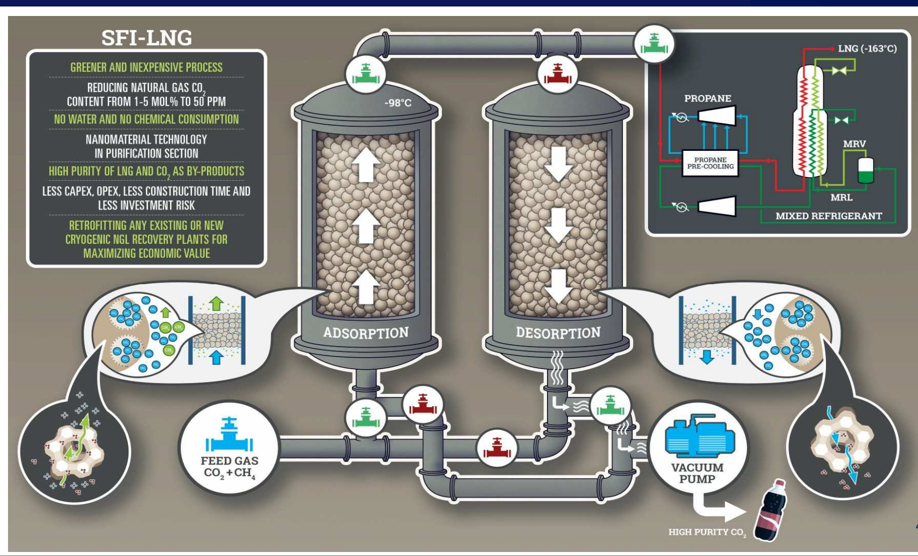


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# Results – Lead Adsorbent

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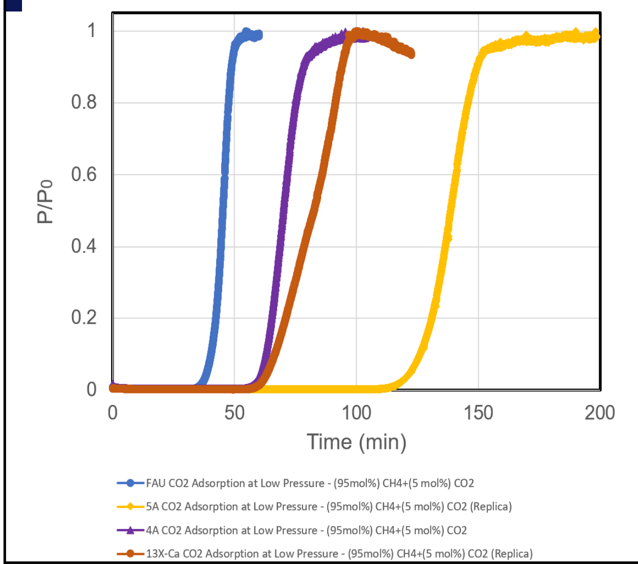


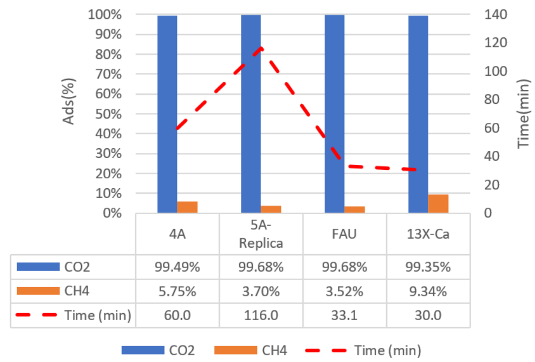


| | 4A | 5A-Replica | FAU | 13X-Ca |
|---|---|---|---|---|
| CO2 | 99.49% | 99.68% | 99.68% | 99.35% |
| CH4 | 5.75% | 3.70% | 3.52% | 9.34% |
| Time (min) | 60.0 | 116.0 | 33.1 | 30.0 |

Adsorption % at break point on 4A, 5A, FAU, 13X-Ca at Low-Pressure and High-Concentration

Unpublished work

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# NG to DME

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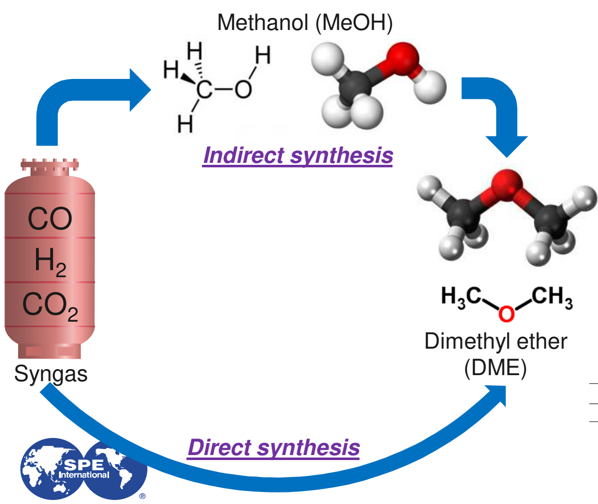


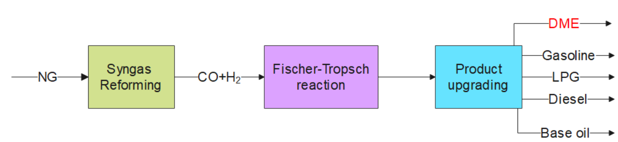


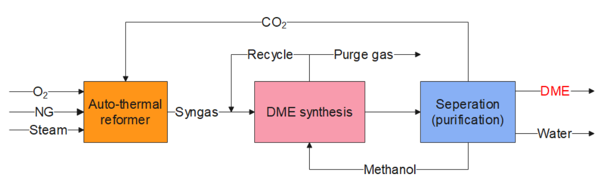


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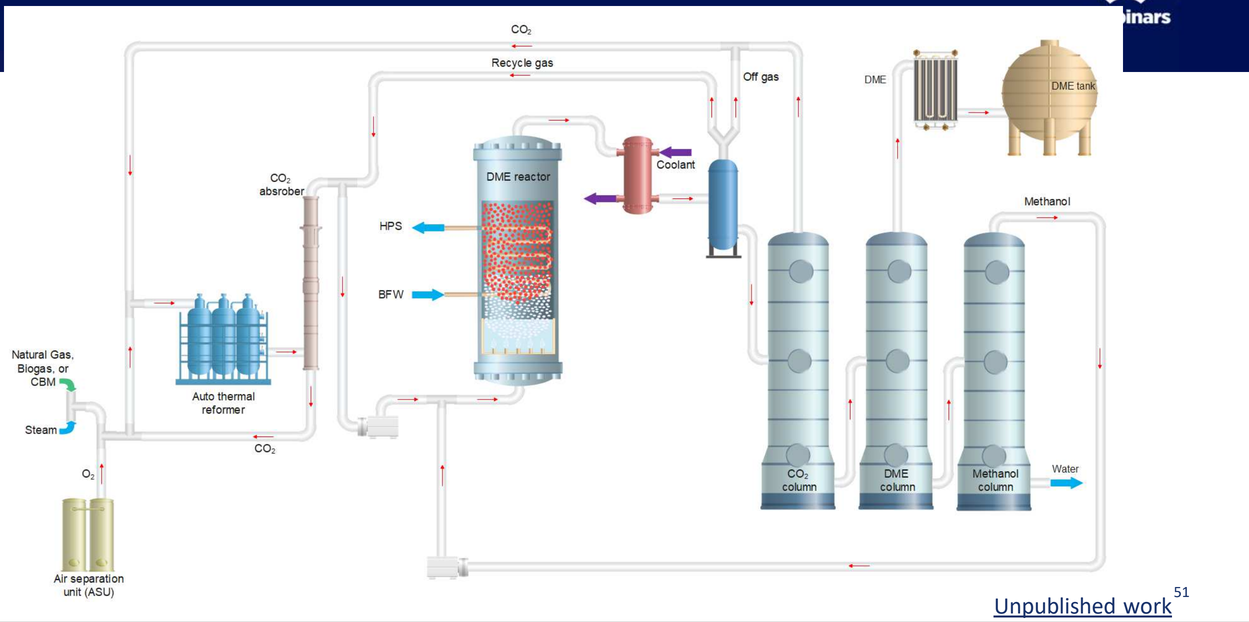
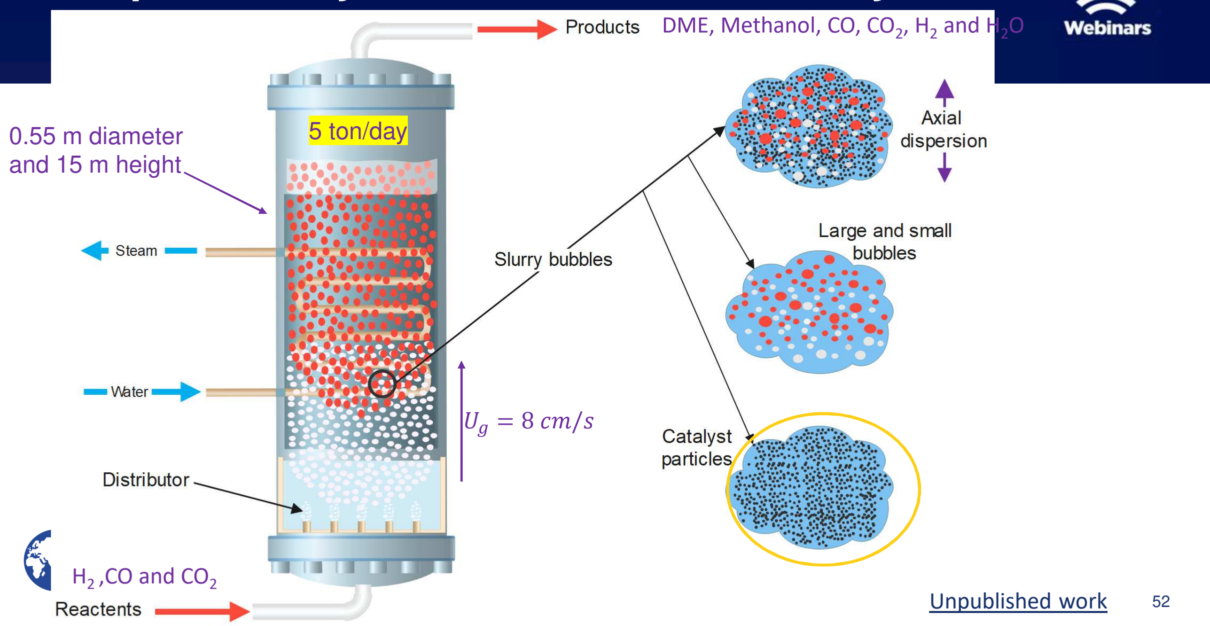
# Process Flow Diagram – 5 metric ton/d DME




Unpublished work 51

# Concept of slurry reactor for direct DME synthesis

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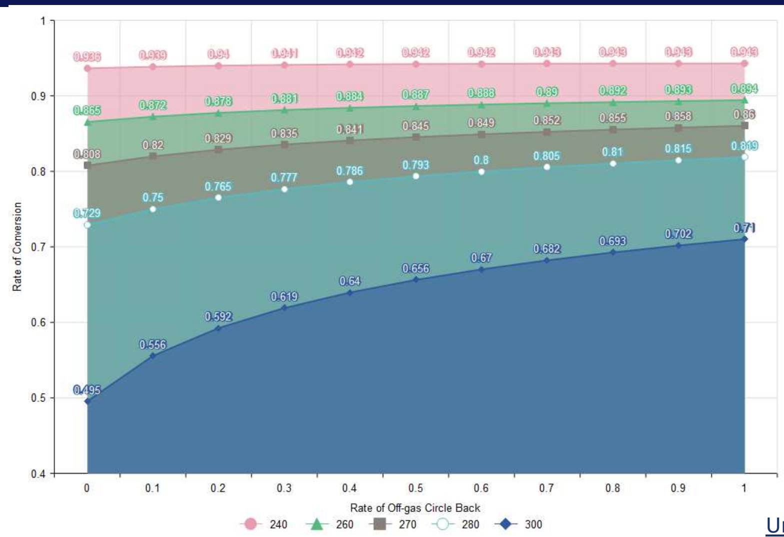
# Rate of Conversion of CO at 50bar

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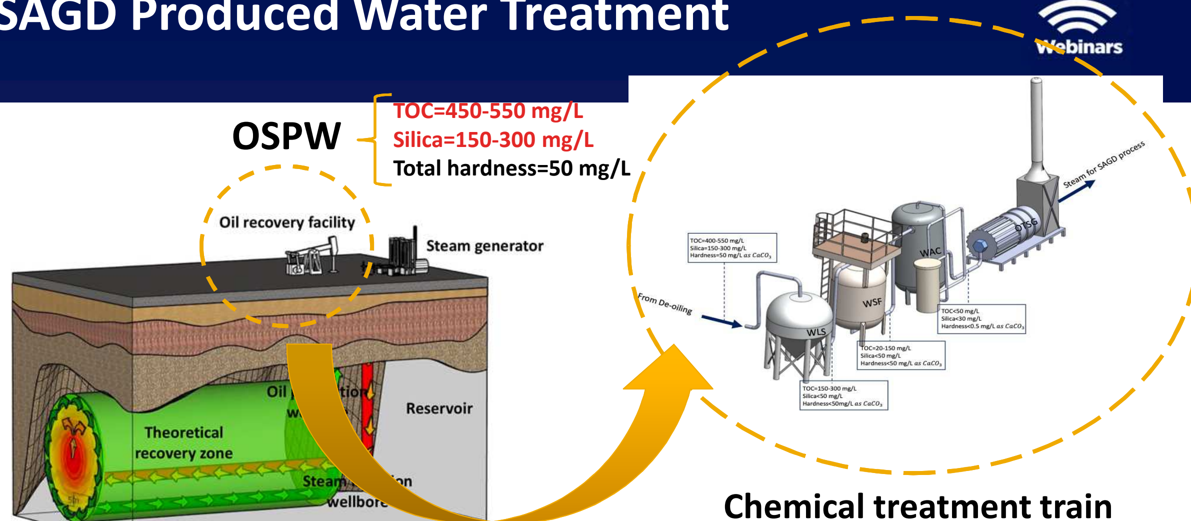
# SAGD Produced Water Treatment

OSPW
TOC=450-550 mg/L
Silica=150-300 mg/L
Total hardness=50 mg/L




SAGD process

Chemical treatment train (Conventional technology)

Hethnawi et al (2021). *Journal of Water Process Engineering, 43*, 102016. 54

# SAGD produced water Treatment

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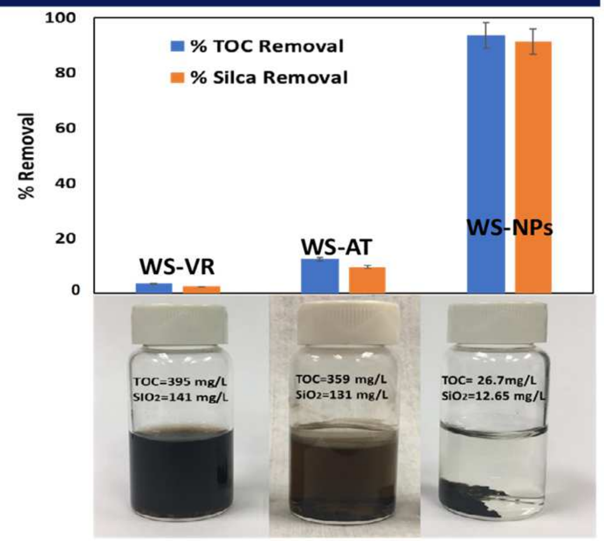


Patent No PCT/CA2021/050255 (Pending)

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# Oil Sands Tailings

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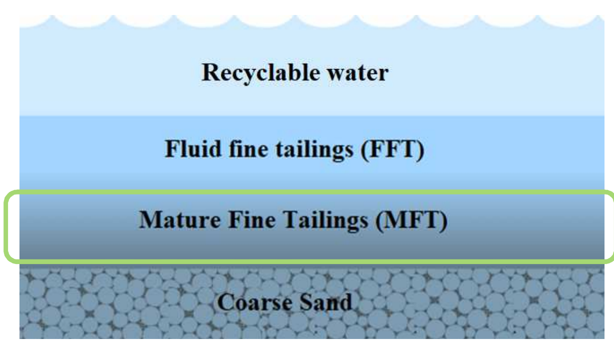


- Tailings ponds currently cover over 220 km$^2$ of land in Alberta.
- Tailings contain toxic materials such as naphthenic acids, phenolic compounds and ammonia.

**Mature Fine Tailing (MFT):**
- Water: ~ 60%
- Solid content: 35 - 40%
- Residual bitumen: 1- 3%

**Image courtesy:** https://www.oilsandsmagazine.com

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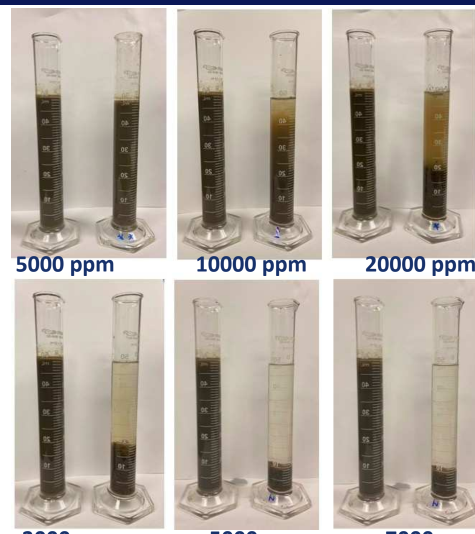
## Enhanced Settling and Dewatering of MFT



**Commercially anionic PAM (CAP)**

**Nanoflocculant**






Patent No. 63/231,083 (Pending)

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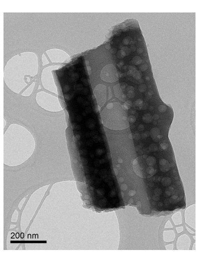
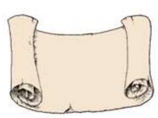
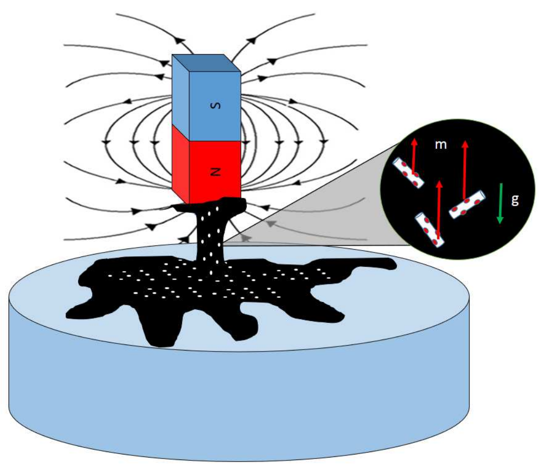
## Nano-scrolls: Oil spill cleanup





| Material | Oil absorption capacity (own weight ratio g/g) |
|---|---|
| Magnetic particles 100% (Bulk) | 15 |
| Magnetic nanoparticles 100% (5 nm) | 20 |
| Magnetic hydrophobic scrolls<br>• Nano-Magnetite 5%<br>• Hydrophobic scrolls 95% | 53 |




ACS Appl. Nano Mater. 2018, 1, 4491–4501
Ind. Eng. Chem. Res. 2018, 57, 13065–13076

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## β-CD Grafted nanopyroxenes for industrial wastewater treatment

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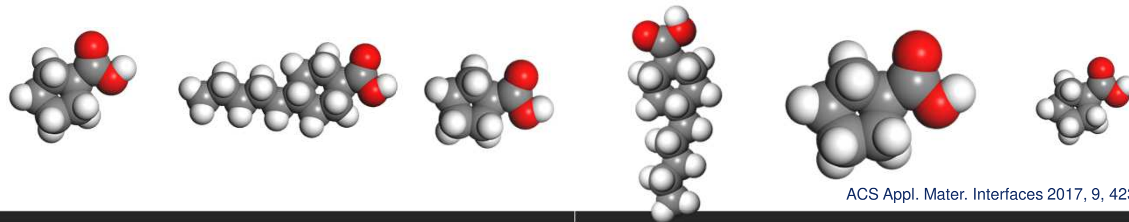
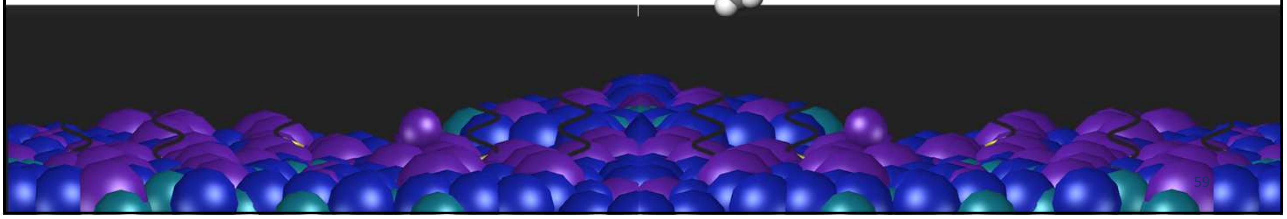
Oil & Gas Industry

Pharmaceuticals Industry



ACS Appl. Mater. Interfaces 2017, 9, 42393–42407



## NanoSoln Inc.: Increasing process efficiency for industrial wastewater treatment.

NANOSOLN

# NanoSoln Inc

Webinars

### NanoFlocculant

**Key Benefits:**

1. >50% Chemical Savings
2. >35% Cost Savings
3. <30 mins for particle settling & dewatering vs 1-2 days
4. Environmentally Friendly

### NanoSorbent

**Key Benefits:**

1. >60% Chemical Savings
2. >57% Cost Savings
3. Area of Implementation:
   - Textile wastewater
   - Tanneries wastewater
   - Carpet Manufacturer

### NanoFilters

**Key Benefits:**

1. >50% Chemical Savings
2. >35% Cost Savings
3. Area of Implementation:
   - O&G: Disposal Water
   - O&G: Produced Water
   - Mining: Lithium Brine

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NANOSOLN

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# Oxy-Cracking: A new technique for converting waste hydrocarbon into valuable product

Webinars

Complex organics → Soluble organics → Organic acids

Hydrolysis

Acetogenesis

Carbohydrates
Proteins

Glucose
Amino Acids

Humic analog

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## Oxy-Cracking a new technique for converting waste hydrocarbon into valuable product

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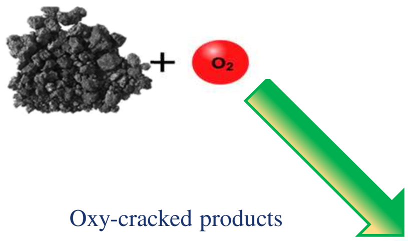
- The global production is150 million metric tons per annum.
- 70% in North America alone.
- 100 MT was stockpiled in Alberta 2016.




Oxy-cracked products

Solid phase

Liquid phase

K Fe Co S Ni V Mo

Minerals Recovery

Humic Acids (Fertilizer)

- Increased Nutrient Uptake
- Decreased Toxins
- Increased Water Retention

ECO FRIENDLY

USA Patent No. S 10,883,060 B2
React. Chem. Eng., 2017, 703-719
Fuel, 2018, 215, 865–878

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## Carbon OxyTech Inc.

A scientific-based technology that provides highly effective and sustainable solution to convert carbon-based materials into valuable products.

Dedicated to providing more convenient, flexible, and cost-effective solution in the fields of agriculture and the environment.

Carbon OxyTech

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# Take-home message

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- Nanoparticle is an enabling technology not a stand alone one
- Success = Nanomaterials + Process integration =
- Naturally-derived nanomaterials can be the best choice for oncethrough process
- Process modeling and scale up provide great ideas for field testing and commercialization
- Process and cost limits exist
- Nanoparticles are for process improvement

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# Acknowledgements

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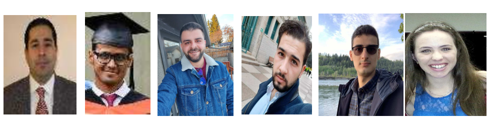
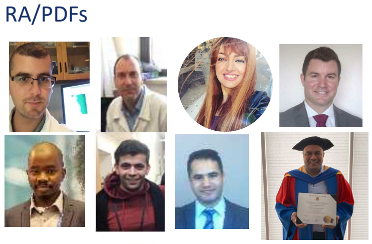
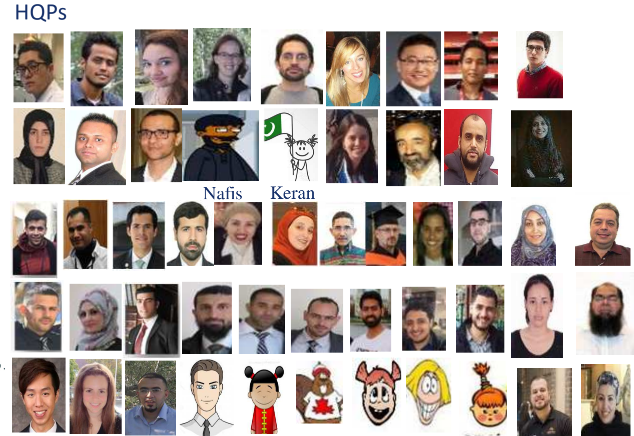
Grad students



RA/PDFs



HQPs

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