ALBERTA INNOVATES

IN SITU SOLVENT ASSISTED AND SOLVENT-BASED RECOVERY: WORKSHOP 1

SOLVENT LEADERSHIP SERIES

May 26, 2017

ALBERTA INNOVATES

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Solvent Leadership Series

WORKSHOP 1: IN SITU SOLVENT ASSISTED AND SOLVENT-BASED RECOVERY

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

Join Alberta Innovates in collaboration with COSIA for a "deep dive" on perspectives from the research community on the role of solvents in recovery of in situ bitumen resources. This session is intended to connect industry players with some of the recent advances and outcomes from experimental, analytical and numerical research programs that can be useful in taking solvent pilots and demonstrations to the next level.

This session is limited to 20 participants.

AGENDA

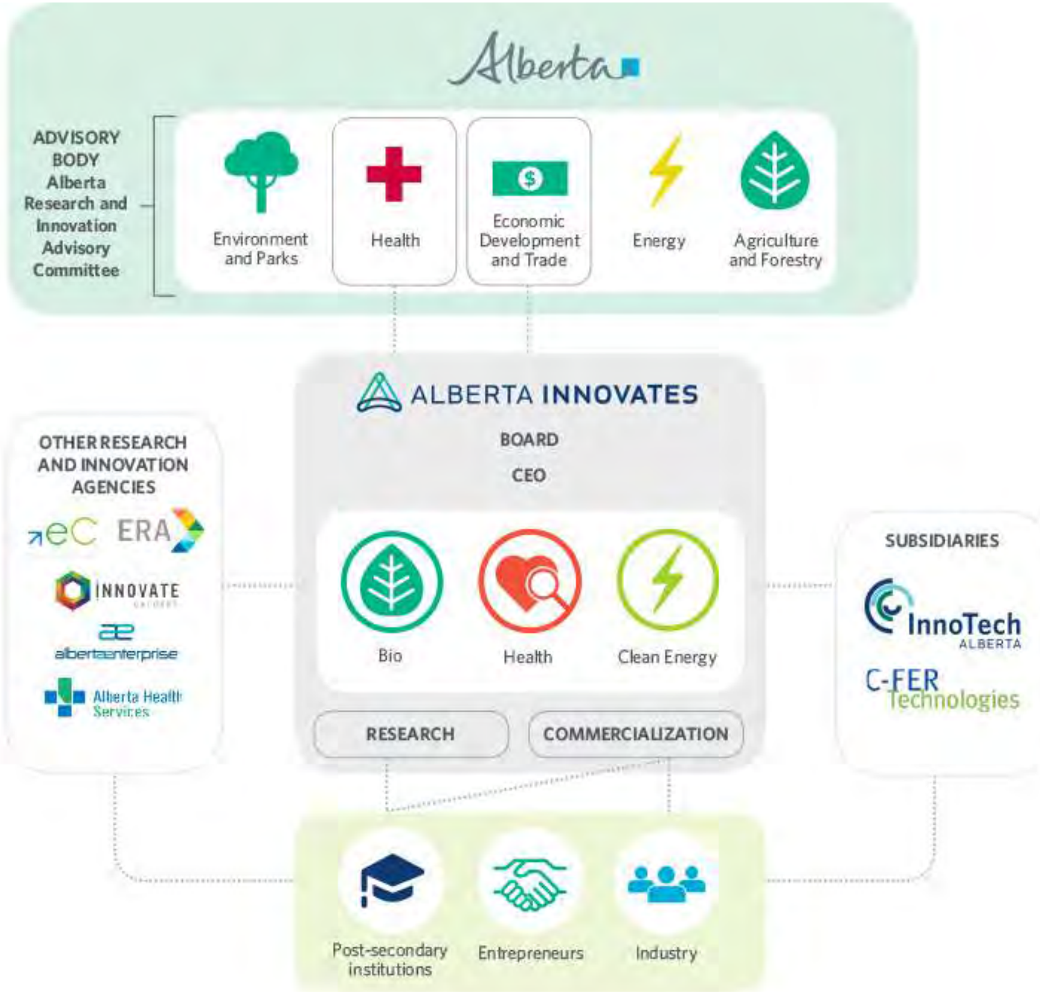
	Sign in and Coffee	8:45 to 9:00 a.m.
1.	Welcome remarks - John Zhou, VP, Clean Energy and Candice Paton, Director, Recovery technologies	9:00 to 9:15 a.m.
2.	Key Presenter: John Shaw – University of Alberta NSERC IRC in Petroleum Thermodynamics. Phase behaviour and transport properties of bitumen and heavy oil + solvent mixtures.	9:15 to 10:15 a.m.
3.	Key Presenter: John Chen – University of Calgary NSERC Foundation CMG IRC in Reservoir Modelling. Advanced steam-additive recovery processes for oil sands	10:15 to 11:15 a.m.
	Coffee Break	11:15 to 11:30 a.m.
4.	Key Presenter: Haibo Huang - Director, AACI Research Program. Linking technology development and field piloting	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.

CLEAN ENERGY

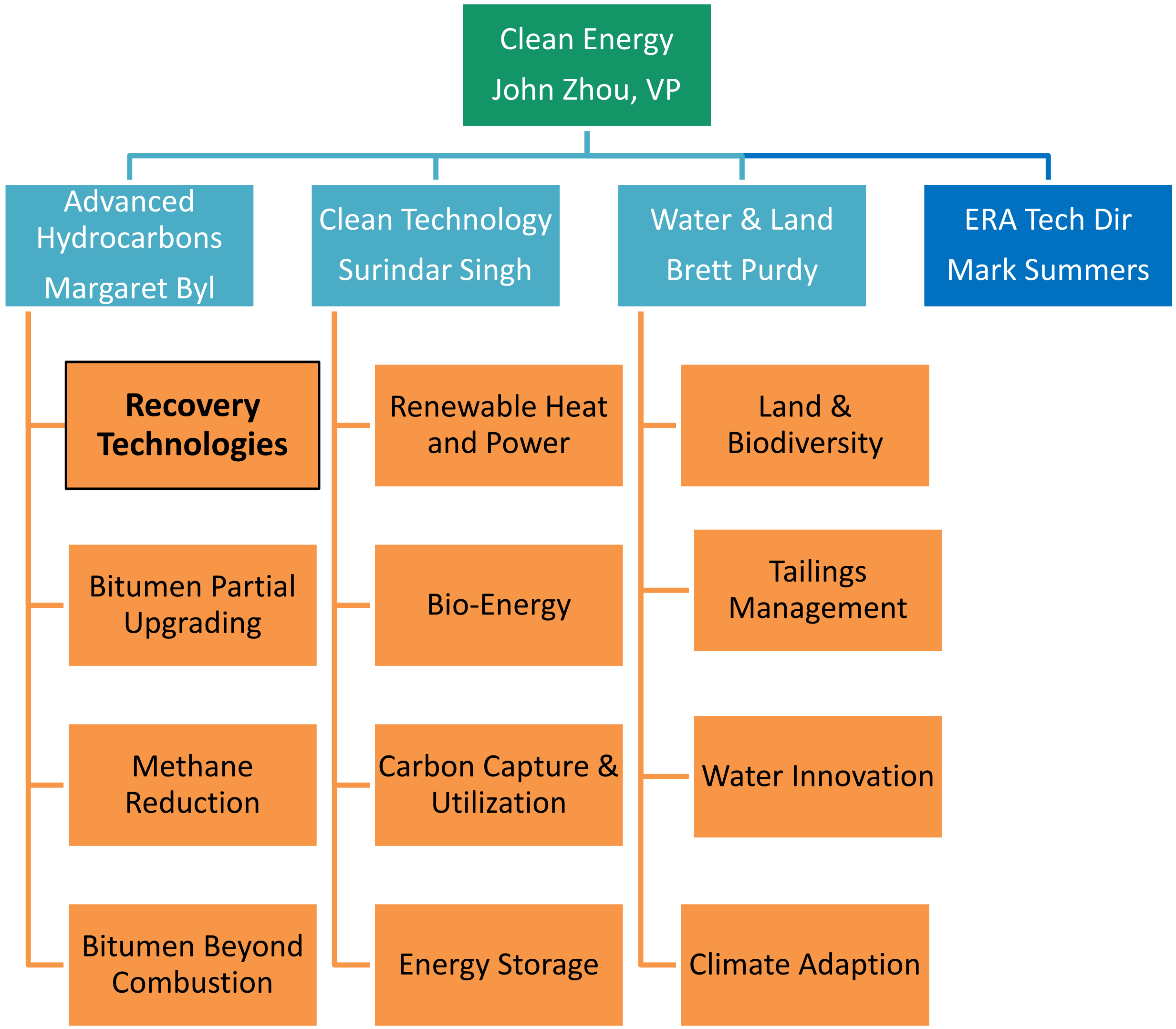
Margaret Byl
Executive Director, Advanced Hydrocarbons

Alberta's Research and Innovation System

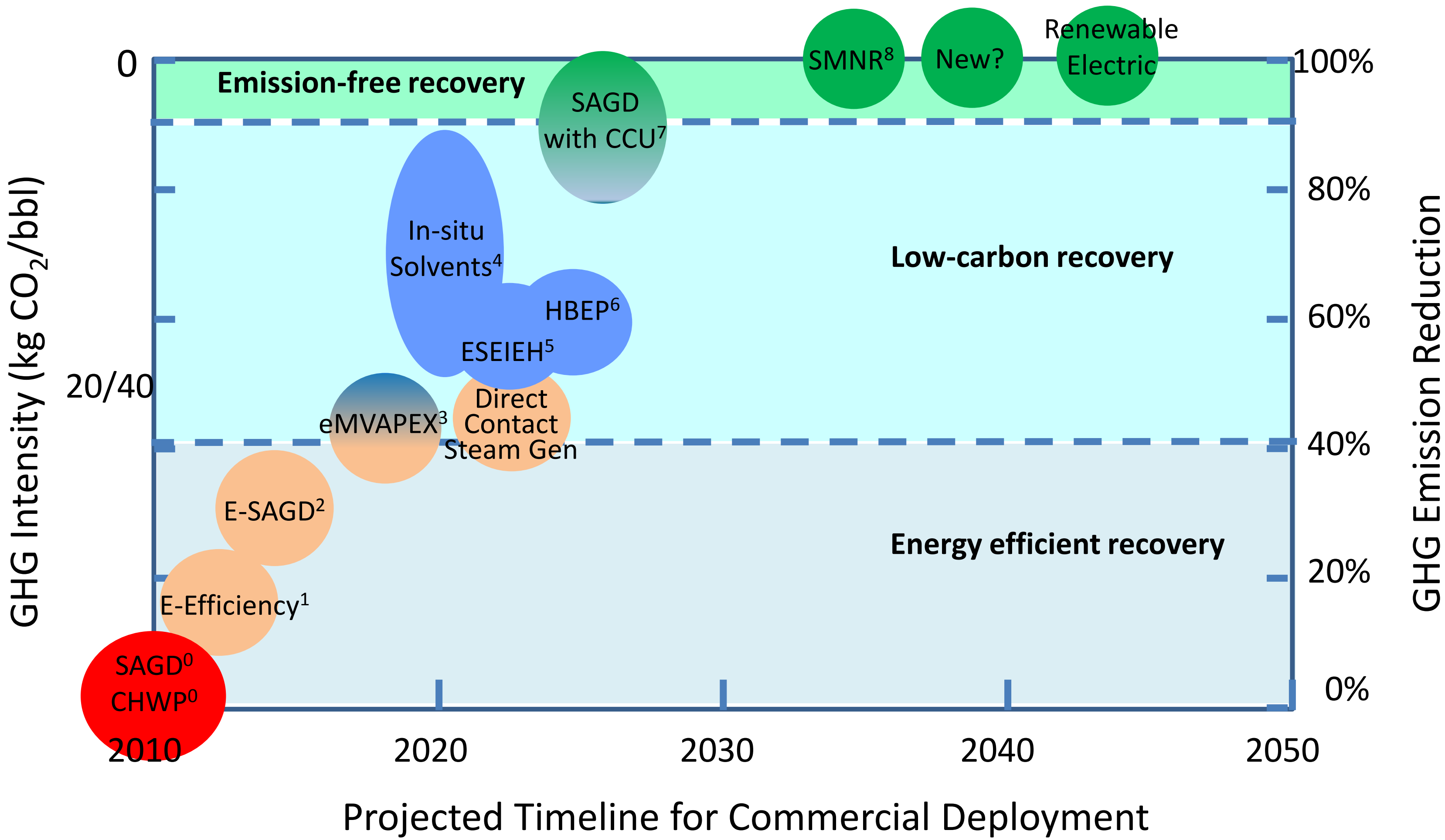
Working together – Cross-Ministry & Cross-Sector



Clean Energy: CORE PROGRAM AREAS



Recovery Technologies (AB's oil: cost & carbon competitive)



[0] SAGD: Steam assisted gravity drainage; CHWP: Clark hot water process; [1]Efficient H_2O treatment, heat recovery, infills, etc.; [2]Various solvent-assisted SAGD processes, and eMSAGP; [3]Enhanced modified VAPour EXtraction (AER 2016); [4]Pure solvent processes: N-Solv, CSP, etc.; [5]Enhanced Solvent Extraction Incorporating Electromagnetic Heating; [6]HBEP = Hybrid bitumen extraction process (surface mining); [7]SAGD with carbon capture and utilization; [8]Small modular nuclear reactors

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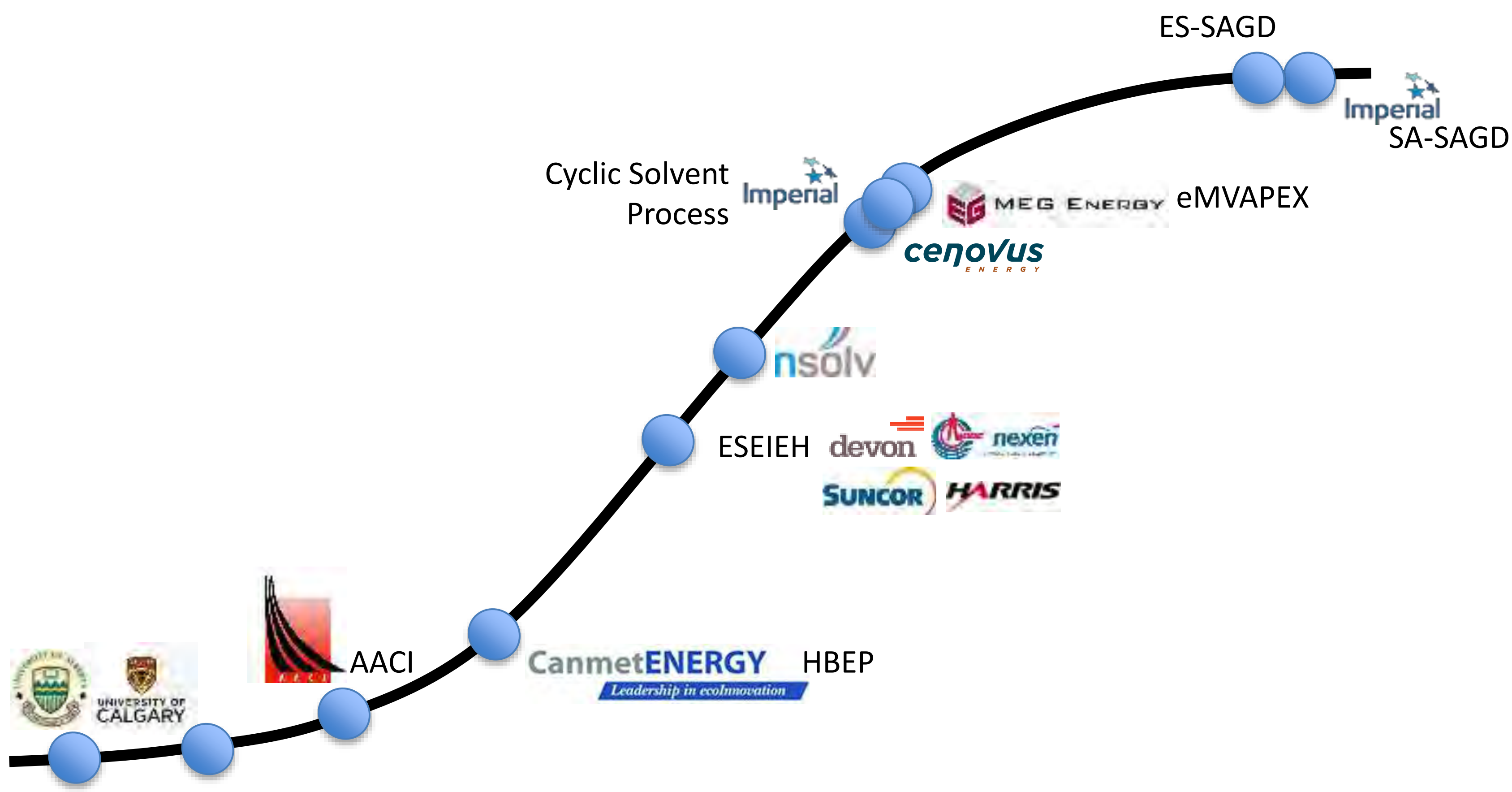
EMISSIONS REDUCTION ALBERTA

Recovery Technologies: SOLVENTS

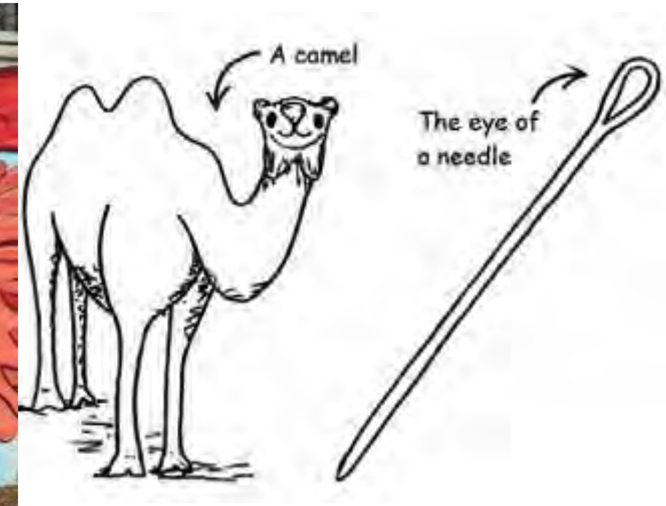
R & D → **Piloting** → **Demonstration** → **Commercial**

* Illustrative for Selected Technologies



ALBERTA INNOVATES

EMISSIONS REDUCTION ALBERTA



Phase Behaviour and Transport Properties of Bitumen and Heavy Oil + Solvent Mixtures

John M. Shaw, Ph.D., P. Eng.
NSERC Industrial Research Chair in Petroleum Thermodynamics
Department of Chemical and Materials Engineering,
University of Alberta
Contact: jmshaw@ualberta.ca
Details: www.jmshaw.ualberta.ca

AI + COSIA Workshop, May 26 2017

Acknowledgements

Colleagues

- Murray Gray, Harvey Yarranton, Kirk Michaelian, Loic Barre, Jean-Luc Daridon, Jerome Pauly, Didier Begue, Isabelle Baraille, Amy McKenna, …

Sponsors

- Natural Sciences and Engineering Research Council of Canada
- Alberta Innovates - Energy and Environment Solutions
- BP Canada
- ConocoPhillips Canada Resources Corp.
- Nexen Energy ULC
- Shell Canada Ltd.
- Total E&P Canada Ltd.
- Virtual Materials Group

Overview

1. Phase behaviour:

    Athabasca Bitumen (AB) phase diagram

    AB + diluent mixtures

    -illustrative phase diagram example AB + propane

    -density relative to water examples with heptane and toluene

    AB + hydrocarbons + water

2. Transport Properties

    Rheology of Heavy Oil

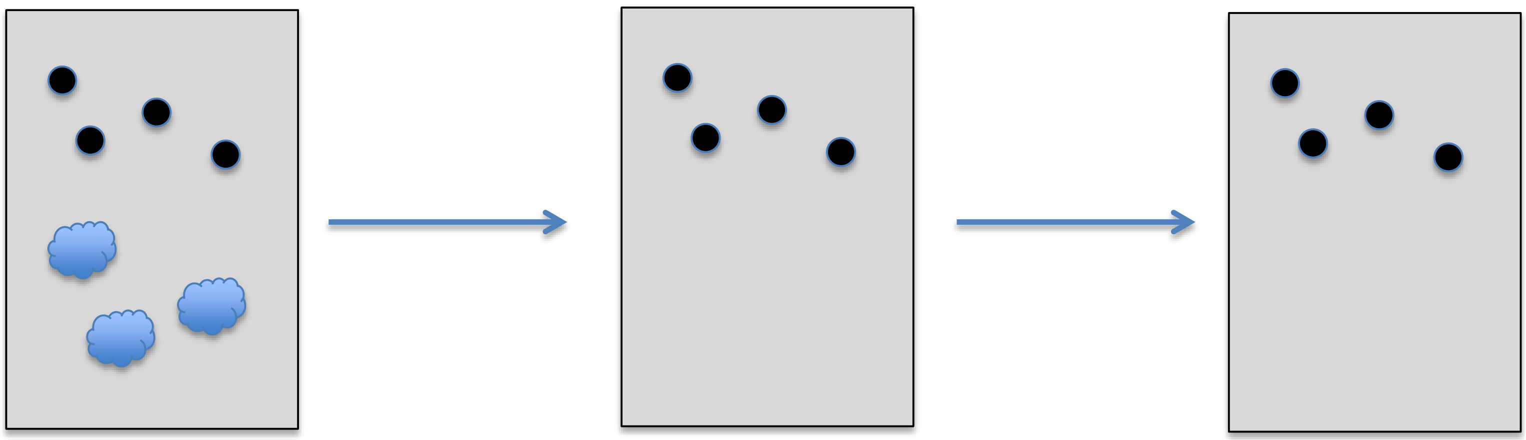
    Emulsion “viscosity”

    Mutual Diffusion in AB + hydrocarbon mixtures - mechanisms

3. Displacement of water from clay and contaminated surfaces by organic compounds

4. Mass Transfer at Bitumen + Solvent Interfaces in Reservoirs

The Phase Behaviour of Heavy Oil/Bitumen - organic constituents



T < 310 K

Liquid maltene matrix
Dispersed phases:
-Nanoscale solid C5 asphaltene-rich domains
-Solid maltene-rich domains

T ~ 310 K

Liquid maltene matrix
Dispersed phase:
-Nanoscale solid C5 asphaltene-rich domains

T ~ 420 K

Liquid maltene matrix
Dispersed phase:
-Nanoscale liquid C5 asphaltene-rich domains

Impacts: All interfacial & transport properties!

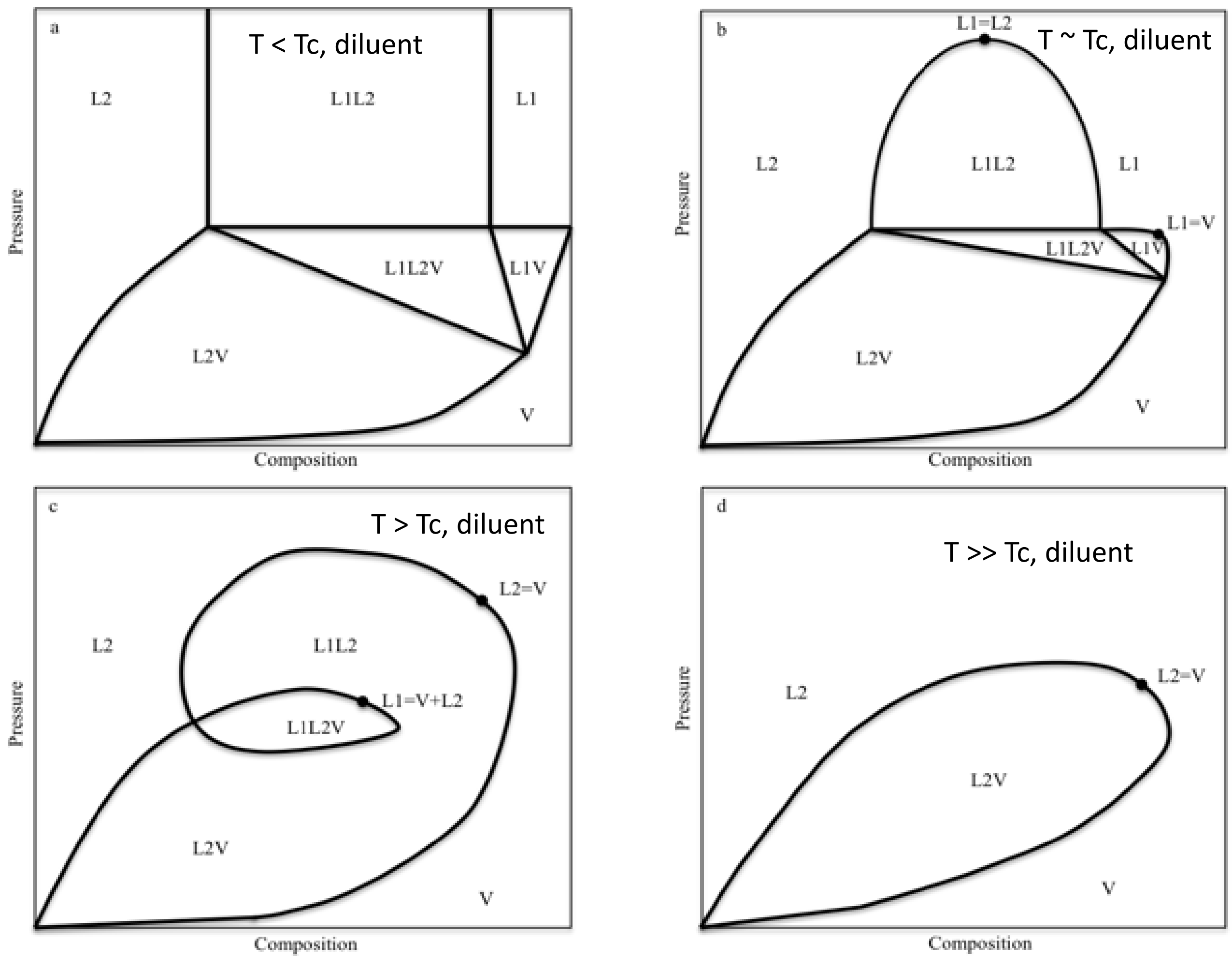
Zhao, B., Shaw, J.M. Energy & Fuels **2007**, 21, (5), 2795-2804
Zhao, B., Becerra, M., and Shaw, J.M Energy & Fuels, 2009, 23, (9), 4431-4437.
Eyssautier, J., Espina, D., Gummel, J., Levitz, P., Becerra, M., Shaw, J.M. and Barre, L., Energy & Fuels, 2012, 26(5), 2670-2687.
Bazyleva, Ala; Fulem, Michal; Becerra, Mildred; Zhao, Bei; Shaw, John M., J. Chemical & Engineering Data 2011, 56. (7) 3242-3253.
Bazyleva, Ala, Becerra, Mildred, Stratiychuk-Dear, Dmytro, Shaw, John M., Fluid Phase Equilibria, Volume 380, 2014. 28-38.
Fulem, M., Becerra, M., Hasan, A., Zhao, B., and Shaw, J.M., Fluid Phase Equilibria 272, (2008), 32-41.

Pressure-Composition Diagrams:
Bitumen + Diluent Pseudo Binary Mixtures = TYPE III

Asphaltene-rich domains are dispersed in L2

Diluent dominates the L1 composition

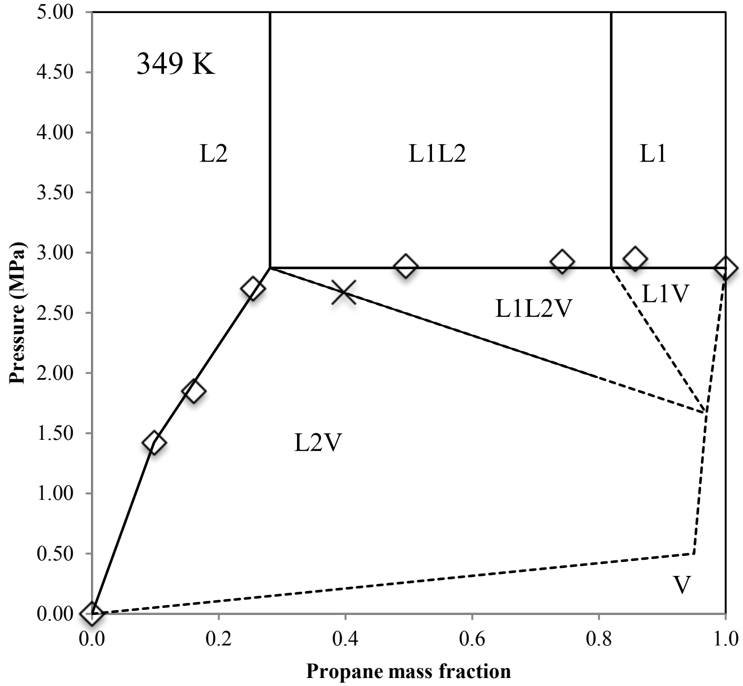
Diluent = n-alkanes, CO_2…
Tc = critical temperature diluent



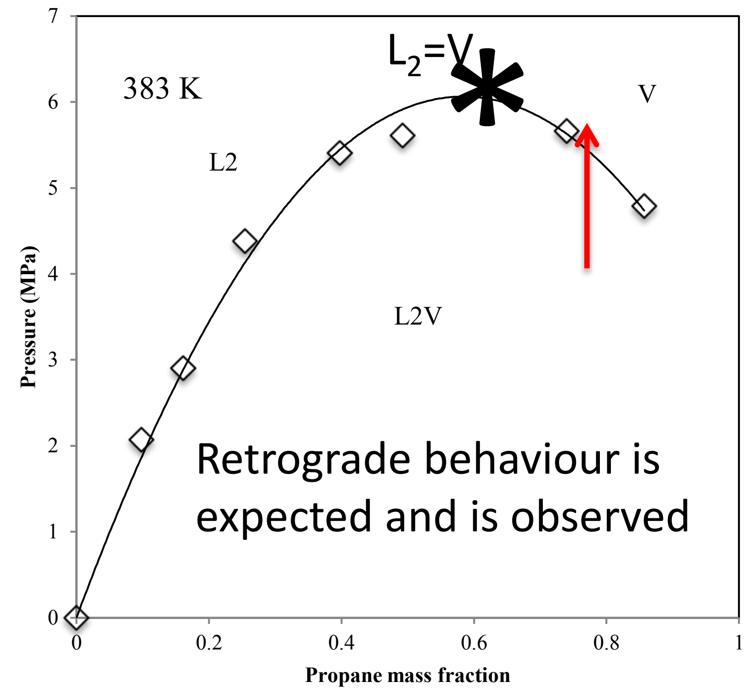
Impact: An enabling/limiting technology for production and separation

Example 1: Athabasca Bitumen + propane

$T < T_C$

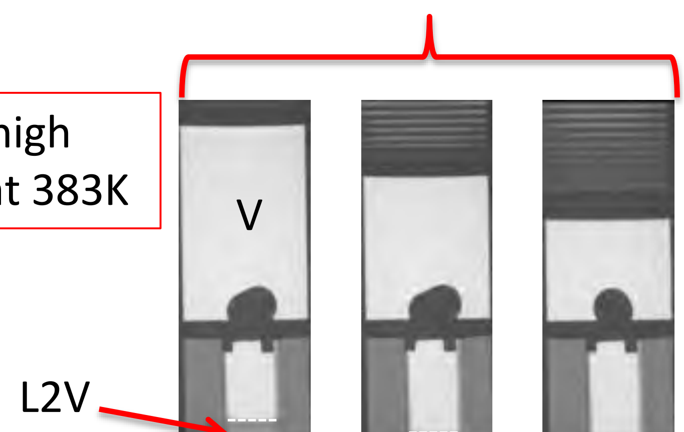


$T >> T_C$



Tc, propane = 369 K

> 30% bitumen in a high pressure gas phase at 383K



Dini, Becerra, Shaw, *J. Chem. Eng. Data*, **2016**, *61* (8), pp 2659–2668

Normalized Phase Diagrams for ***<u>ALL</u>*** Relevant Cases

Normalized Pressure is a function of diluent Pc, and acentric factor

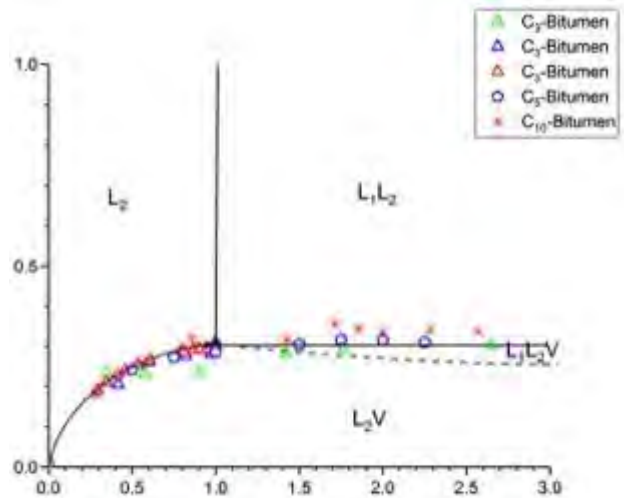
Normalized Solubility is function of diluent Tc, and Mw, UOP

Work in progress with visiting Prof. Mohammad J. Amani (Farshad)

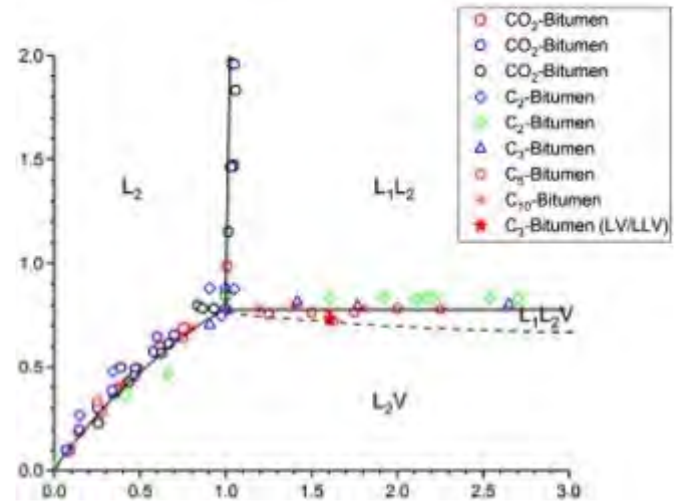
Normalized Pressure-Composition Phase Diagrams

Normalized Pressure

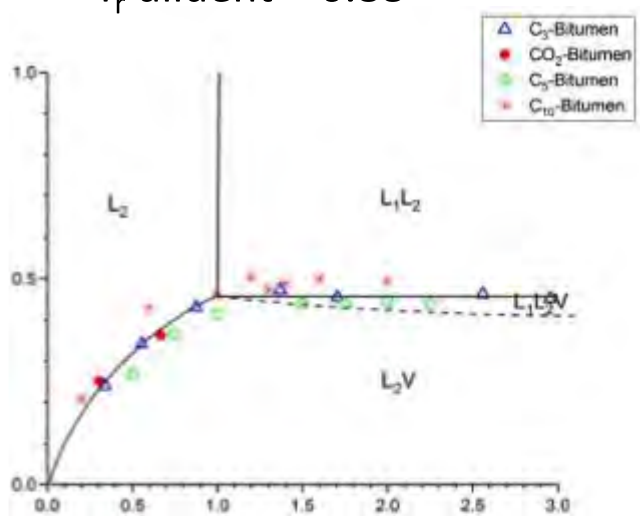
T_r diluent = 0.82



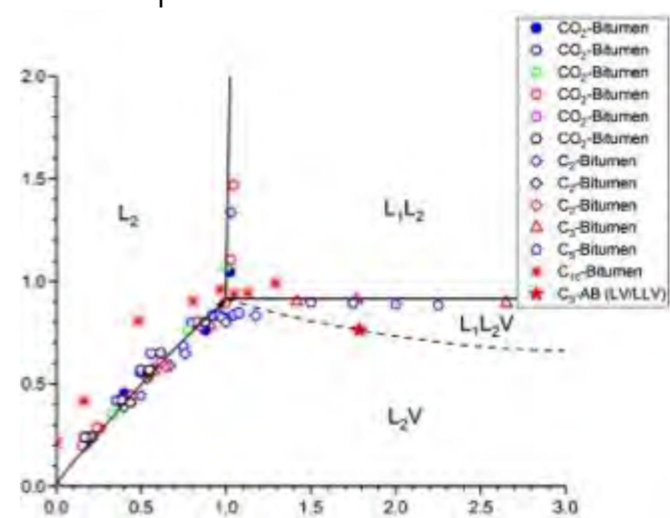
T_r diluent = 0.96



T_r diluent = 0.88

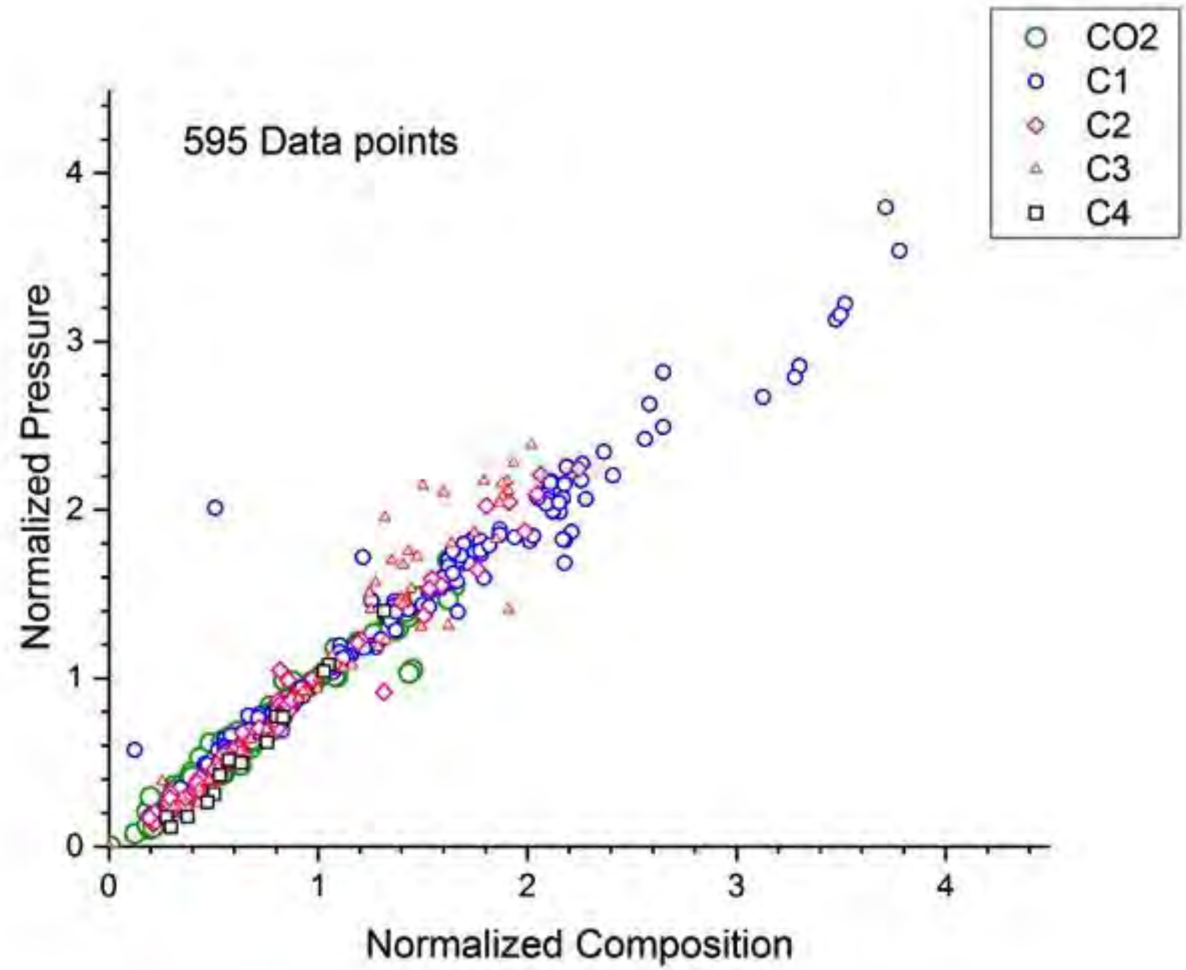


T_r diluent = 0.98



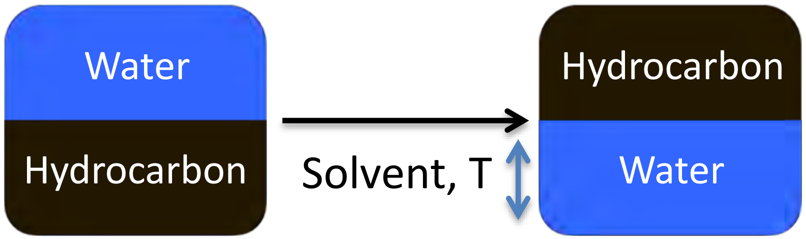
Normalized composition

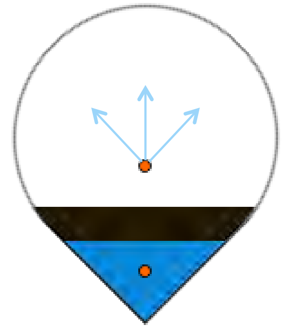
Normalized Solubility of Diluents at Temperatures Exceeding the UCEP of their mixtures with Bitumen



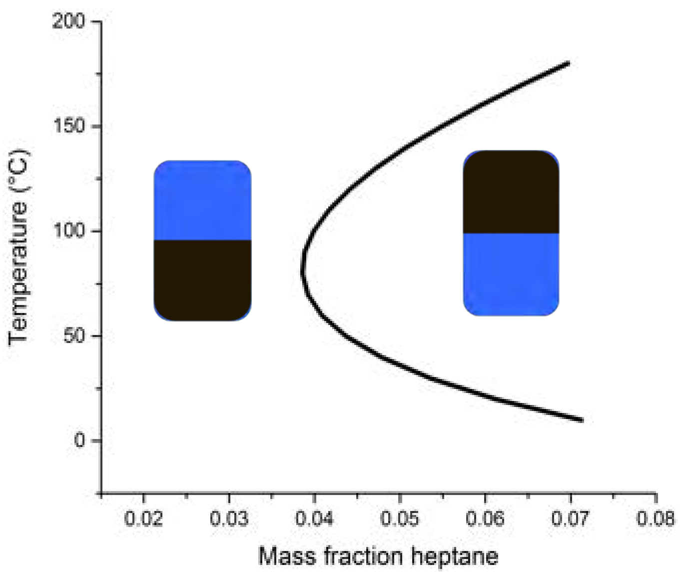
Work in progress with visiting Prof. Mohammad J. Amani (Farshad)

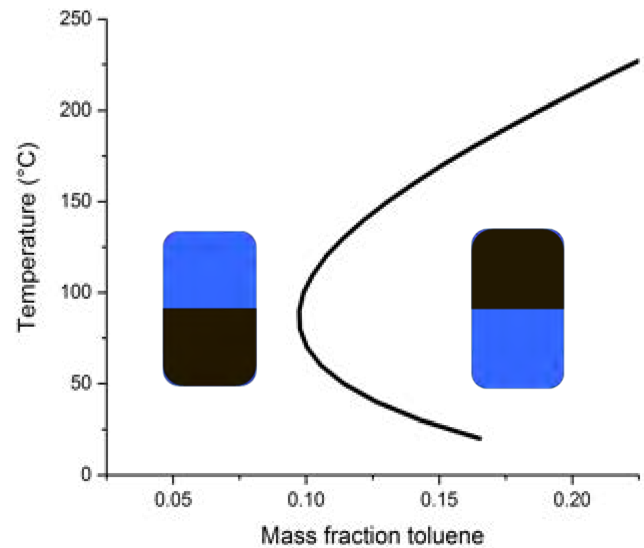
Example 2: Oil/Water Phase Order Inversion





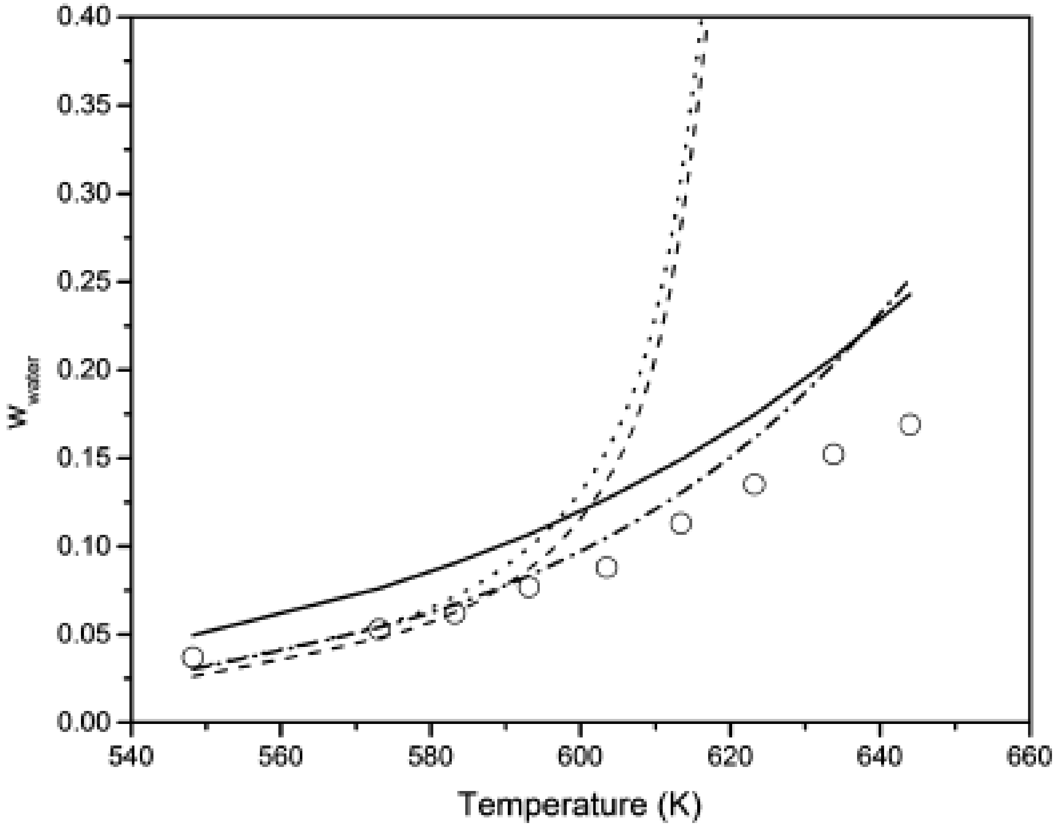
Impact: down hole design and surface separation





Stewart, Wood, Murowchuck, Shaw, [Energy & Fuels 2014, 28(7), pp 4835-4848.]

Solubility of water in Athabasca Bitumen



Heavy oils + water exhibit Type IIIb pseudo binary phase behavior. The database used to create water solubility models do not account for this.

Two new options are presented to resolve this issue.

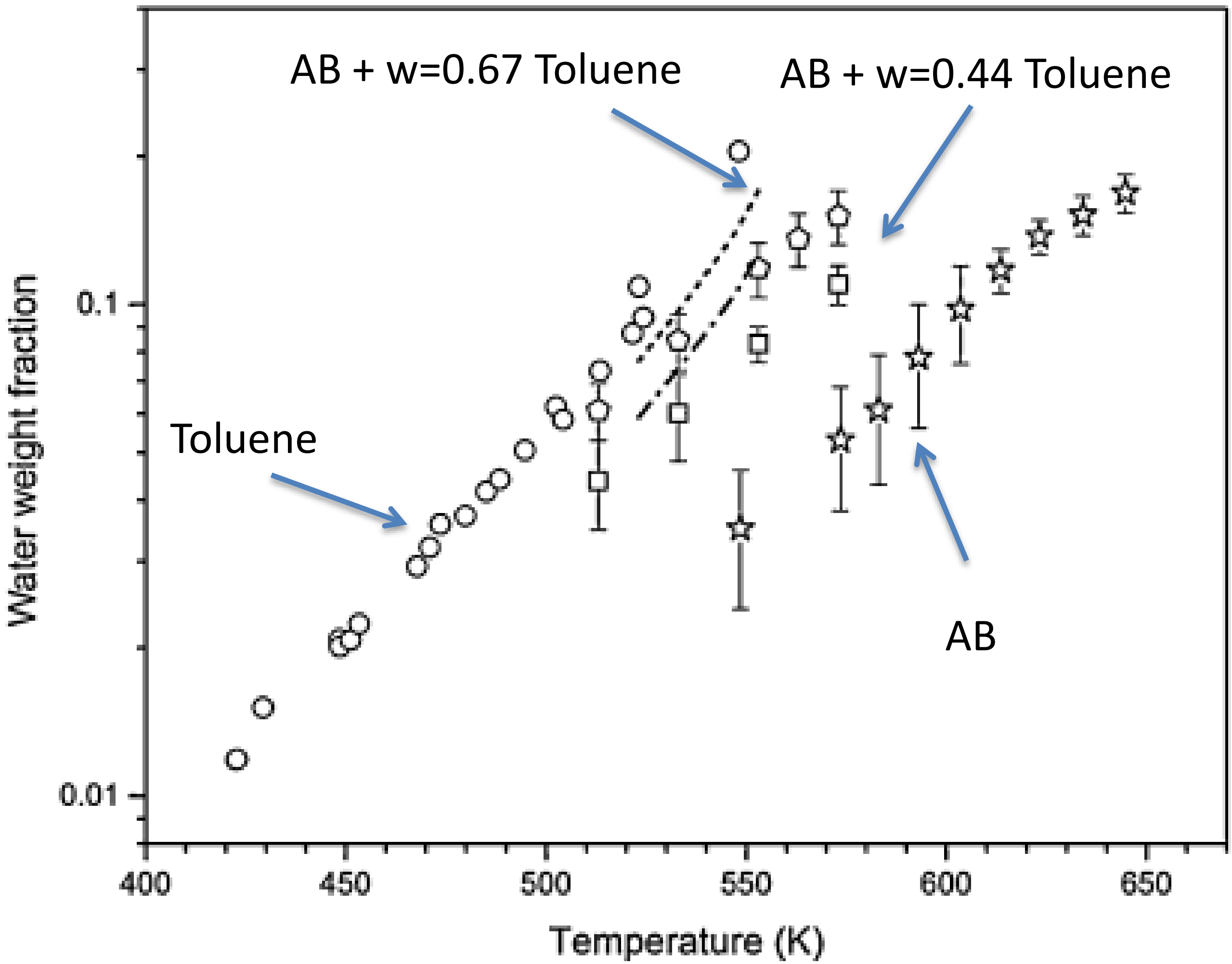
Correlation of supercritical water solubility in hydrocarbons requires further study.

Amani, Gray, Shaw,
Fuel 2014, 134(0), pp 644-658.

Impact: standard solubility correlations diverge from data at high temperature.

Satyro, Shaw, Yarranton, Fluid Phase Equilib 2013;355:12–25.
API Technical Data Book: Petroleum Refining, 6th ed. 1997.

Water Solubility in Athabasca Bitumen + toluene mixtures

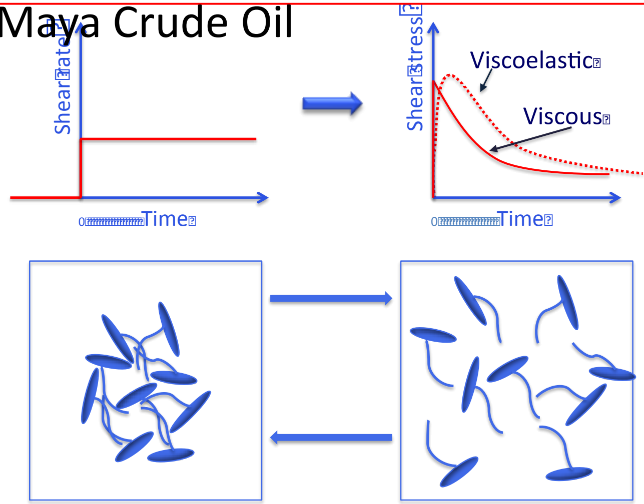


Impact: diluents increase water solubility dramatically.

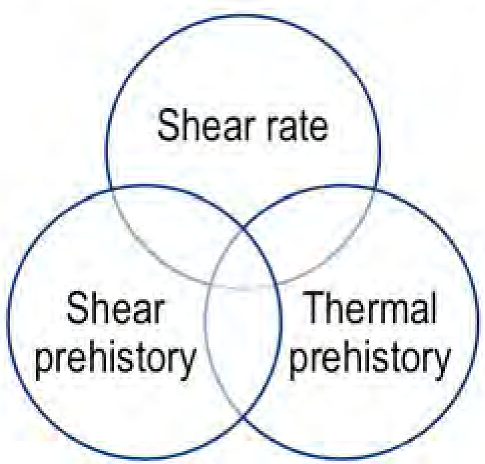
Amani, Gray, Shaw, Fluid Phase Equilibria 2014, 370(0), pp 75-84.

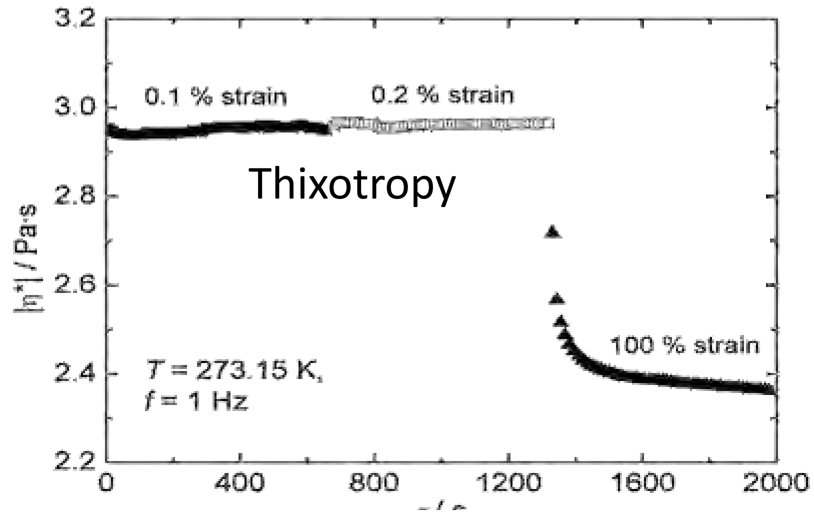
Impact of Materials Complexity on Rheology: pipeline/process restart, blending …. – example

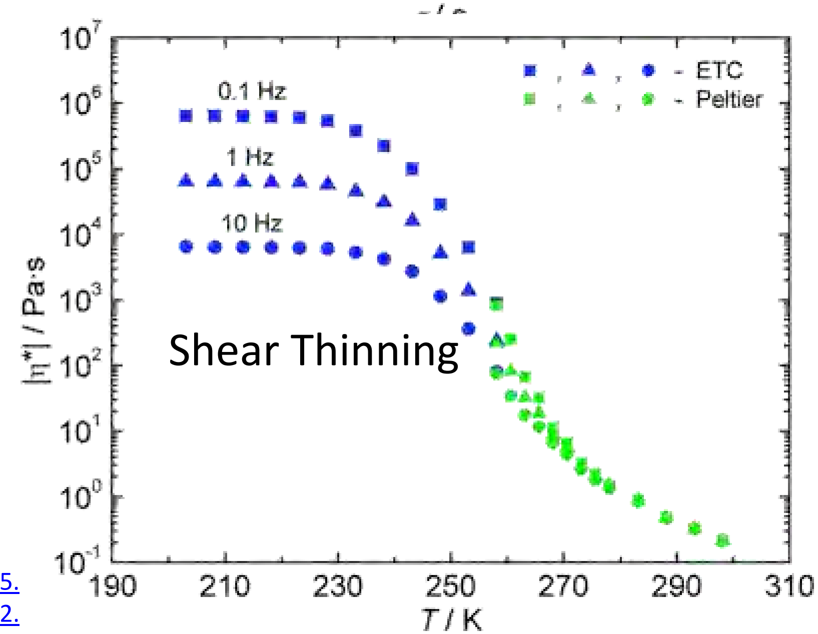
Maya Crude Oil



Apparent viscosity dependence

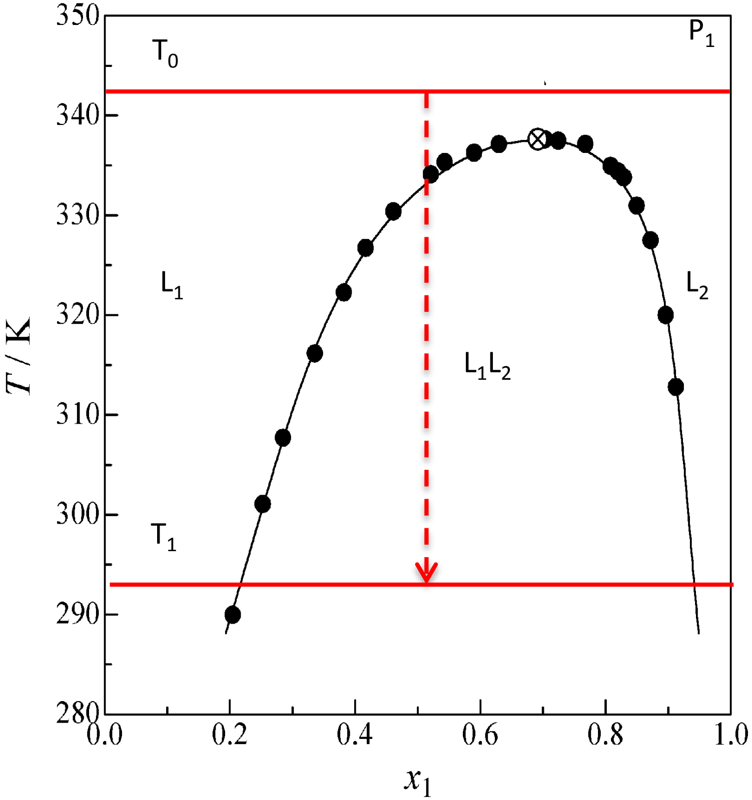


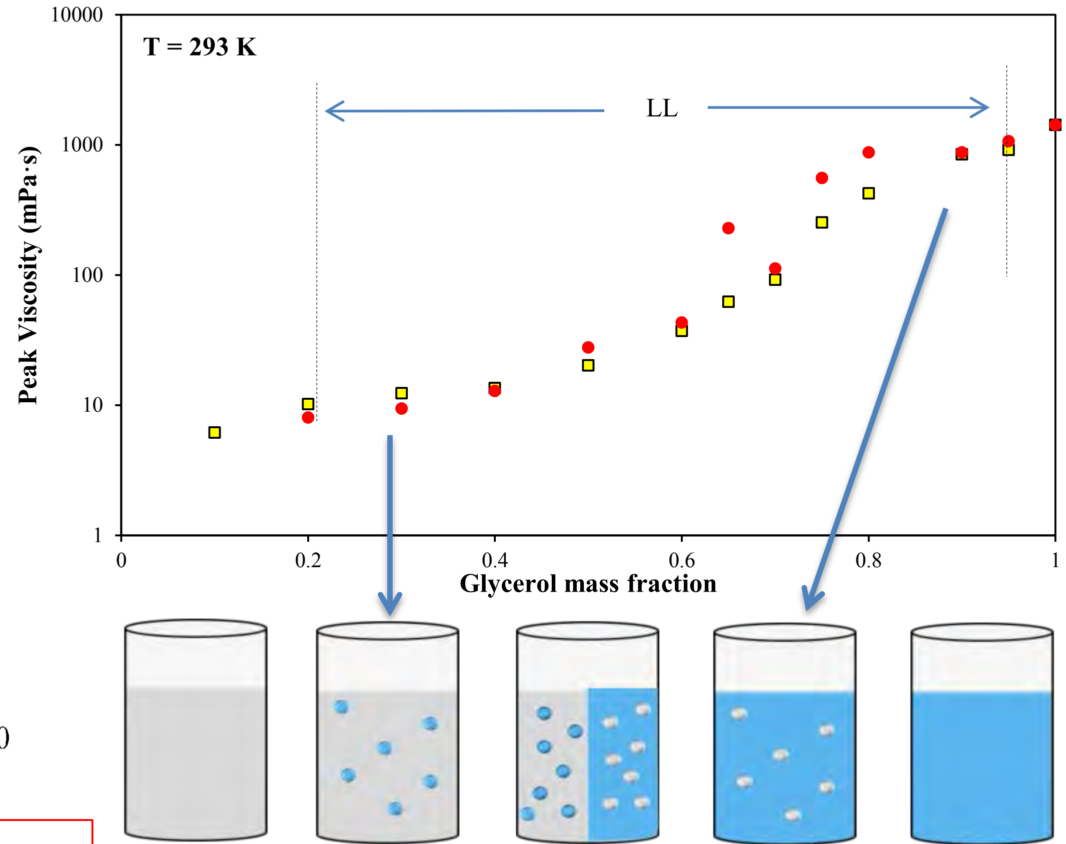




Mortazavi-Manesh, Shaw, Energy & Fuels, 2014, 28(2) 972-979
Mortazavi-Manesh, Sepideh, Shaw J.M., Energy & Fuels, 2016, 30(2), pp 759-765.
Mortazavi-Manesh, Sepideh, Shaw J.M., Energy & Fuels, 2016, 30(2), pp 766-772.
Bazyleva, Anwarul, Fulem, Becerra, and Shaw, J. Chem. Eng. Data, 2010, 55,(3), 1389-1397.

Impact of L➔ LL phase Transition on Apparent Viscosity





Glycerol drops in pentanol rich liquid

Pentanol drops in glycerol rich liquid

Impact: “viscosities” are lower than expected based on standard mixing cases! Order of magnitude uncertainties in viscosity values depending on phase distributions!

Viscosity Data: Sahil Sood UofA MSc Thesis 2017

Phase Diagram: Matsuda, H.; Fujita, M.; Ochi, K. *J. Chem. Eng. Data* **2003**, *48*, 1076–1080.

Diffusion Confusion:

Key parameter in reservoir simulation models

Experimental challenges

- -Input data measurement methods
- -Data analysis methods
- -Example: mutual diffusion coefficient values for liquid mixtures of bitumen + carbon dioxide vary over two orders of magnitude when different analysis methods are applied to the *same* pressure drop data (Tharanivasan et al., 2004)

Impact: Mutual diffusion coefficient values for binary asymmetric mixtures of hydrocarbons are bracketed by the self diffusion coefficient values for the heavy component and the light hydrocarbon component in the phase state being evaluated!

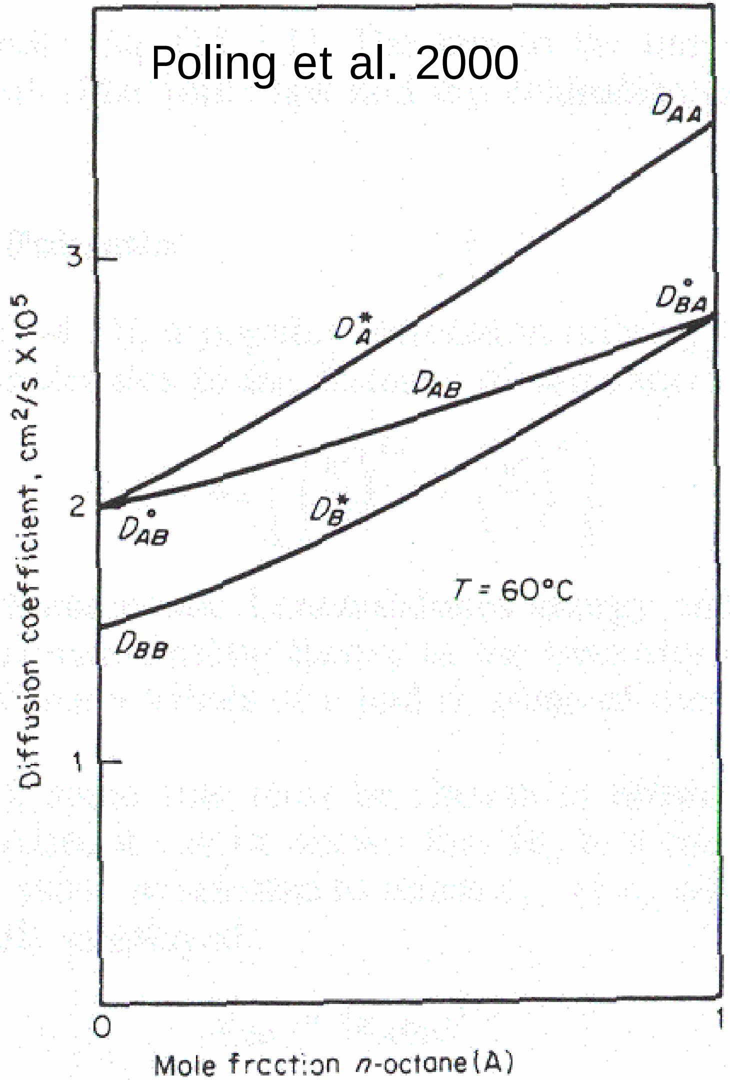


FIGURE 11-2 Mutual, self-, and tracer diffusion coefficients in a binary mixture of n-octane and n-dodecane. (*Van Geet and Adamson, 1964.*)

Basics to get us going!

- **Pressure Drop Measurement Method:** Mutual diffusion coefficients for CO_2 + bitumen depend on assumptions about interfacial mass transfer and concentration gradients at interfaces (Tharanivasan et al., 2004):

  Highest : > 2.5×10^{-8} m^2/s (too high – a gas phase value)

  Lowest: 8×10^{-11} m^2/s (too low? – elephants diffusing through concrete?)

  Measurements meaningless!

- **Time dependent mutual diffusion coefficients**

  don't arise in the known universe.

Self diffusion coefficients:

$CO_2 < 2 \times 10^{-10}$ m^2/s (liquid state) Robinson, Stewart *Ind. Eng. Chem. Fundamen.*, 1968, 7 (1), 90–95

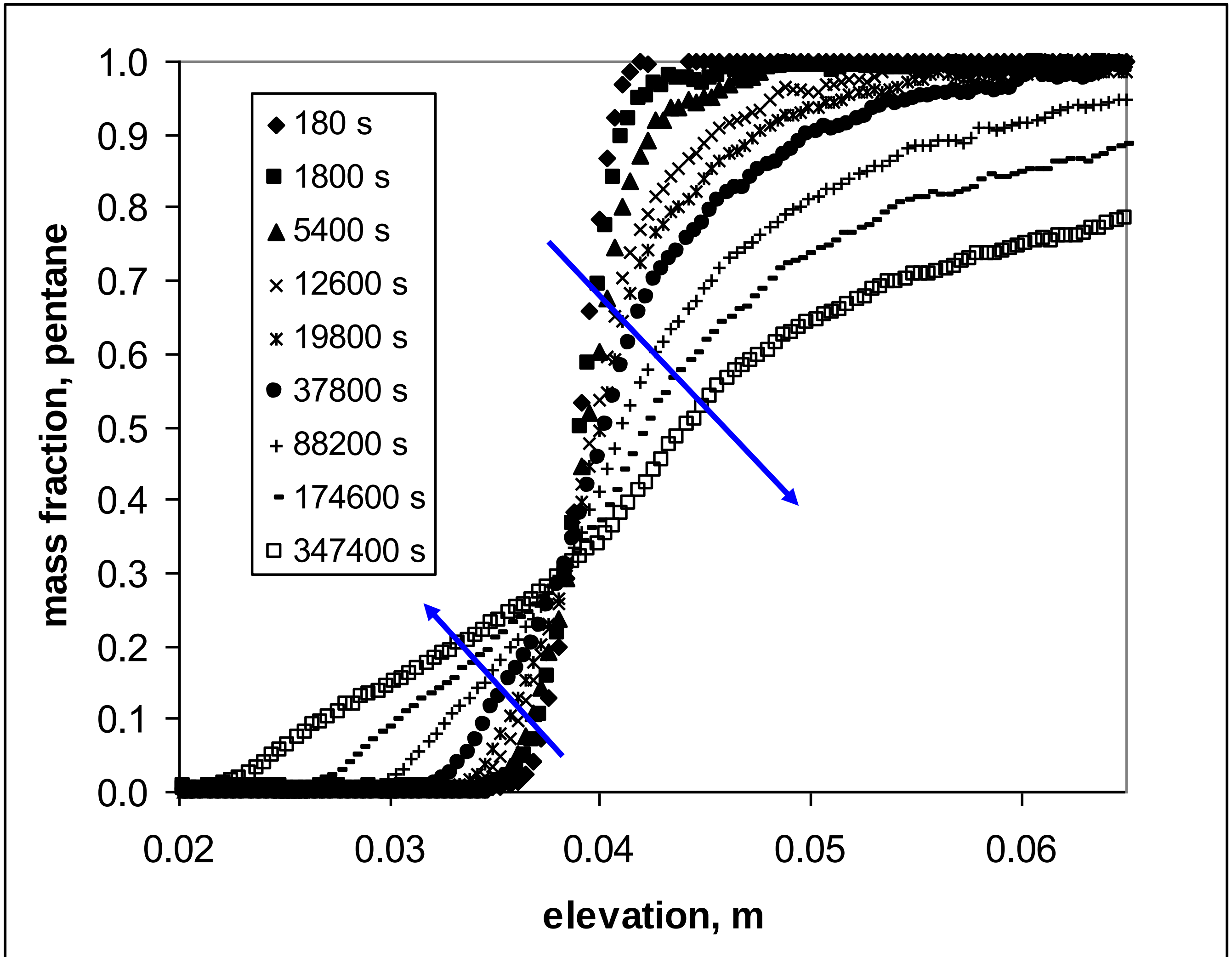
triacontane (n-C30) and n-C154 just above there melting points

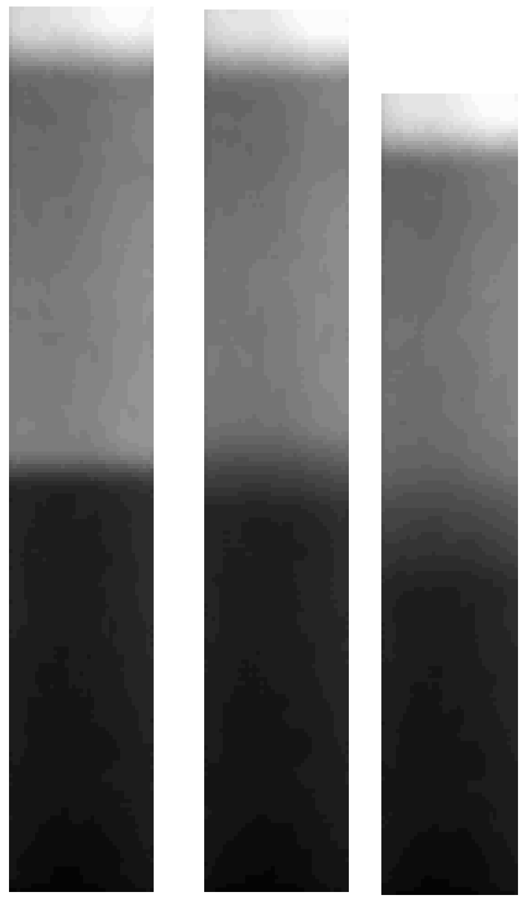
~ 1×10^{-10} and ~ 3×10^{-11} m^2/s

Zhang, X, Shaw, J.M., Liquid Phase Mutual Diffusion Coefficients for Heavy Oil Plus Light Hydrocarbons, Petroleum Science and Technology, 25:773–790, 2007.

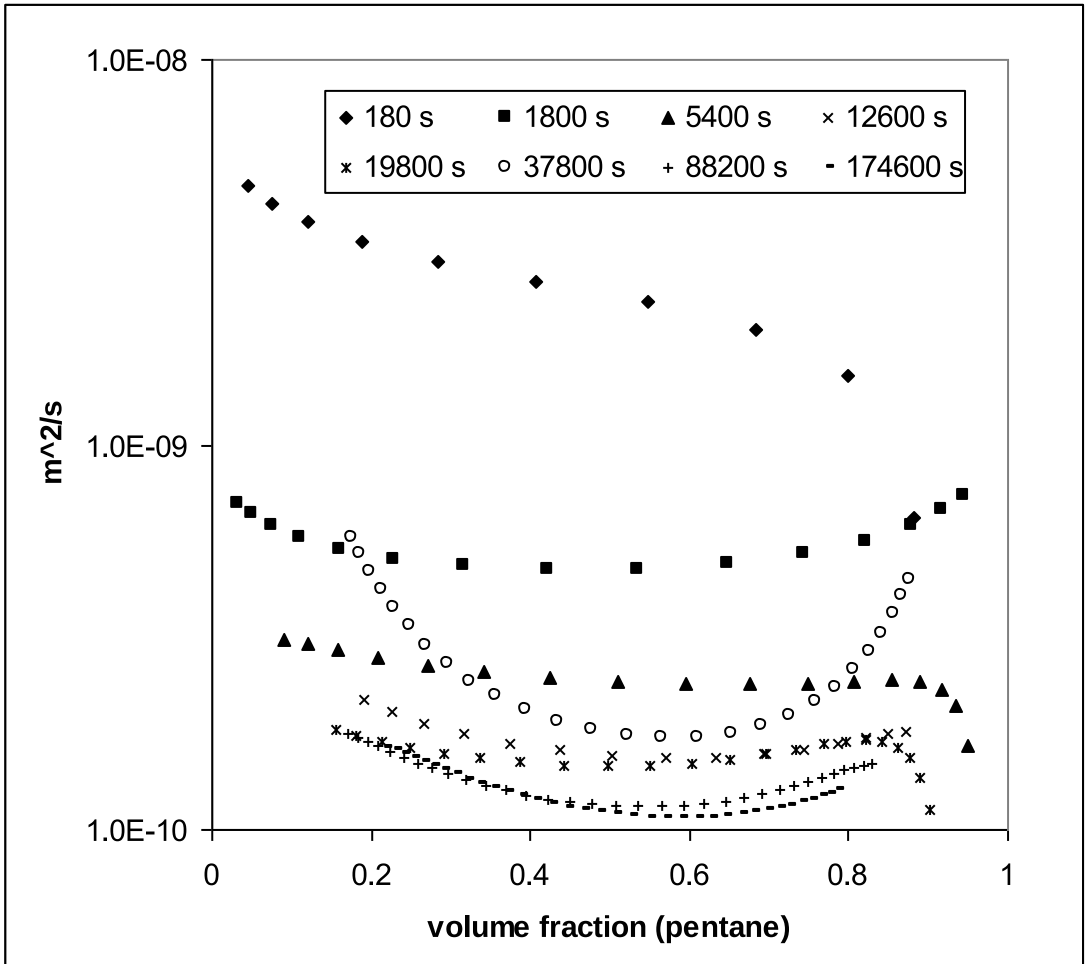
Zhang, X.H., Fulem, M., Shaw, J.M., Liquid-Phase Mutual Diffusion Coefficients for Athabasca Bitumen + Pentane Mixture, Journal of Chemical & Engineering Data, 52, 691-694, 2007.

Mass fraction of pentane as a function of position and time in Athabasca bitumen





Conventional Data Treatment

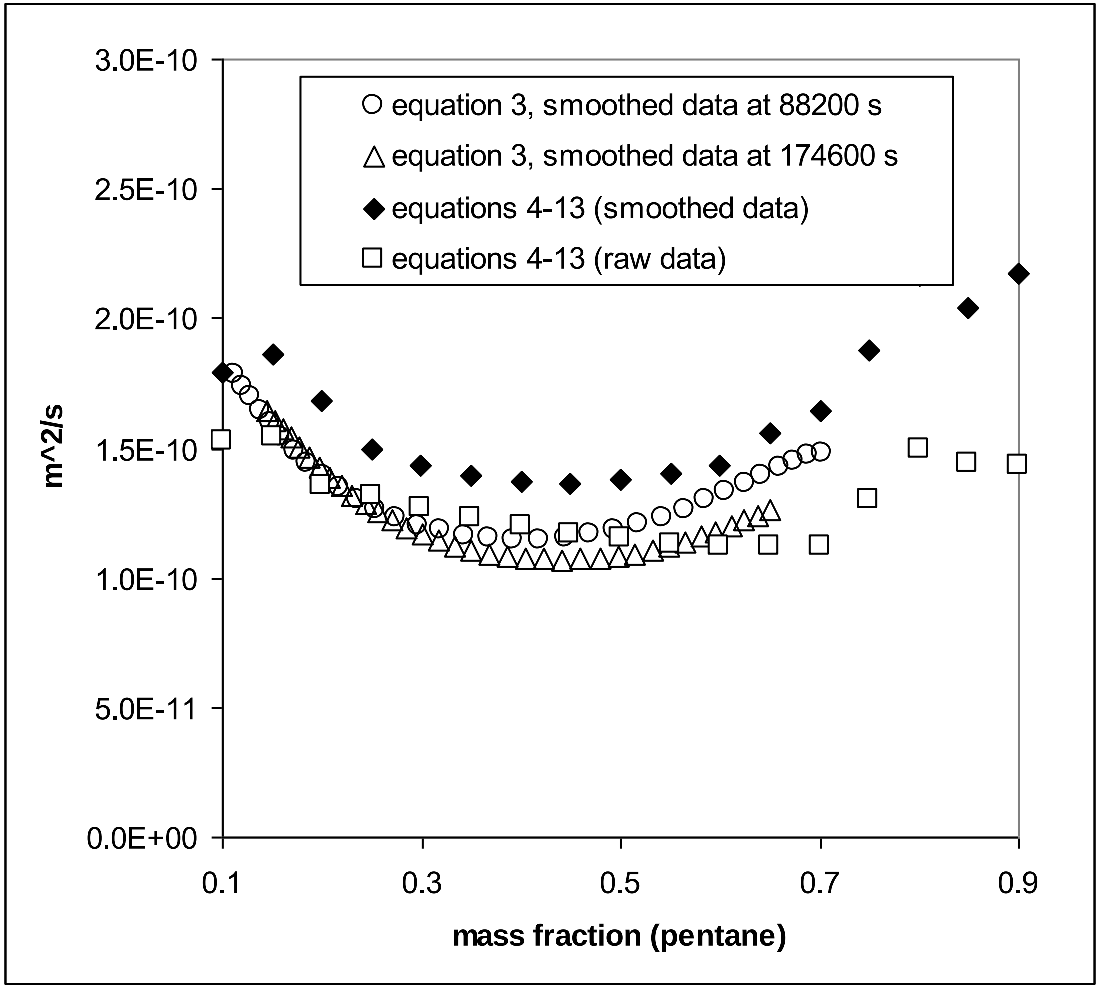


$$D_{AB,V_{fi}} = -\frac{1}{2t\left[\frac{\partial x}{\partial V_f}\right]_{V_{fi}}} \int_0^{V_f i} x \partial V_f$$

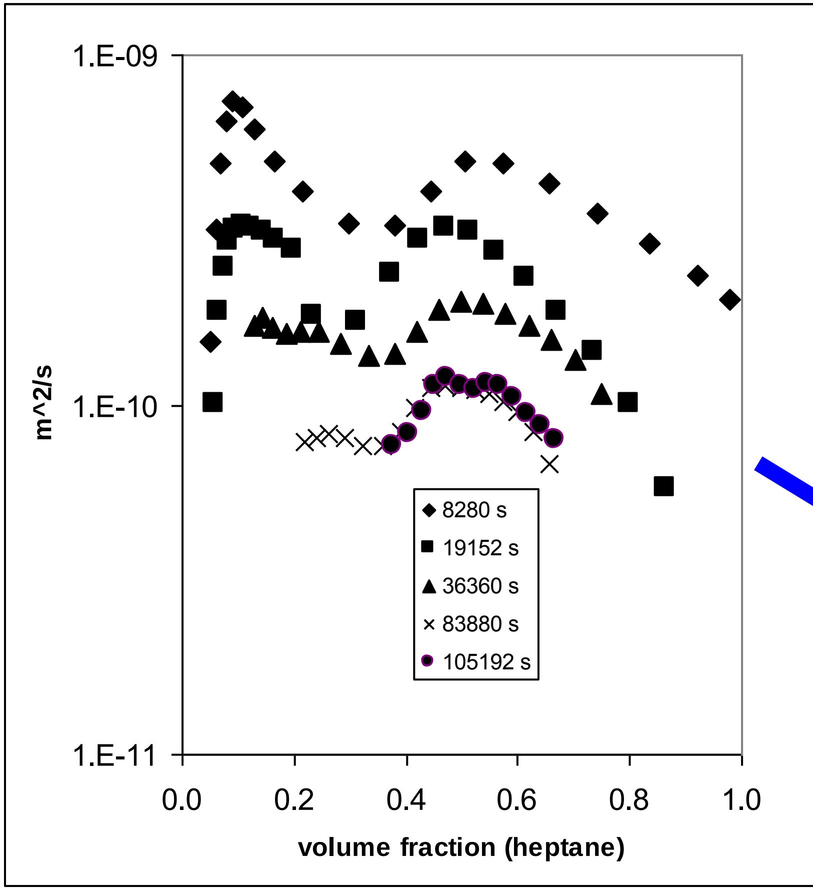
mutual diffusion coefficients values are apparently time dependent. This is inconsistent with relevant theories and exogenous data sets in the known universe!

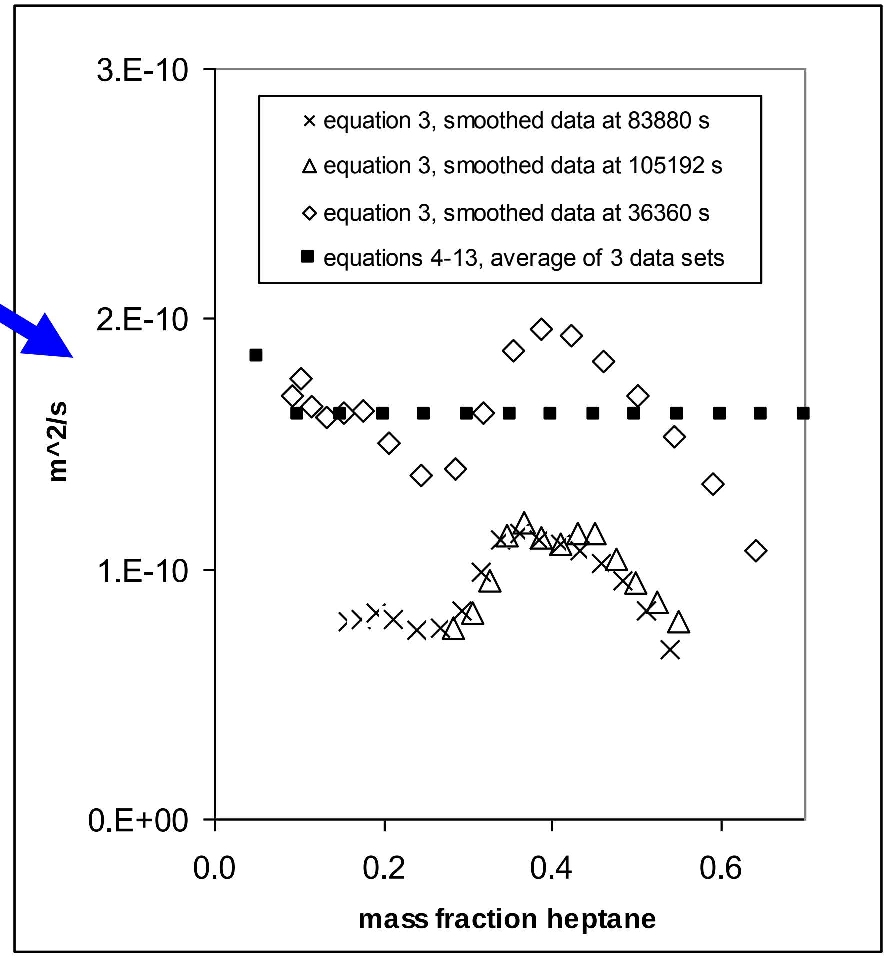
If we allow for density variation with composition, or only include data where density gradients are small

the analysis is more complex and the data quality demands are more exacting but the mutual diffusion coefficients values are consistent with relevant theories and exogenous data sets!



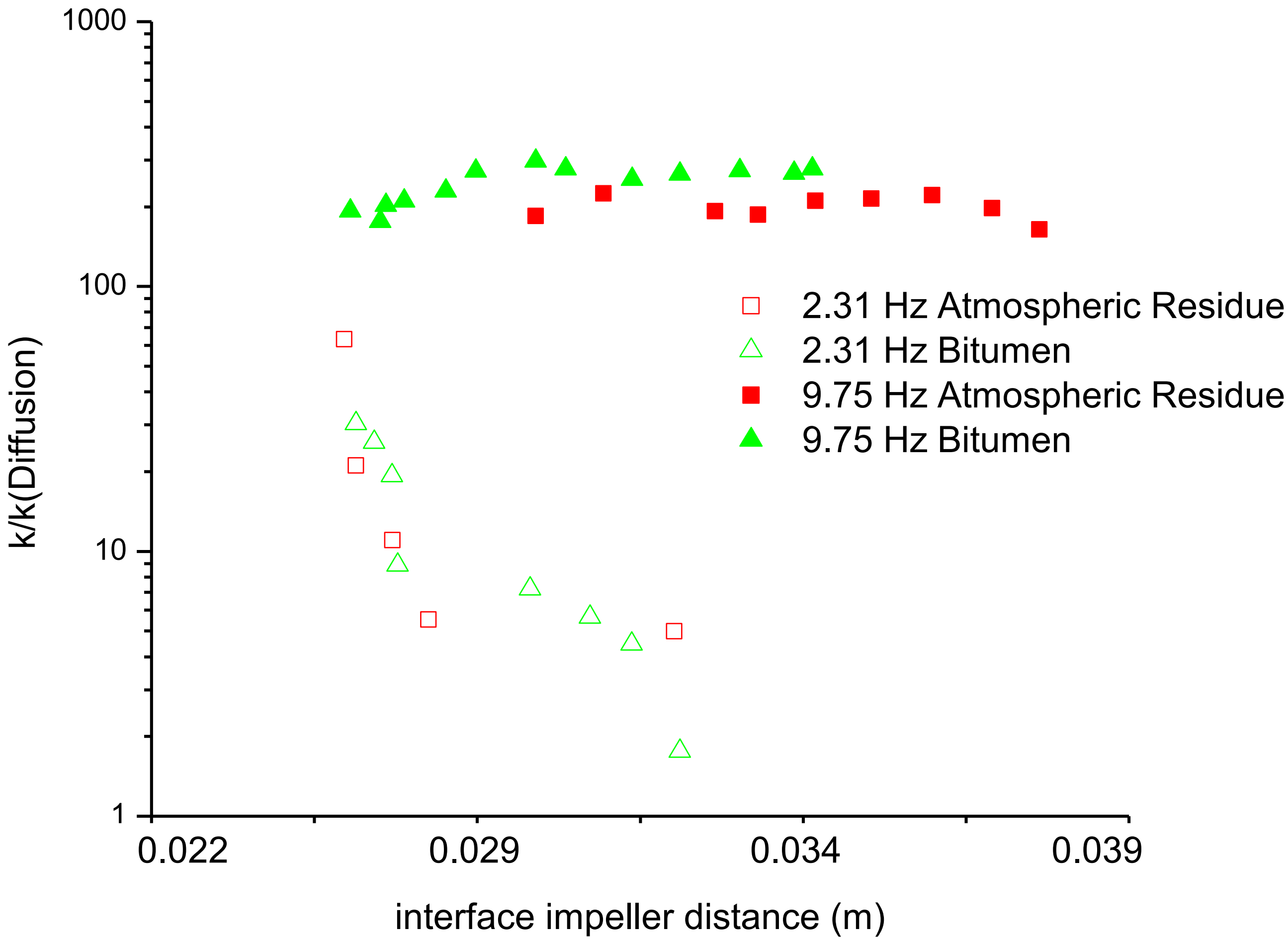
... applying this analysis approach to previously published time dependent values ...

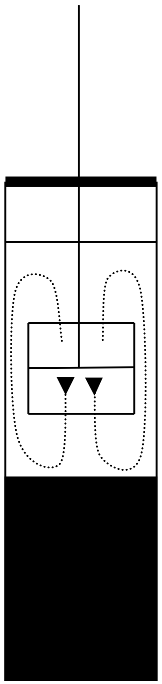




Cold Lake Bitumen + heptane (composition profile data at 295 K from Wen et al., 2004)

Normalized Mass Transfer Rate Between Pentane and Athabasca Atmospheric Residue and Bitumen

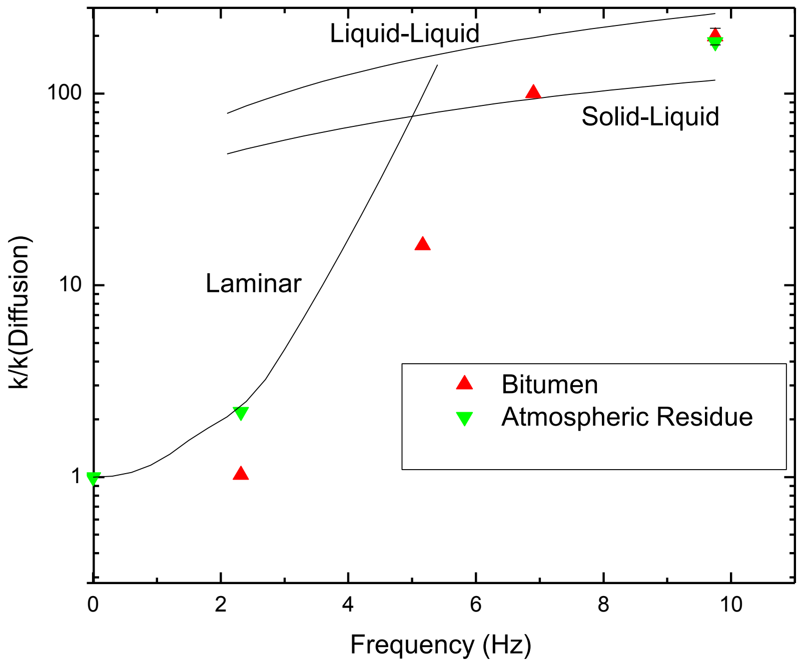




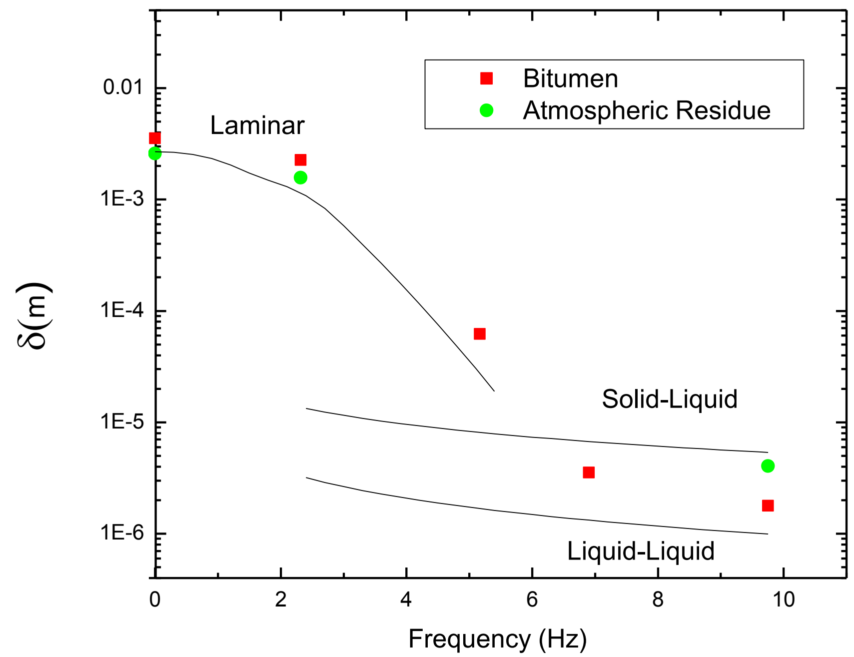
Sadighian, A.; Becerra, M.; Bazyleva, A.; Shaw, J. M. Forced and Diffusive Mass Transfer between Pentane and Athabasca Bitumen Fractions. Energy & Fuels 2011, 25 (2), 782-790.

Comparison with Solid-Liquid and Liquid-Liquid Mass Transfer ***Theory*** - Bitumen or Atmospheric Residue + Pentane (96%)

Normalized Mass Transfer Rate



Boundary Layer Thickness



Sadighian, A.; Becerra, M.; Bazyleva, A.; Shaw, J. M. Forced and Diffusive Mass Transfer between Pentane and Athabasca Bitumen Fractions. Energy & Fuels 2011, 25 (2), 782-790.

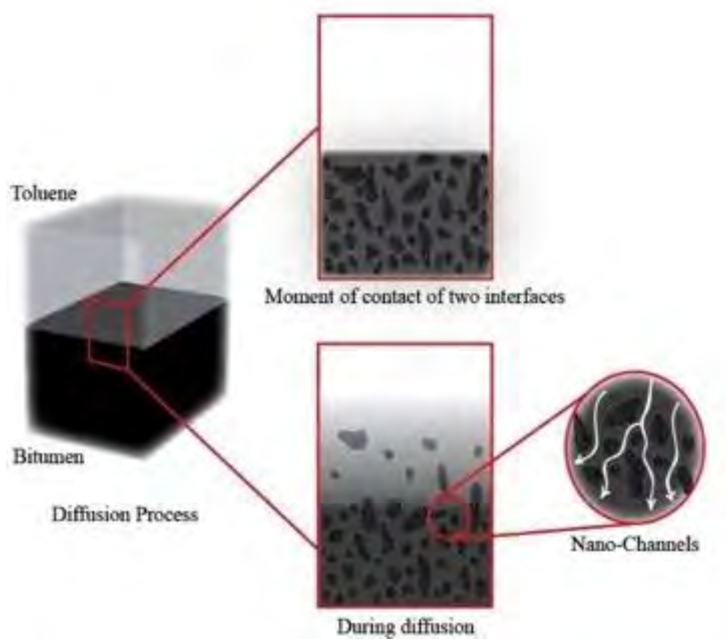
Impact of Materials Complexity on Diffusion Mechanisms Arising in L2

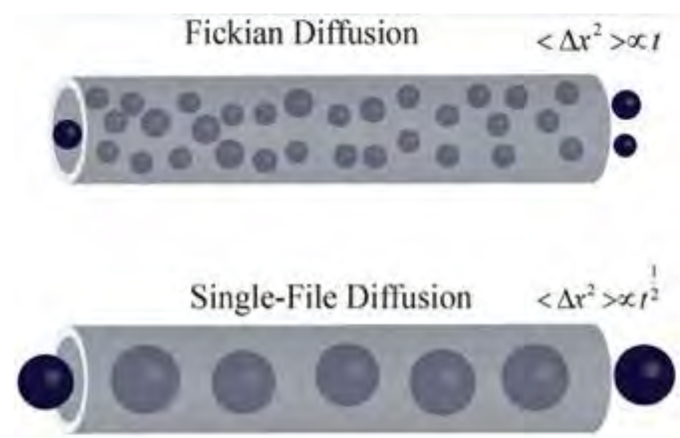
Fickian Diffusion: $$\frac{\partial}{\partial t}(\rho c) = \frac{\partial}{\partial x}\left[\rho D \frac{\partial c}{\partial x}\right]$$

Single-File Diffusion: $$\frac{\partial C}{\partial t} = F\frac{\partial^4 C}{\partial x^4}$$

Sorption by dispersed domains: $$\frac{\partial}{\partial t}(c) = \frac{\in -1}{\in} \times \frac{\partial c_p}{\partial t}$$

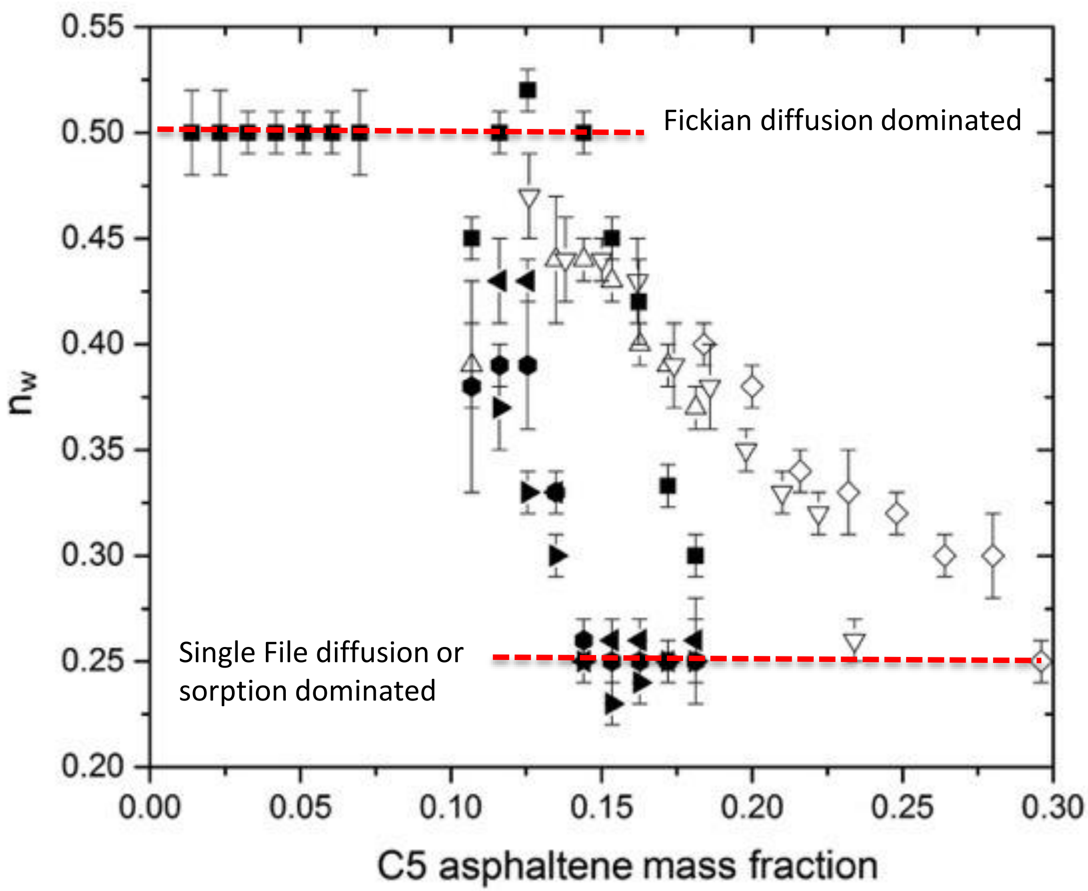
Impede diffusion front movement
Difficult to discriminate mathematically





Alizadehgiashi, Shaw, Energy & Fuels, 2015, 29 (4), pp 2177-2189.
Mohammad Pourmohammadbagher, MSc Thesis in progress

Diffusion mechanism identification for Athabasca bitumen + light hydrocarbon mixtures



- Sample pretreatment & handling are uncontrolled variables
- Samples + n-alkanes (open symbols)
- Samples + toluene (closed symbols)

Athabasca bitumen C5 asphaltenes ~ 20 wt%

Asphaltene-rich domains aggregate in n-alkanes increasing the mean distance and reducing the surface area per unit mass

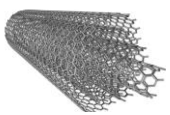
Impact: alkane diluents are preferred over aromatic ones

Data:
Athabasca bitumen + toluene, Fadaei, H.; Shaw, J. M.; Sinton, D. *Energy Fuels* **2013.**
Cold lake bitumen + heptane, Wen, Y. W.; Kantzas, A. *Energy Fuels* **2005.**
Athabasca bitumen + pentane, Zhang, X.; Fulem, M.; Shaw, J.M. J. *Chem. Eng. Data* **2007.**
Athabasca bitumen + toluene at 0, 25, 40 ºC, Alizadehgiashi, M.; Shaw, J.M. , *Energy and Fuels* **2015**.

Alizadehgiashi, Shaw, Energy & Fuels, 2015, 29 (4), pp 2177-2189.
Mohammad Pourmohammadbagher, MSc Thesis in progress

Active Diffusion Mechanisms in Toluene + Polybutene + Nano Particle Mixtures

Nanoparticle Properties



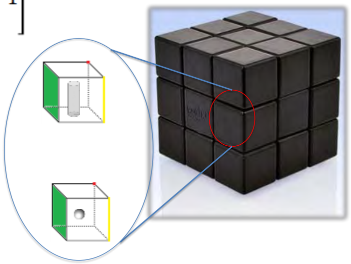
Cylindrical carbon nanotubes
Adsorbs toluene
Median diameter = 6.6 nm
Length = 1.6 μm
Density = 2.1 g/cm^3

Spherical nano-diamonds
Diameter : 65 nm and 12 nm
Does not adsorb toluene
Density = 3.1 g/cm^3

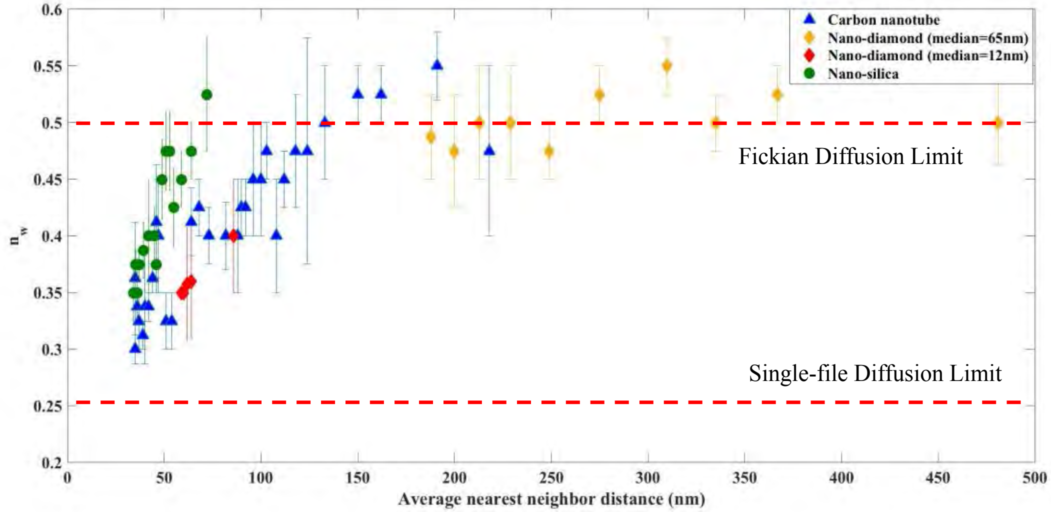
Spherical nano-silica
Diameter : 7 nm
Does not adsorb toluene
Density = 2.3 g/cm^3

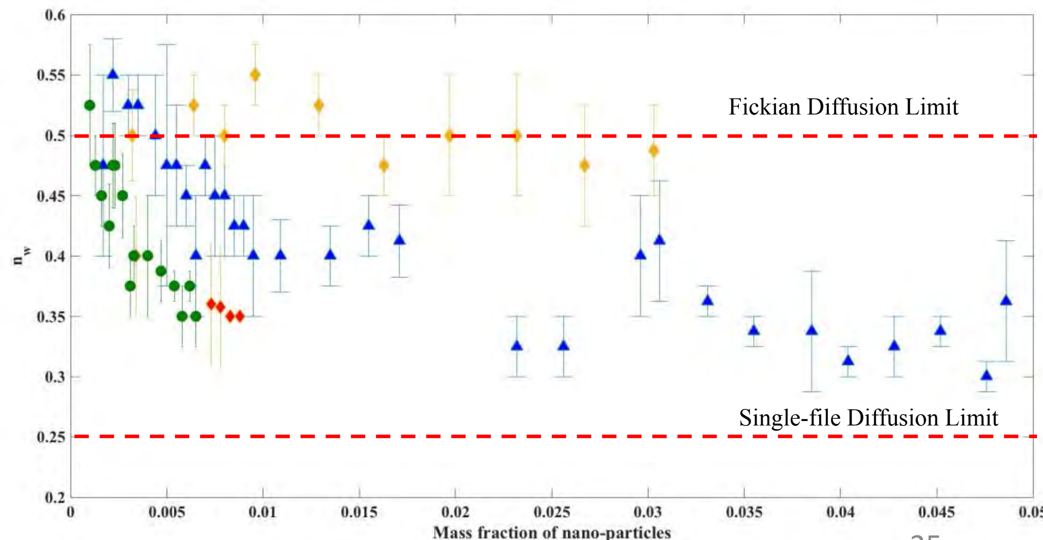
Average Nearest Neighbor Distance

- Spherical (nanodiamonds, asphaltenes, nano silica) $L = D\left[\left(\frac{\Pi}{6\emptyset}\right)^{\frac{1}{3}} - 1\right]$
- Cylindrical (carbon nanotubes) $L = D\left[\left(\frac{\Pi}{4\emptyset}\right)^{\frac{1}{2}} - 1\right]$



Diffusion Mechanism Depends on Average Nearest Neighbor Distance and Mass Fraction of Nano-Particles

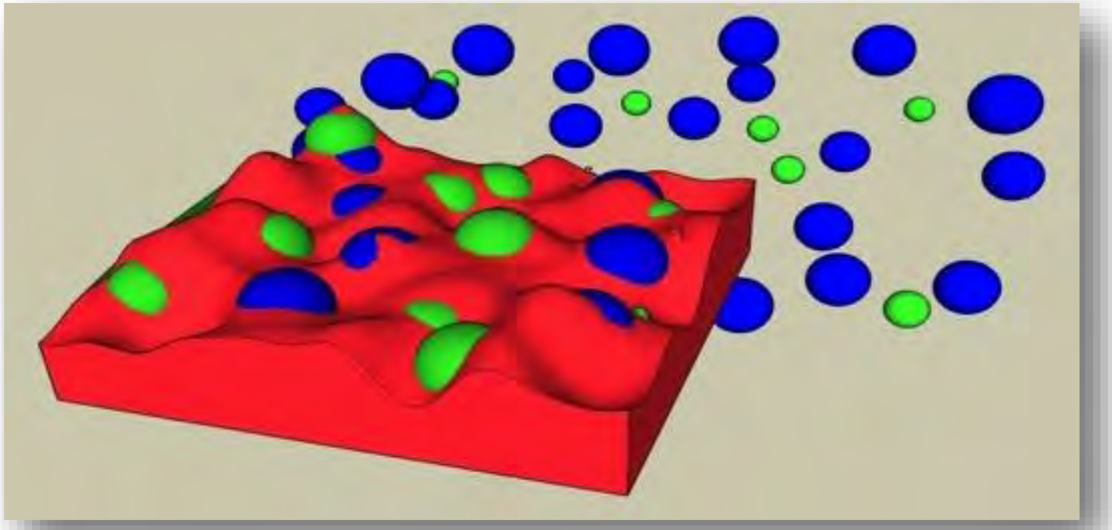




Mohammad Pourmohammadbagher, MSc thesis (in progress)

Displacement of Water from Kaolinite and Illite Clays by Organic compounds

Enthalpy of Solution Measurements



$$\Delta h_s = \Delta h_s^0 + \Delta h_{solvent\ sorption/desorption} + \Delta h_{TC\ sorption/desorption} + \Delta h_{surface,TC}$$

Δh_s^0 : Impact of surface energy in pure solvent (– / +)

$\Delta h_{solvent\ sorption/desorption}$: Solvent sorption/desorption (– / +)

$\Delta h_{TC\ sorption/desorption}$: Trace component sorption/desorption (– / +)

$\Delta h_{surface,TC}$: Effect of sorption/desorption of trace species on the surface energy (– / +)

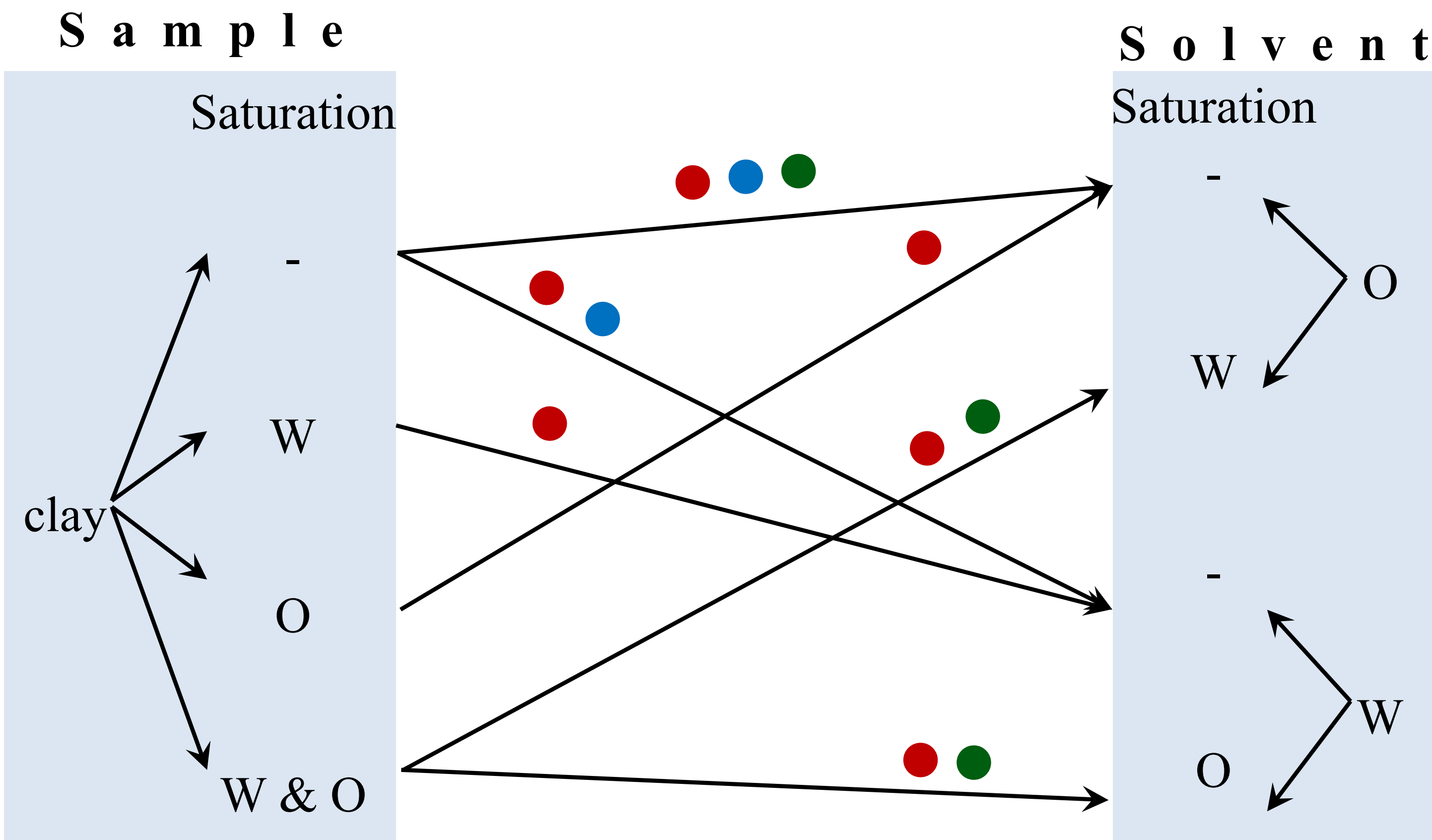
A. Pourmohammadbagher and J. M. Shaw, Environ. Sci. Technol. 2015, 49, 10841-10849

A. Pourmohammadbagher and J. M. Shaw, Energy & Fuels 2016, 30 (8) 6561-6569

A. Pourmohammadbagher and J. M. Shaw, Energy & Fuels 2016, 30 (7) 5964-5969

Ollinger, Pourmohammadbagher, Quast, Becerra, Shumaker-Parry, Shaw, *Energy Fuels*, 2016, *30* (12), pp 10148–10160

$$\Delta h_s = \Delta h_s^0 + \Delta h_{solvent\ sorption/desorption} + \Delta h_{TC\ sorption/desorption} + \Delta h_{surface,TC}$$



O: Organic solvent, W: Water

Detailed Enthalpy of Solution + Mass Balance Model

$$\Delta h_s = \Delta h_s^0 + \Delta h_{solvent\ sorption/desorption} + \Delta h_{TC\ sorption/desorption} + \Delta h_{surface,TC}$$

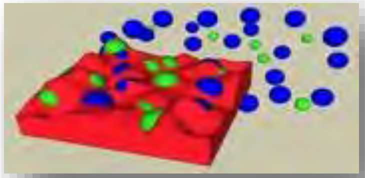
$$\Delta h_s = \Delta h_s^0 - (x_s^F - x_s^I)(h_{f,s}) + (x_{TC}^F - x_{TC}^I)[\frac{\Delta h_{surface,TC}^{sat}}{x_{TC}^{sat}} - (h_{s,TC} + h_{f,TC})]$$

$$x_s^F + x_{TC}^F = \gamma \qquad\qquad x_s^F = \gamma + \alpha y_{TC}$$

$$\Delta h_s = \Delta h_s^0 - (\gamma + \alpha y_{TC} - x_s^I)(h_{f,s}) + (-\alpha y_{TC} - x_{TC}^I)[\frac{\Delta h_{surface,TC}^{sat}}{x_{TC}^{sat}} - (h_{s,TC} + h_{f,TC})]$$

Δh_s^0: Impact of surface energy in a pure solvent as a reference enthalpy of solution
x^F_s , x^F_{TC} : Final mass fraction of solvent and trace contaminant
x^I_s , x^I_{TC} : Initial mass fraction of solvent and trace contaminant
x^{sat}_{TC} : Saturation mass fraction of trace contaminant
$h_{s,TC}$: Enthalpy of solution of the trace contaminant in the solvent/water
$h_{f,s}$ and $h_{f,TC}$: Enthalpy of fusion of the solvent and trace contaminant
$\Delta h^{sat}_{surface,TC}$: Enthalpic effect of surface modification due to saturation of particles with trace contaminant

Permanent Solvent Loss In Reservoirs



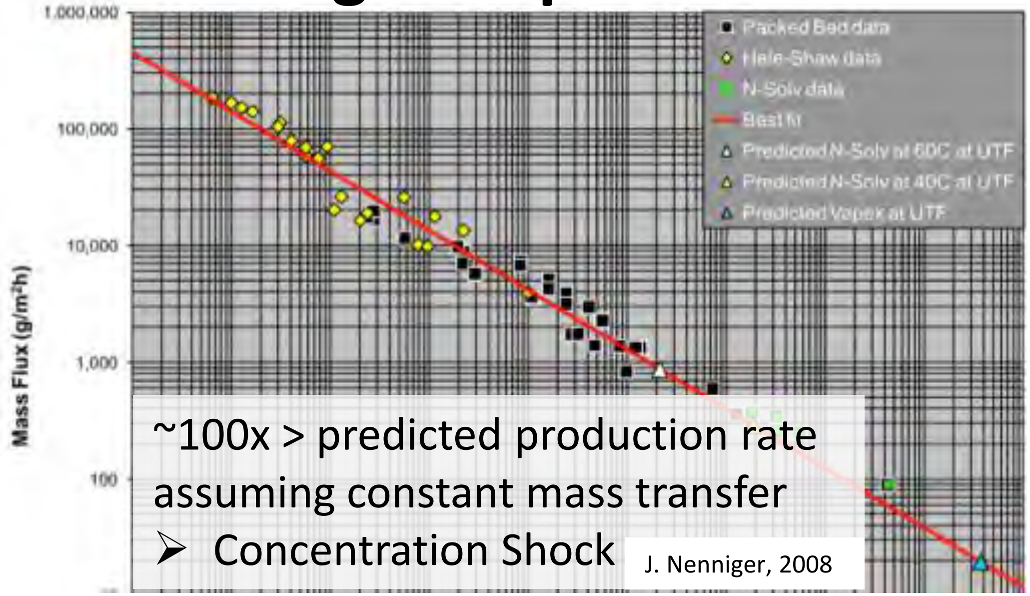
Solvent	Contaminant	Kaolinite $x^F_{H_2O}$	Illite $x^F_{H_2O}$
Toluene	-	0	0.002
	Water*	0.005	0.003
Heptane	-	0.001	0.001
	Water*	0.006	0.004
Pyridine	-	0.003	0.003
	Water**	0.005	0.002
Water	-	0.01	0.005
	Toluene*	0	0
	Heptane*	0.003	0.001

* Saturated at 60C
** 0.022 mole fraction

Impact: Displacement of water from clay surfaces by trace organic compounds even in water!

Whether clays are contaminated with oil or are contaminant free initially the same behavioral trends arise.

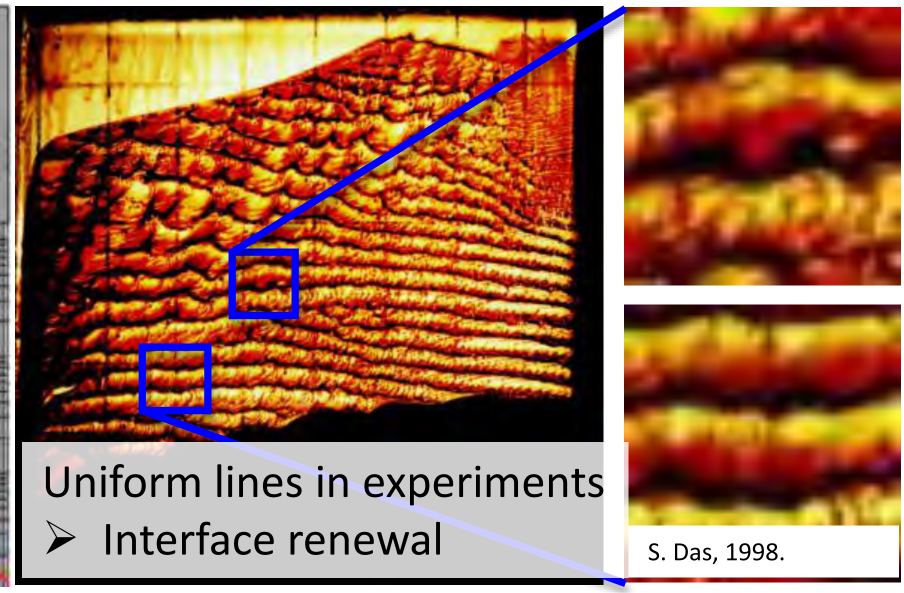
Bitumen + solvent Interface Mass Transfer: Observations and Scaling Groups



~100x > predicted production rate assuming constant mass transfer

➢ Concentration Shock

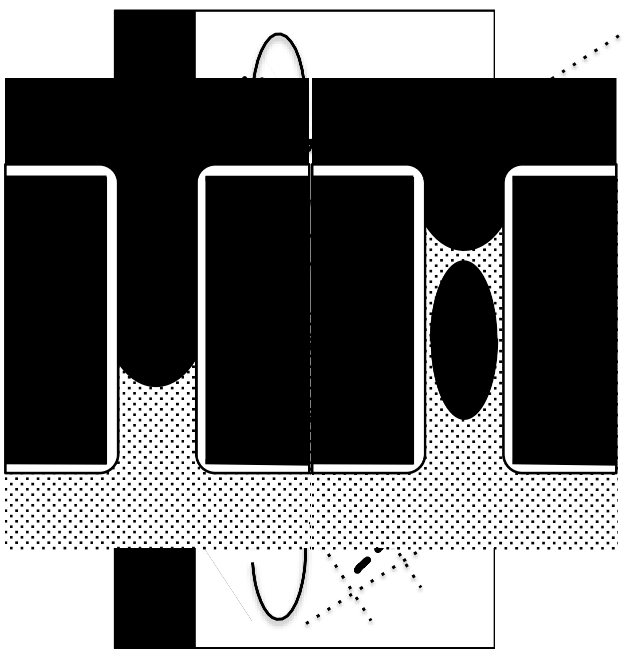
J. Nenniger, 2008



Uniform lines in experiments

➢ Interface renewal

S. Das, 1998.



Three forces on fluid—Buoyancy must overcome interfacial and viscous forces for fluid to flow

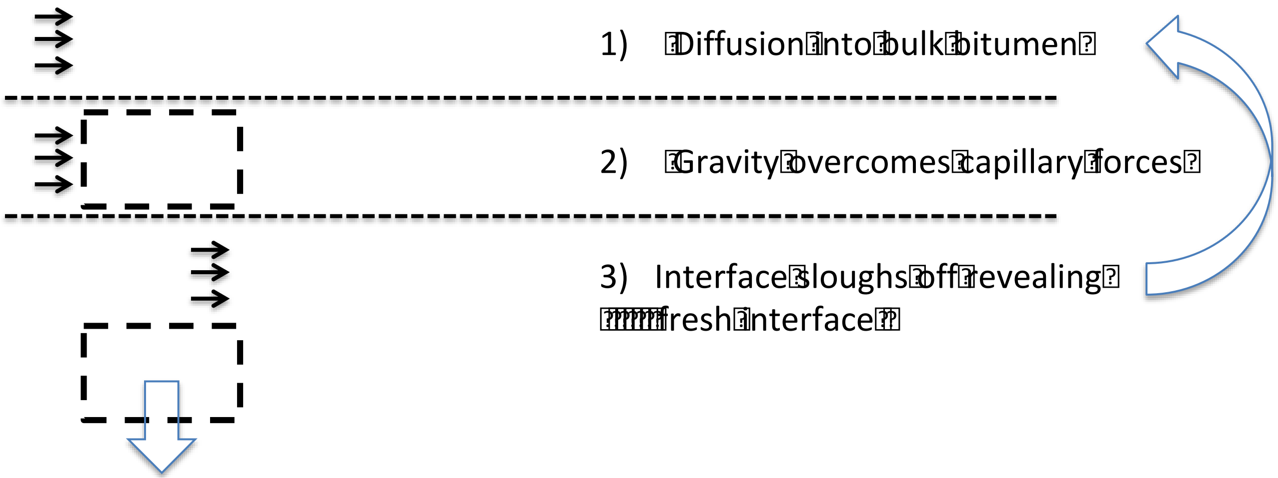
Archimedes # suggests no natural convection

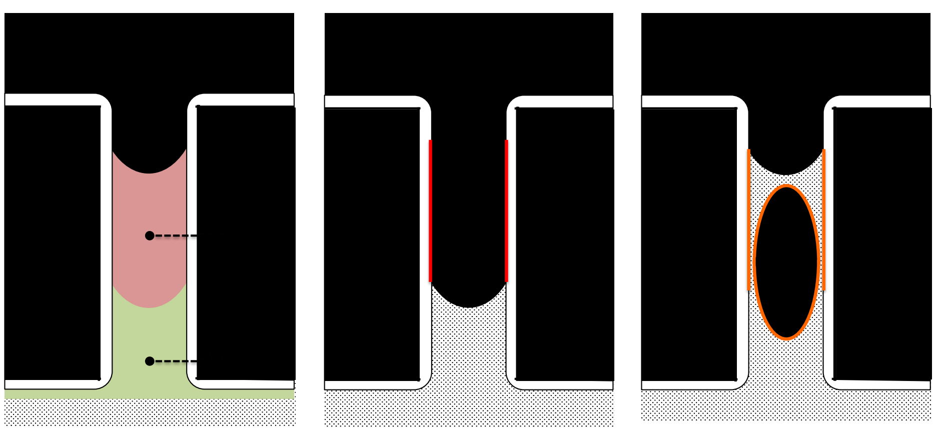
Bond # suggests interfacial tension important

Schmidt # >>1 therefore momentum transfer much faster than diffusion mass transfer

Sloughing Mechanism

Concentration shock AND interface renewal happening simultaneously





a) b) c)

Drop Mobilization occurs when $\sigma_{WD} < \sigma_{DP} + \sigma_{WP}$

$\Delta E = (\sigma_{WD} + \sigma_{DP} - \sigma_{WP})\ \Delta A + g\ z\ (\rho_D - \rho_P)\ \Delta V$

(const P,T)

Sloughing occurs when $\Delta E > 0$

Stewart, R. A.; Shaw, J. M. On Vibration-Induced Fluid and Particle Motion in Unconsolidated Porous Media: Observations and Dimensional Scaling Analysis. Transport in Porous Media 2017, 116 (3), 1031-1055.

Stewart, R. A.; Shaw, J. M. Interface Renewal and Concentration Shock Through Sloughing — Accounting for the Dissonance Between Production Models and Measured Outcomes for Solvent-Assisted Bitumen Production Processes. *SPE Reservoir Evaluation & Engineering* (in press 2017)

Discussion Topics

1. Phase behaviour:
    - Athabasca Bitumen (AB) phase diagram
    - AB + diluent mixtures
        - -illustrative phase diagram example AB + propane
        - -density relative to water examples with heptane and toluene
    - AB + solvent + water

2. Transport Properties
    - Rheology of Heavy Oil
    - Emulsion “viscosity”
    - Mutual Diffusion in AB + solvent mixtures - mechanisms

3. Displacement of water from clay and contaminated surfaces by organic compounds

4. Mass Transfer at Bitumen + Solvent Interfaces in Reservoirs

ENGINEERING LEADERS.

Challenges and Lessons Learnt from Solvent-Aided Recovery Processes

Zhangxing John Chen
Reservoir Simulation Group
Department of Chemical and Petroleum Engineering
Schulich School of Engineering
University of Calgary

Outline

- Background
- Solvent-Aided Processes
- Recent Industrial Solvent-Aided Pilots
- Lessons Learnt
- Challenges
- Way Ahead

Outline

- **Background**
- Solvent-Aided Processes
- Recent Industrial Solvent-Aided Pilots
- Lessons Learnt
- Challenges
- Way Ahead

Our Petroleum Challenges!

High costs and low prices

Global competition

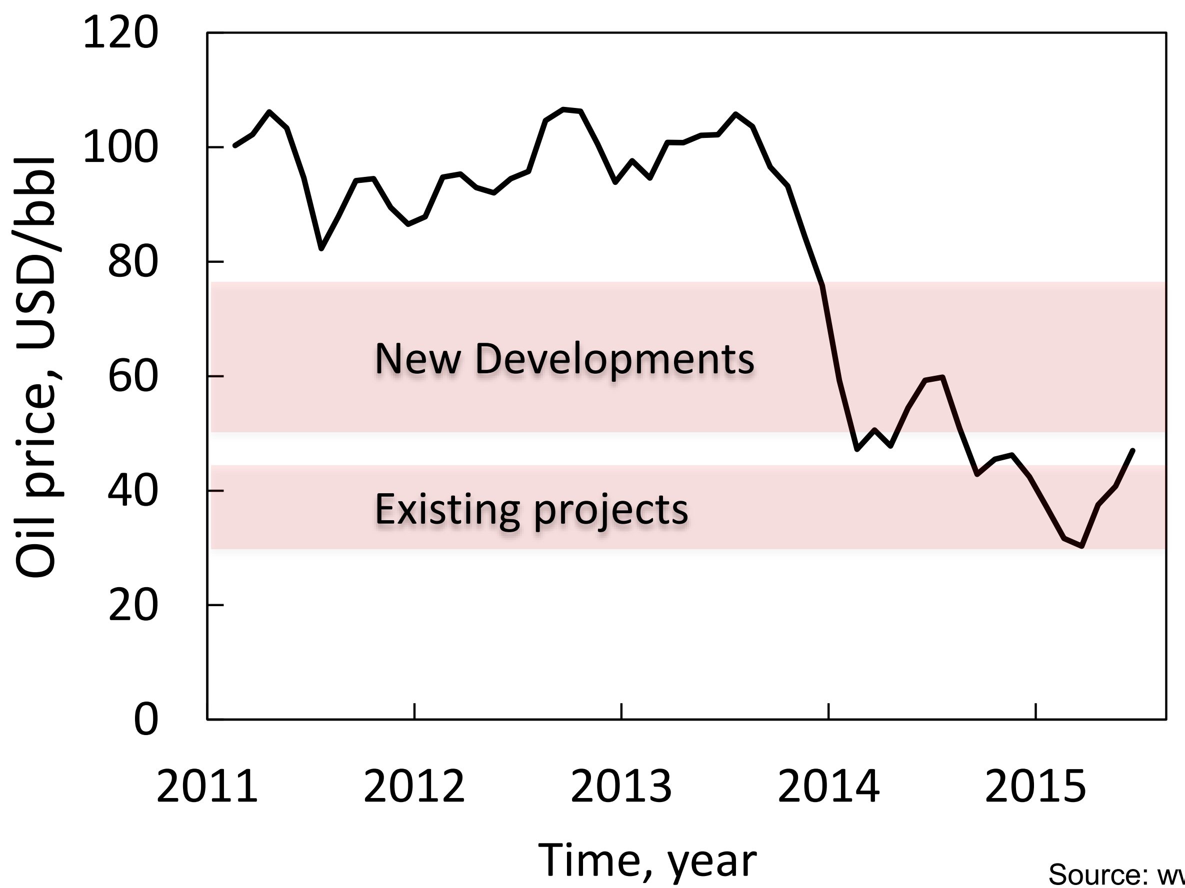
Market access

Environmental footprint

Social pressure and acceptance

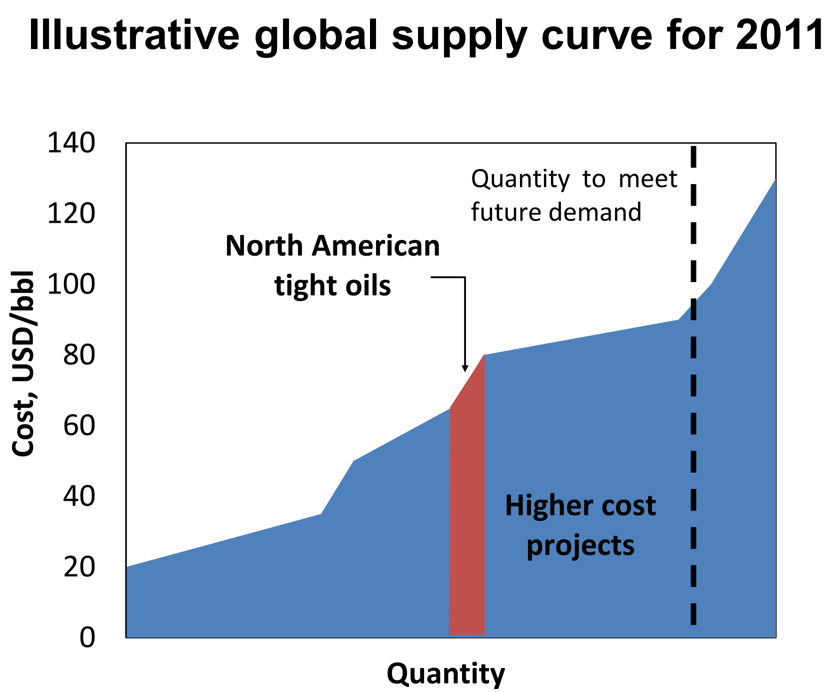
Changing policies/regulations

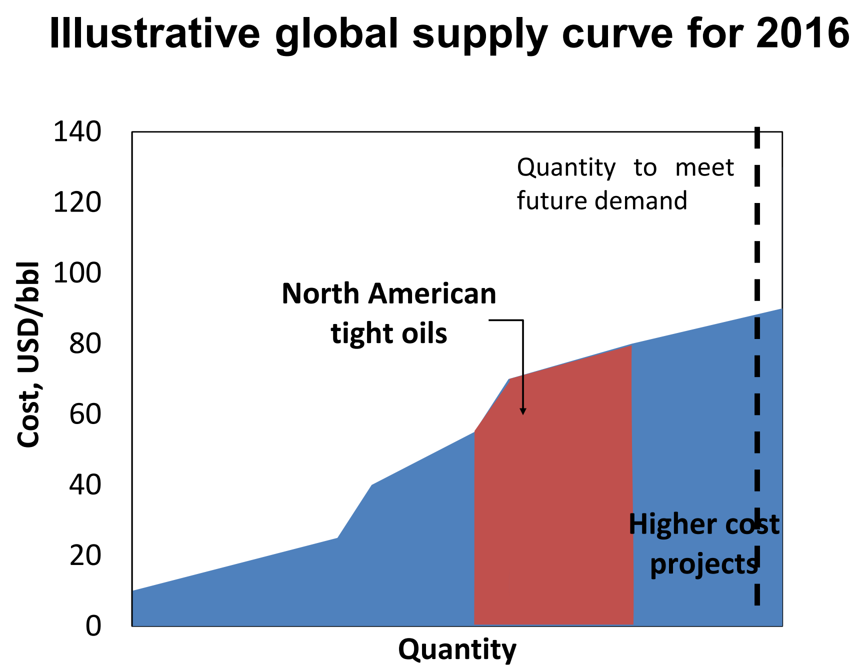
High Costs and Low Oil Prices



Source: www.Bloomberg.com

Global Competition

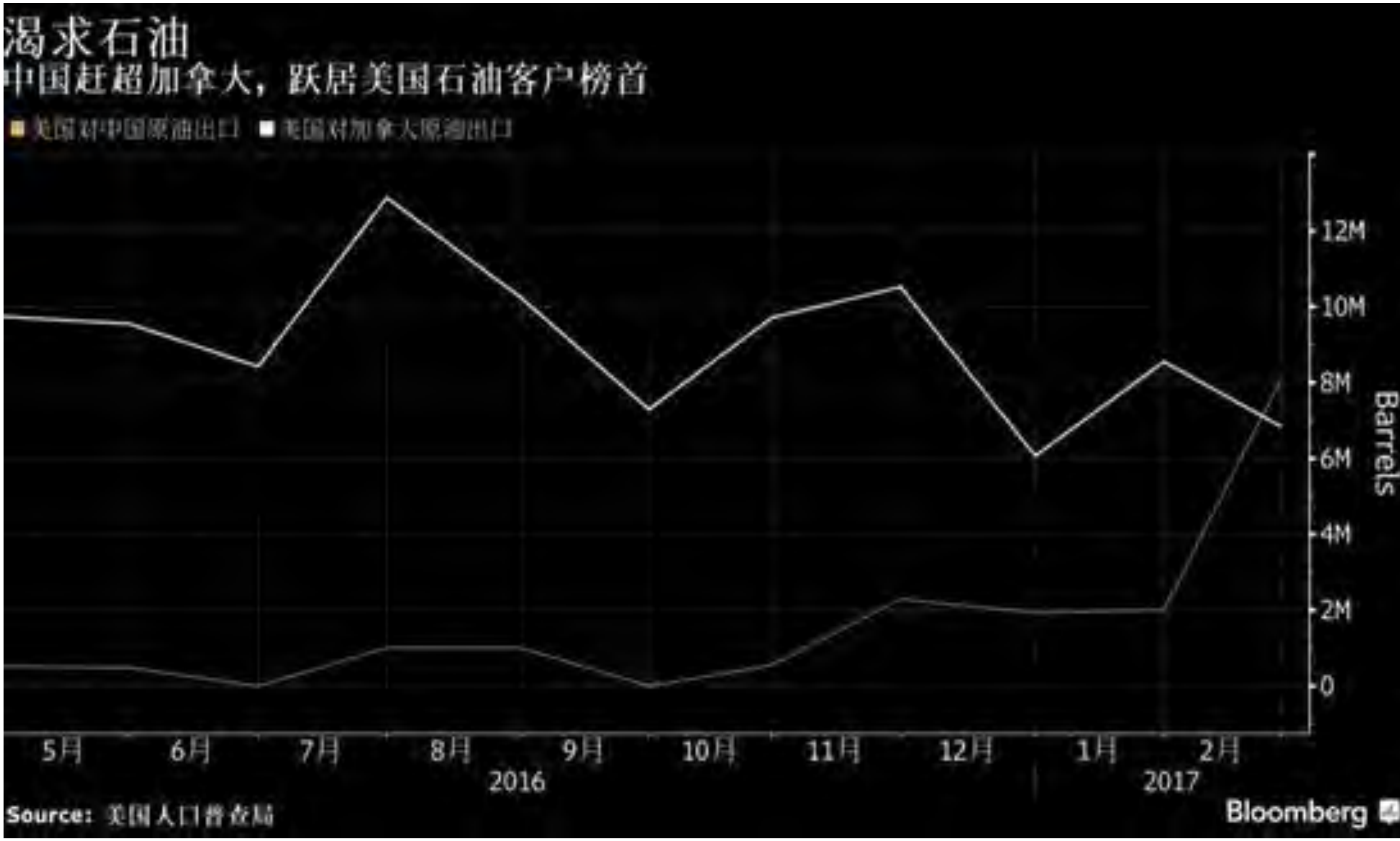




Source: ARC Financial Corporation

Increased share of North America tight/shale oils has pushed some of the higher cost projects (including some of the oil sands projects) beyond market's demand.

Market Access



China imported 8.08M barrels of oil from US in February 2017.

Free Trade Between Canada and China

Inaugural China-Alberta Energy and C

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Environmental Concerns, Social Pressure and Changing Policies

Land

Water

Air

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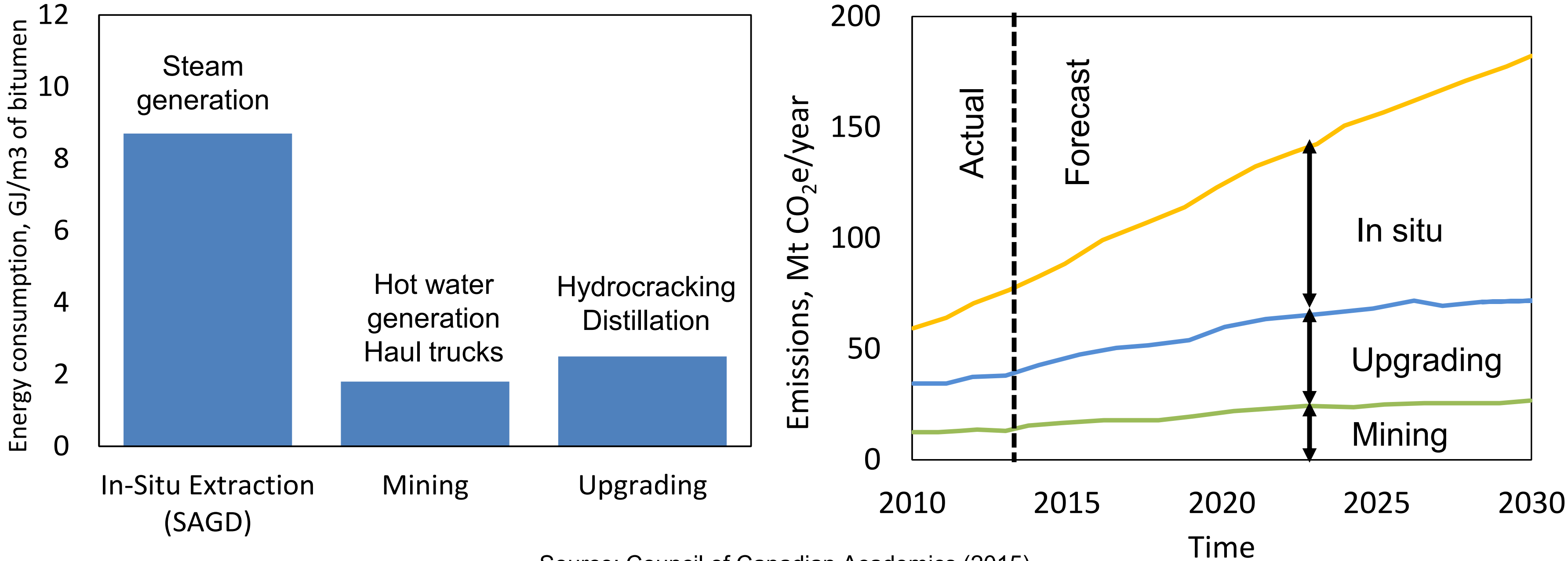
Where Do GHGs Come From?

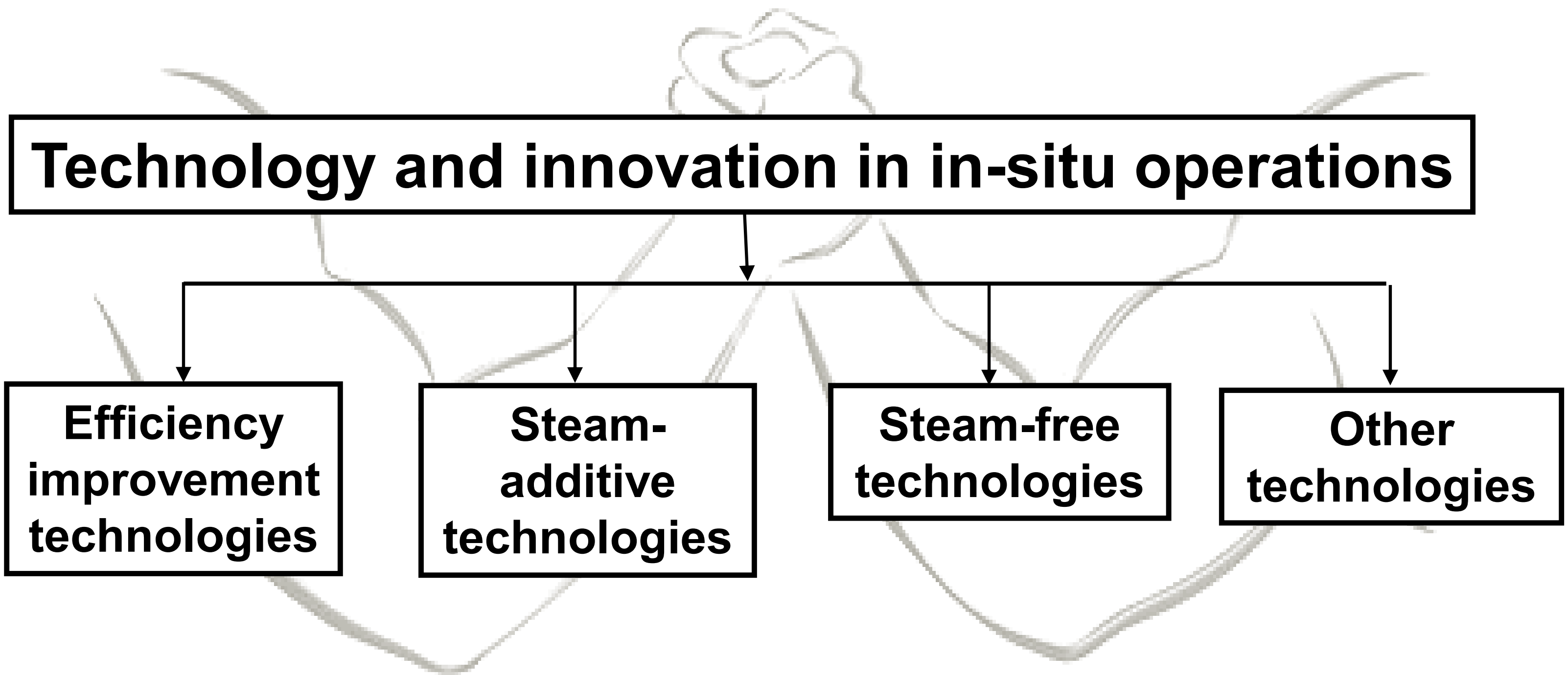


Source: Council of Canadian Academics (2015)

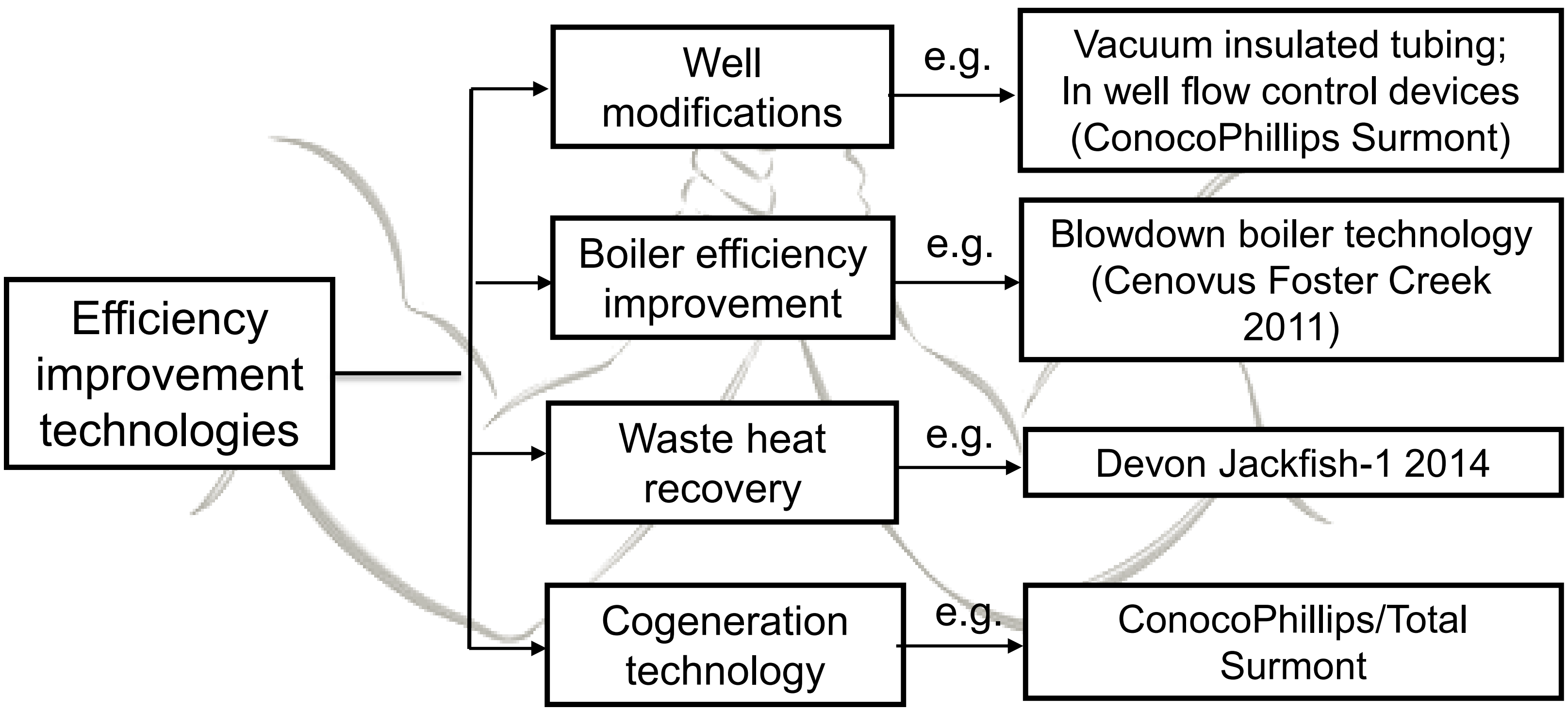
The main contribution to GHG emissions comes from in-situ operations resulting from the burning of natural gas to generate the steam.

 RESERVOIR SIMULATION GROUP

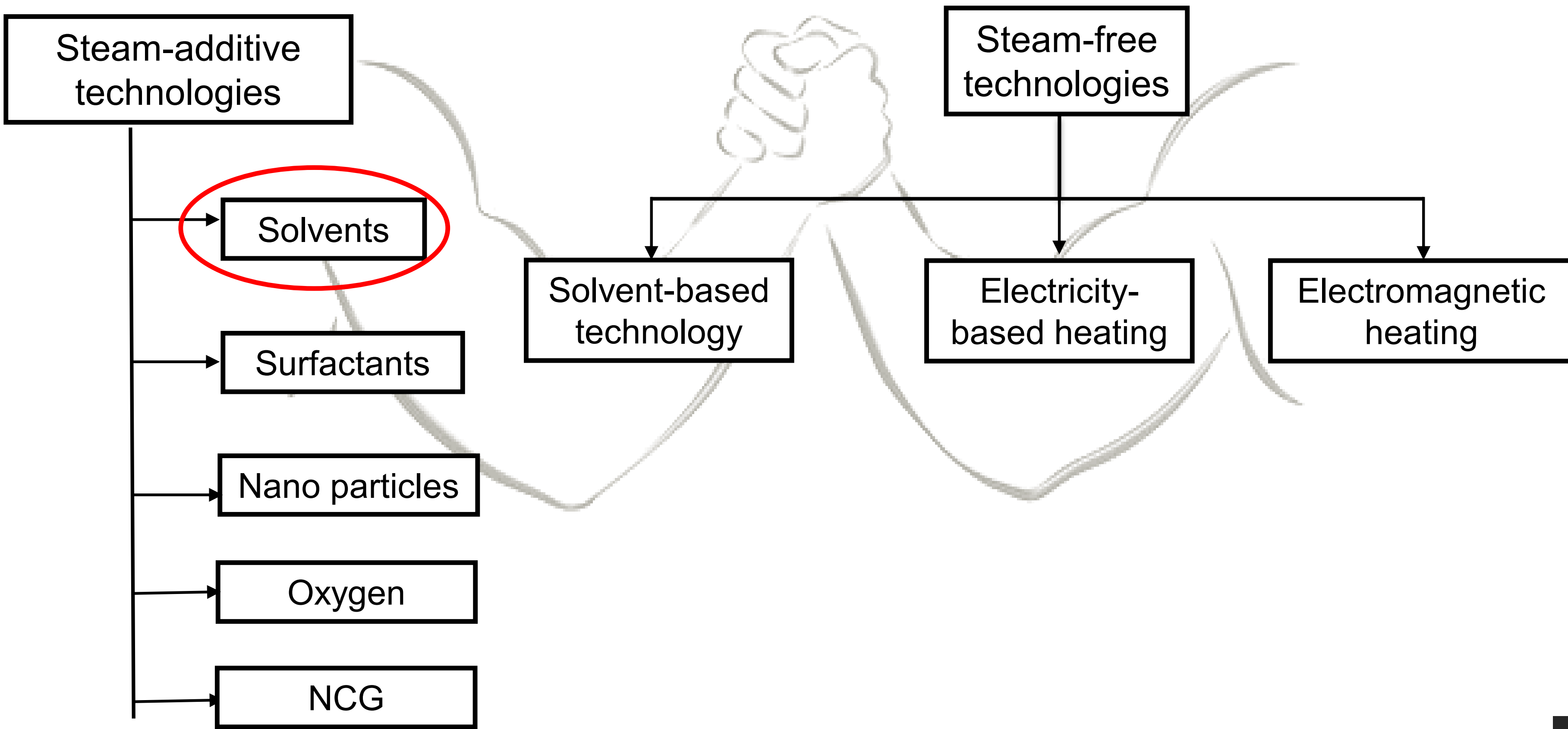
Technology Meets the Challenges!



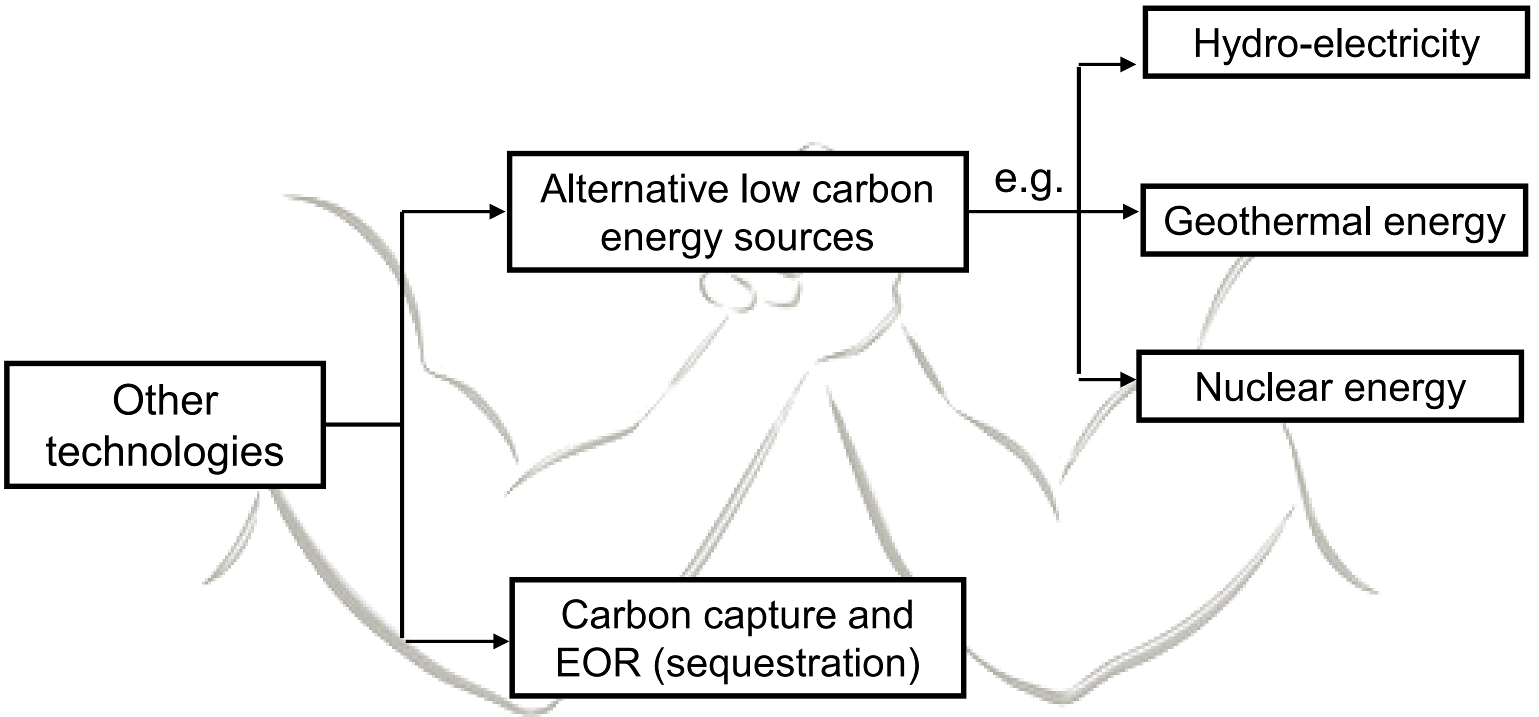
Technology Meets the Challenges!



Technology Meets the Challenges!



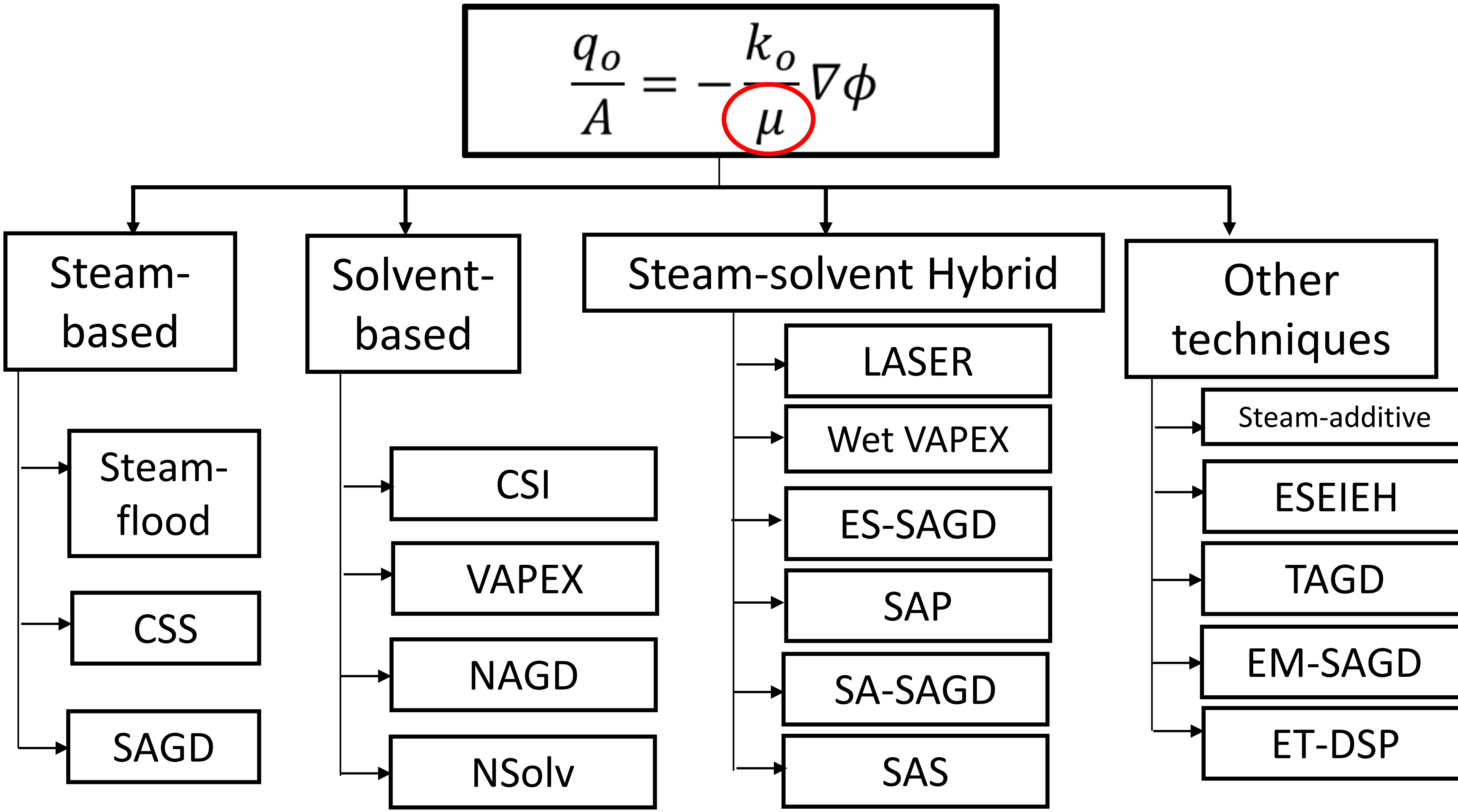
Technology Meets the Challenges!



Outline

- Background
- **Solvent-Aided Processes**
- Recent Industrial Solvent-Aided Pilots
- Lessons Learnt
- Challenges
- Way Ahead

Theory

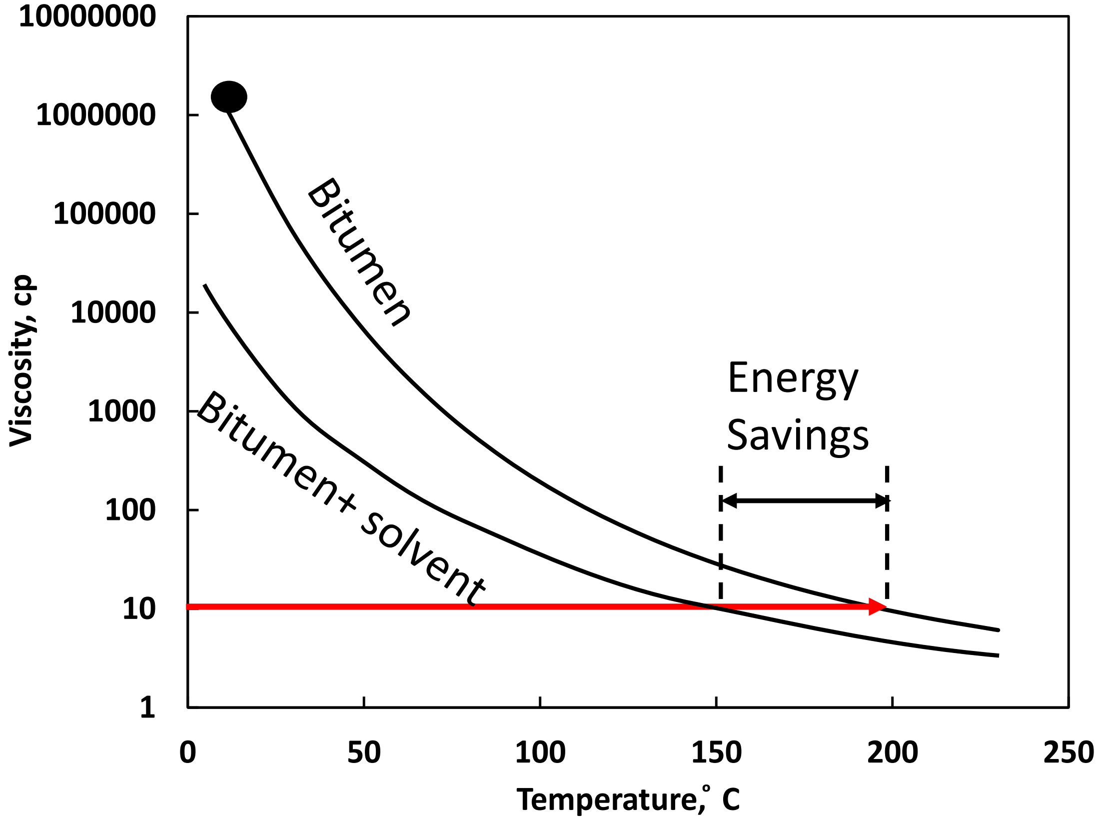


$$\frac{q_o}{A} = -\frac{k_o}{\mu}\nabla\phi$$
Steam-based
Steam-flood
CSS
SAGD
Solvent-based
CSI
VAPEX
NAGD
NSolv
Steam-solvent Hybrid
LASER
Wet VAPEX
ES-SAGD
SAP
SA-SAGD
SAS
Other techniques
Steam-additive
ESEIEH
TAGD
EM-SAGD
ET-DSP

Steam-Solvent Co-Injection

- ✓ Reduced water demand
- ✓ Reduced GHG emissions
- ✓ Uplift in the oil production rate
- ✓ Shorter project life
- ✓ Reduced SOR (energy intensity)
- ✓ Higher ultimate recovery factor
- ✓ Reduced requirements for pipeline transportation
- ✓ Potential for wider well spacing
- ✓ Potential for operation in areas with operating pressure constraint
- ✓ Potential for unlocking currently uneconomical reservoirs

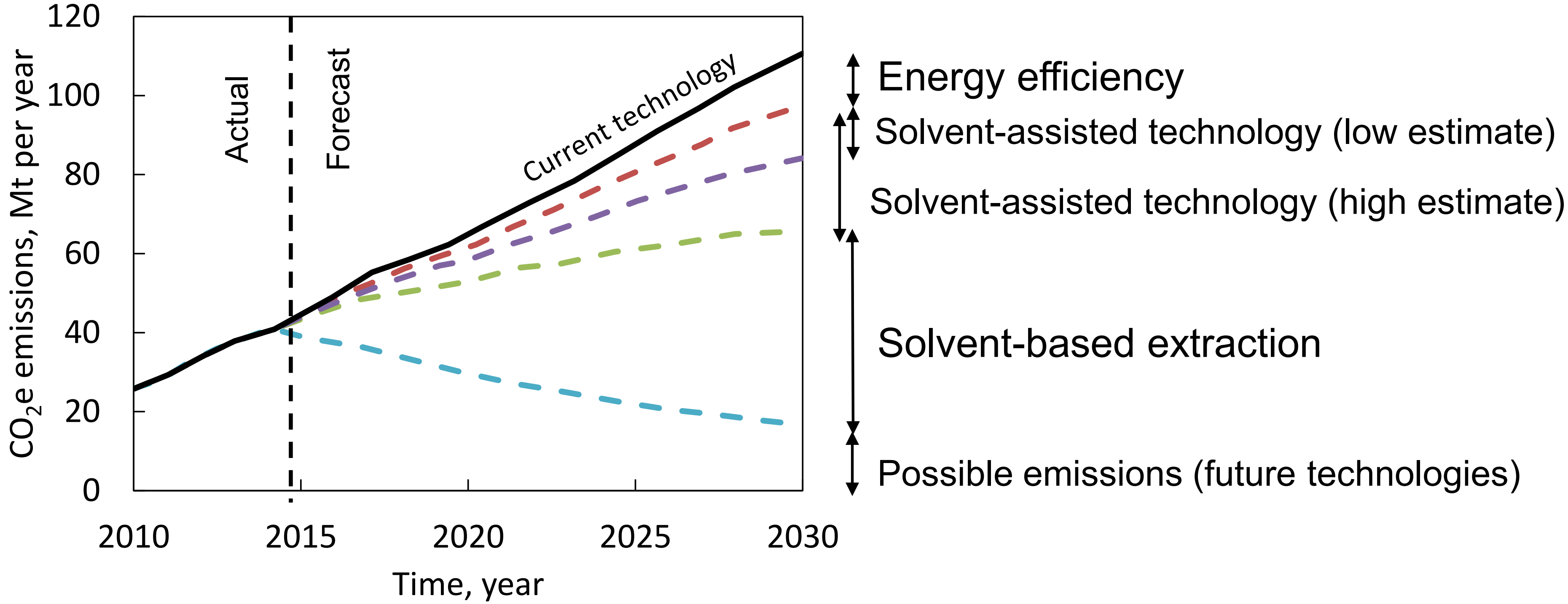
Energy Savings from Solvent Co-Injection



Target bitumen viscosity in most gravity drainage processes is ~10 cp.

With the aid of solvent, this viscosity can be achieved at a much lower temperature.

Impact of Solvent-Assisted on GHG Emissions



Source: Council of Canadian Academics (2015)

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Recent Industry Pilots

Company and project	Operating Pressure	Solvent	Concentration and duration	Performance w.r.t. base SAGD		
				Light*	Medium	Heavy
Encana/Cnv Senlac SAP (2002)	5000 kPa	C_4	15 wt% for 7 months	Improved oil rate and SOR	NA	NA
Encana/Cnv Christina Lake SAP (2004)	Not reported	C_4	15 wt% for ~1 year (initial co-injection plan: 3 years)	Improved oil rate and SOR	NA	NA
Cnv Christina Lake SAP (2009)	Variable (2200 to 2900 kPa)	C_4	Less than 25 wt% for ~2 years	Improved oil rate and SOR	NA	NA
Nexen Long Lake ES-SAGD (2006)	~1400 kPa	Jet B (consisting of mainly C_7 to C_{12})	5 vol% for 2 months	NA	NA	No improvement observed
IO Cold Lake SA-SAGD (2010)	~3500 kPa	Diluent (mixture of C_3 to C_{10})	up to 20 vol% for 8 months in WP-2 and then switched to WP-1	NA	Improved oil rate and SOR	NA

* Solvents are divided into three main categories in terms of their volatility: light solvents (volatility comparable to C4 and lighter), heavy solvents (volatility comparable to C8 and heavier) and medium solvents (in between the first two categories). For multi-component solvents, an average molecular weight is used as the criteria to include them in one of these categories.

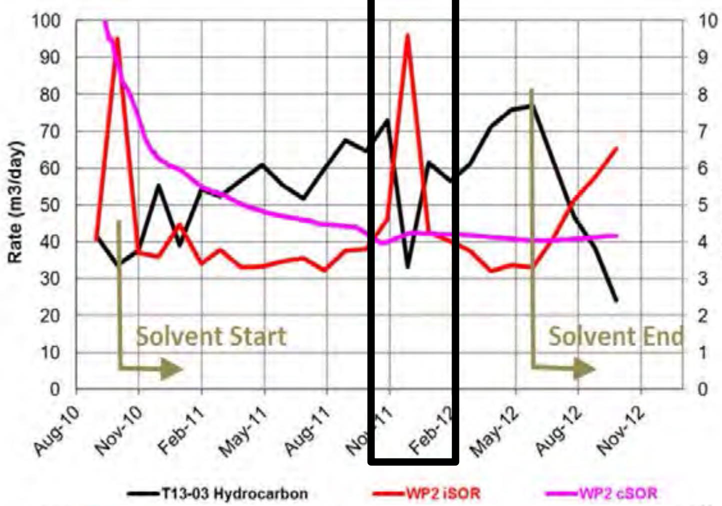
Recent Industry Pilots

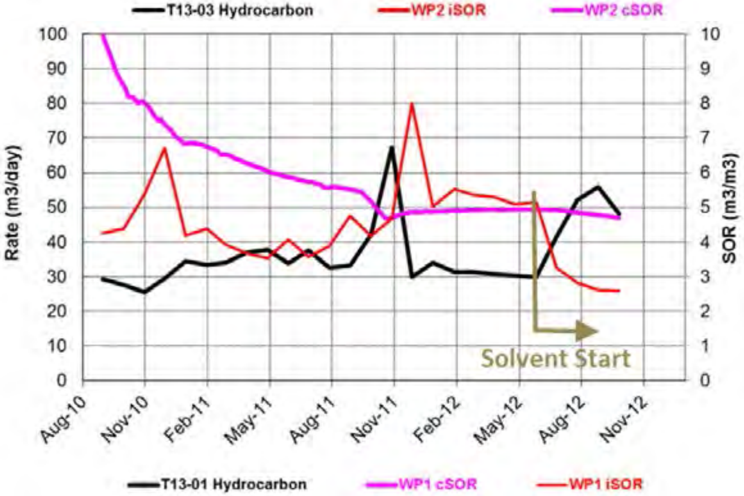
Company and project	Operating Pressure	Solvent	Concentration and duration	Performance w.r.t. base SAGD		
				Light*	Medium	Heavy
Connacher Algar SAGD+ Phase 1 (2011)	3500-4000 kPa	Condensate (consisting of mainly C_4 to C_8)	10 to 15 vol% for 5 months	NA	Improved oil rate and SOR	NA
Connacher Algar SAGD+ Phase 1.5 (2012)	3500-4000 kPa	Condensate (consisting of mainly C_4 to C_8)	10 to 15 vol% for ~ 3 years	NA	Improved oil rate and SOR	NA
Suncor Firebag ES-SAGD (2005)	~2500 kPa	Naphtha (mixture of C_7 to C_9)	15 vol% in one well pair and 2 vol% in the other well pair	NA	NA	Inconclusive
ConocoPhillips Surmont E-SAGD (2012)	~3500 kPa	A blend composed of mainly C_3, C_4 and C_6	18 vol% in one well pair and 20 vol% in the other well pair	Improved oil rate and SOR	Improved oil rate and SOR	NA
Devon JF SCI pilot (2013)	~2800 kPa	C_6	Up to 20 vol%	NA	Reduced both oil rate and steam requirements	NA

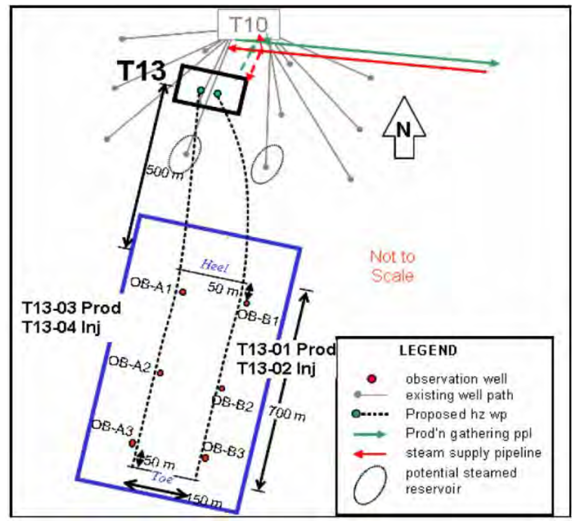
* Solvents are divided into three main categories in terms of their volatility: light solvents (volatility comparable to C4 and lighter), heavy solvents (volatility comparable to C8 and heavier) and medium solvents (in between the first two categories). For multi-component solvents, an average molecular weight is used as the criteria to include them in one of these categories

Closer Look at Imperial Oil SA-SAGD Pilot (2010)

Temporary stop in co-injection due to surface facility issues







Reservoir oil	Bitumen
Operating pressure	3500 kPa
Co-injected solvent	Mixture of C_3 to C_{10}
Co-injection start	After 3 months of SAGD in WP2 and ~2 years in WP2
Concentration	Up to 20 vol%

Reference: Dittaro, L.M. et al. 2013. Findings from a Solvent-Assisted SAGD Pilot at Cold Lake. Presented at the SPE Heavy Oil Conference Canada, Calgary, Alberta, Canada, June 11-13. SPE-165434.

- WP-2 HC production increased from 40 to 75 m^3/day and SOR reduced from 6 to less than 4 Sm^3/Sm^3 . WP-1 HC rate increased from 30 to 50 m^3/day and SOR reduced from 5 to less than 3 Sm^3/Sm^3.
- Solvent recovery from WP-2 more than 75%.

Closer Look at Nexen's ES-SAGD Pilot (2006)

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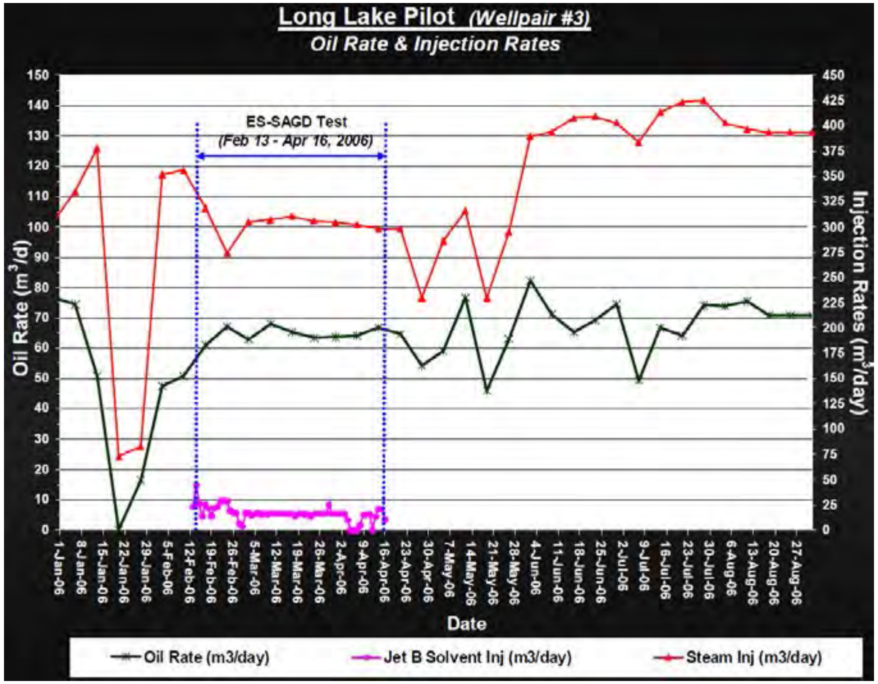

Reservoir oil	Bitumen
Operating pressure	1500 kPa
Co-injected solvent	Jet B (Blend of C_7 to C_{12})
Co-injection start	After 3 years of SAGD
Concentration	5 volume%
Duration	~ 2 months

Reference: Orr, B.W. 2009. ES-SAGD; Past, Present and Future. Presented at the SPE International Student Paper Contest at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA. October 4-7. SPE-129518.

- No significant changes in oil production rate and SOR were observed.
- Further phase behavior and simulation studies showed that a better performance may be expected with a lighter solvent such as Hexane.

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Upcoming Projects

- Cenovus FCCL Ltd (ConocoPhillips Canada, Alberta Innovates): Foster Creek, Alberta
- MEG Energy Corp. (Western Research Institute, Alberta Innovates): Near Conklin, Alberta
- Imperial oil is seeking approval for a commercial scale SA-SAGD in Cold Lake
- Suncor is planning to implement an ES-SAGD demonstration project in Firebag on half-pad scale in 2018
- More coming …

Lessons from Previous Pilots

- **Several pilots were inconclusive because of poor design and/or execution:**

- The Nexen 2006 pilot used a too heavy solvent for a too brief period of time,
- The Suncor Firebag 2005 pilot used a too low concentration (2 vol % was used), and
- The Devon 2013 pilot was conducted where the oil recovery was already at 54% which was much too high given that the solvent should be injected early to have a greatest effect.

Lessons from Previous Pilots

- Very thorough sampling and analysis of produced fluids is required in field tests to obtain a reliable value for solvent recovery.

- A good baseline is established with steam only to allow for proper comparison. Steady operation is also required to remove the effect changes in operating parameters.

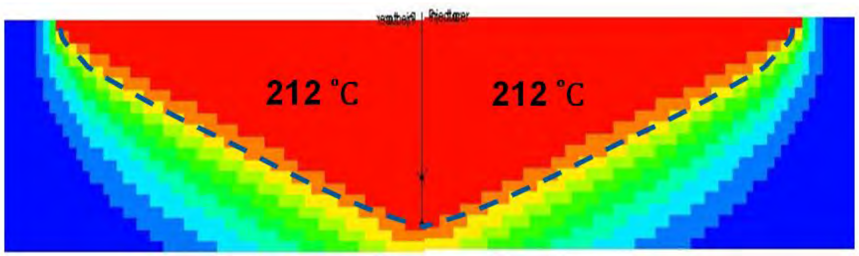
- The effects of reservoir heterogeneity on solvent/steam injection are not well understood.

Outline

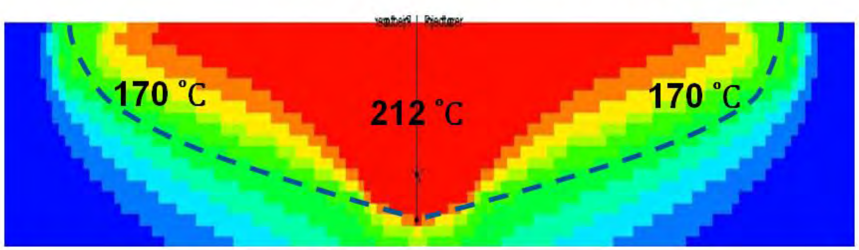
- Background
- Solvent-Aided Processes
- Recent Industrial Solvent-Aided Pilots
- **Lessons Learnt from Modeling Research**
- Challenges
- Way Ahead

Lessons Learnt

1. Addition of solvent alters the temperature profile inside a steam chamber (lower temperature in the vicinity of the chamber interface):



SAGD operating P = 2000 kPa



C_5- SAGD operating P = 2000 kPa
Continuous co-injection for 3 years (2 mole% of C_5)

Solvent volatility ⇧ ⇩ Temperature

Solvent accumulation

Lessons Learnt

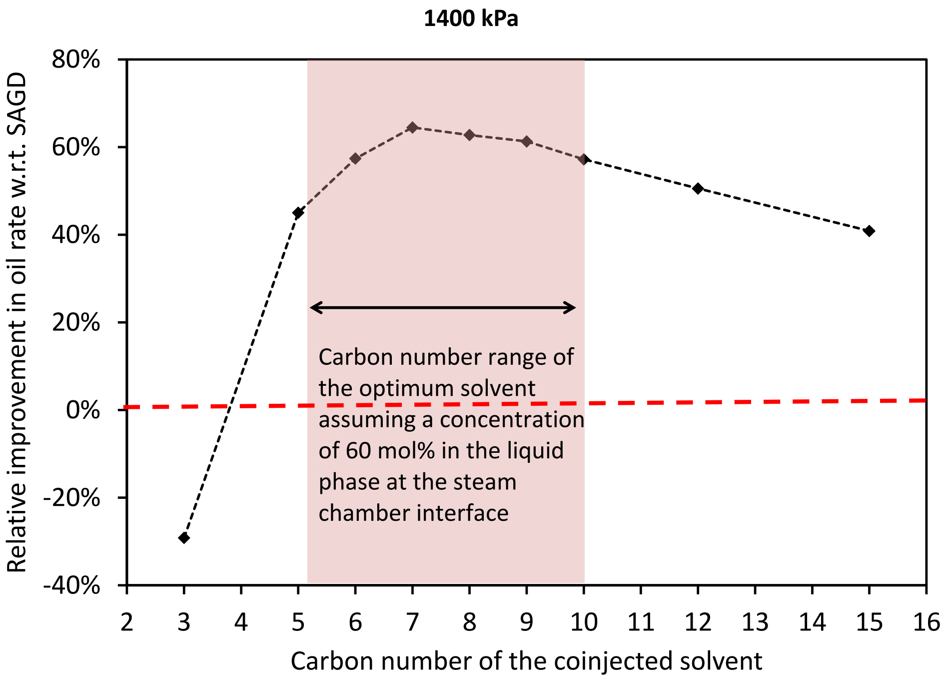
2. The oil rate uplift is a result of a tradeoff: lowered temperature at the steam interface (↓) and dilution as a result of mixing with solvent (↑).

Figure below comes from a co-injection analytical model developed by Keshavarz et al. (2016) for a typical Athabasca reservoir.

Very volatile solvents (e.g., C_3) may result in significant temperature drop.

Very heavy solvents (e.g., C_{12} and heavier) are not as efficient in diluting bitumen.

Both of these categories may be a sub-optimum choice of solvent for the oil rate uplift.



Properties	Values
Operating pressure	1400 kPa
Initial oil saturation	0.84
Residual oil saturation	0.14
Porosity	0.34
Horizontal permeability	2.35 (D)
Vertical permeability	1.99 (D)
Thermal diffusivity of the fully saturated reservoir	7E-7 (m^2/s)
Bitumen API	6.87
Solvent concentration in the liquid phase at the steam interface	60 mole%

Lessons Learnt

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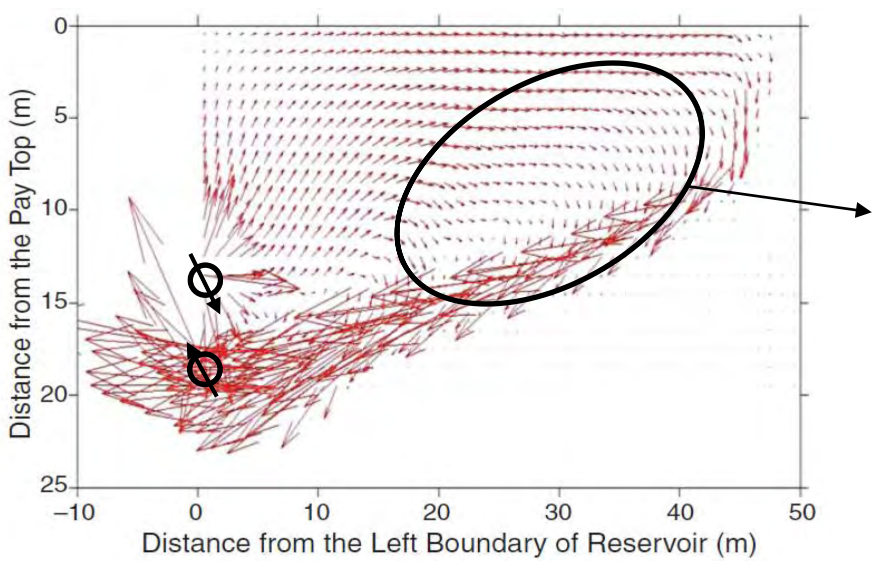
3. There is lots of inconsistency in terms of performance (in particular, an oil rate) improvement among industry applications.

4. An optimum choice of solvent varies with operating conditions and bitumen characteristics.

5. Most popular belief in industry: Proximity of steam and solvent saturation temperature will promote co-condensation at a steam front. This is not always true. In ES-SAGD, condensation of steam always occurs earlier than solvent.

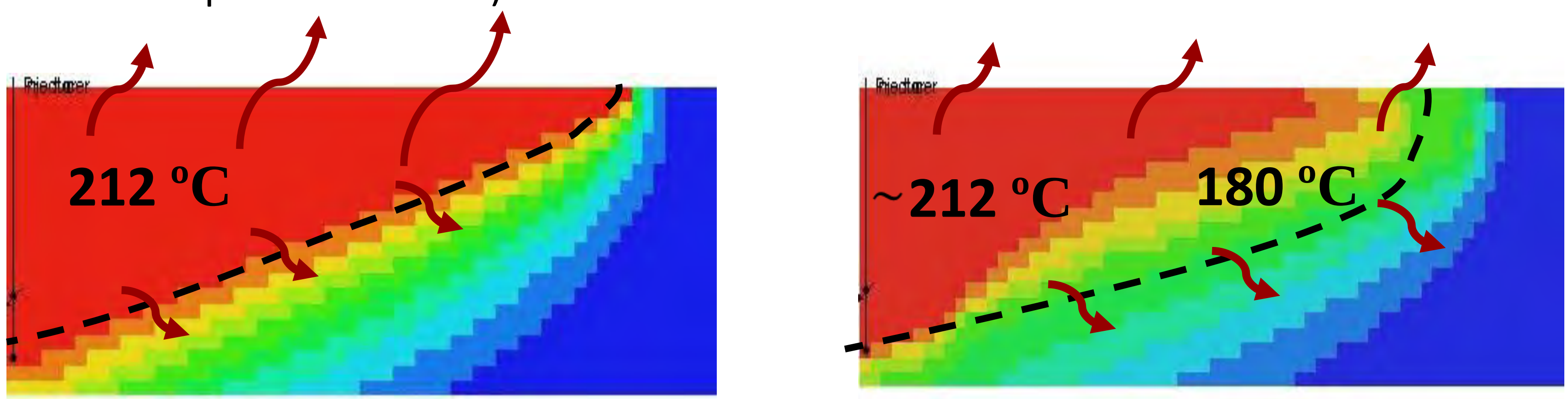


Picture shows vectors of water/steam flux in an ES-SAGD simulation with half of a symmetrical reservoir model. Condensation of steam happens deep inside the steam chamber.

Reference: Keshavarz et al. 2014b. Optimal application conditions for steam-solvent coinjection. *SPE Reservoir Engineering and Evaluation*, **18** (1): 20-38.

Lessons Learnt

6. Improvement in a steam-oil ratio compared to SAGD is due to two contributing factors:
   a. An improved oil production rate compared to SAGD.
   b. Reduced heat losses compared to SAGD (lower average temperature reduces heat loss to overburden and heat stored inside a chamber in the already depleted reservoir).



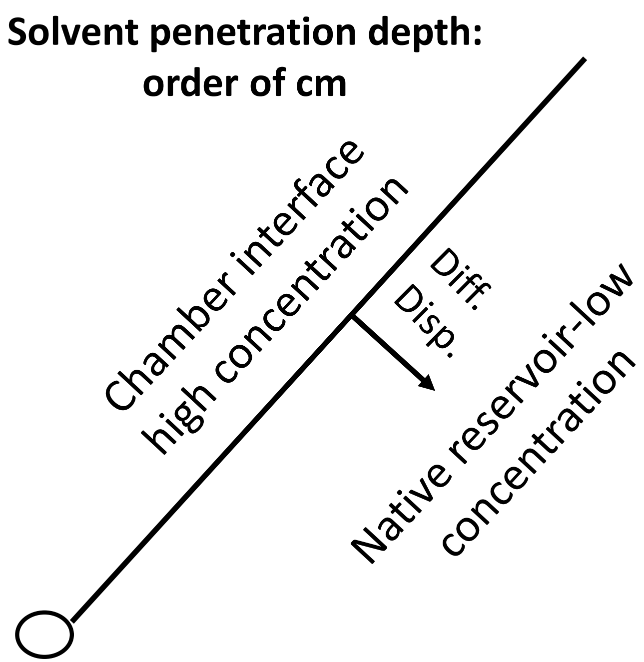
SAGD (2000 kPa)

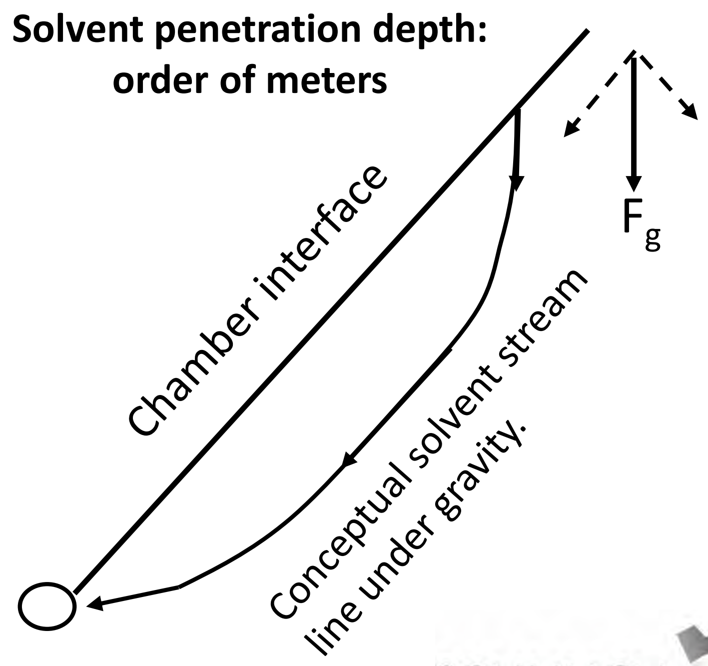
ES-SAGD (2000 kPa)

Lessons Learnt

7. The dominant mechanism in the mixing of solvent and bitumen at a steam interface seems to be convective flow under the impact of gravity rather than diffusive flow due to concentration gradient.

Mass transfer at the interface of steam chamber:
- Dispersion/Diffusion (drive: concentration gradient)
- Convection (drive: potential gradient)

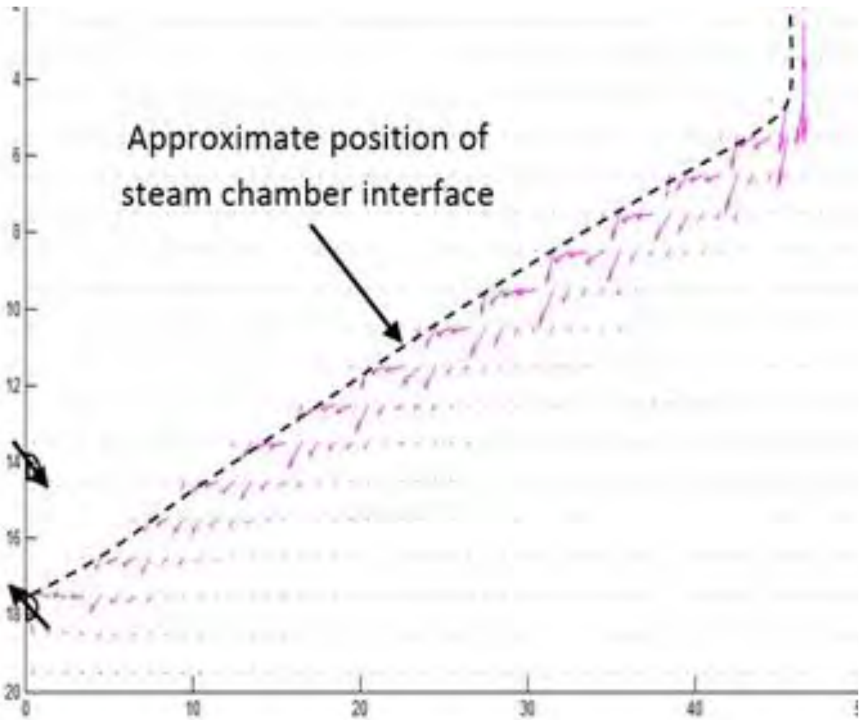




Lessons Learnt

7. The dominant mechanism in the mixing of solvent and bitumen at steam an interface seems to be convective flow under the impact of gravity rather than diffusive flow due to concentration gradient.

Evidence from numerical simulation



Chaotic arrangement of solvent flux vectors at the steam chamber interface due to convection enhances the mixing process.

Thickness of a mixing zone can be in the order of meters, well beyond what is expected of diffusion/dispersion alone.

Reference: Keshavarz et al. 2014b. Optimal application conditions for steam-solvent coinjection. *SPE Reservoir Engineering and Evaluation*, **18** (1): 20-38.

Lessons Learnt

7. The dominant mechanism in the mixing of solvent and bitumen at a steam interface seems to be convective flow under the impact of gravity rather than diffusive flow due to concentration gradient.

Evidence from the literature:

Successful history-matching of field applications without molecular diff./disp. or with grid-blocks coarser than required to capture them:

Encana/Cenovus SAP	⟶	Gupta et al. 2003; Keshavarz et al. 2014b
Imperial Oil SA-SAGD	⟶	Khaledi et al. 2015; Dickson et al. 2013
Connacher SAGD^{+TM}	⟶	Lau et al. 2012
Nexen ES-SAGD	⟶	Keshavarz et al. 2014b

Gupta and Gittins (2012): back-calculated diffusion coefficients 3 to 4 orders of magnitude greater than expected to match SAP field results.

VAPEX experiments: back-calculated diffusion coefficients orders of magnitude larger than expected to match experimental results (Dunn et al. 1989, Das and Butler 1998, Boustani and Maini 2001, …).

Lessons Learnt

8. Guidelines for a co-injection strategy:

   a. Solvent co-injection is mainly an acceleration process. Early start of co-injection expedites solvent benefits and allows enough time for its recovery after ceasing co-injection.
   b. Terminating co-injection during the final stages of the process and continuing with pure steam injection to allow sufficient time for solvent return.
   c. Retained solvent can be partially re-evaporated with pure steam injection (due to increased average reservoir temperature), which can then be produced/recovered.
   d. Re-evaporation of solvent can result in lower residual oil saturation inside a steam chamber compared to SAGD.

Outline

- Background
- Solvent-Aided Processes
- Recent Industrial Solvent-Aided Pilots
- Lessons Learnt
- **Challenges**
- Way Ahead

Challenges

1. Challenges in PVT modeling:

- Complex phase behavior, particularly with a multi-component solvent.
- Phase behavior modeling of bitumen-solvent-water mixtures with a cubic EOS.
- Modeling of potential asphaltene precipitation due to solvent dilution.
- Mixing models for conventional oils fail to give a reliable estimation of the density and viscosity of a bitumen-solvent mixture.
- These challenges require a lot of experimental data to tune the EOS/available correlations and reduce their predictive capabilities.

Challenges

2. Challenges in numerical simulation:

- Reliable representation of mixing mechanisms in the vicinity of a steam chamber interface is a challenge.
- Numerical dispersion when using coarse grid-blocks may result in overestimation of bitumen-solvent mixing in the vicinity of the chamber interface.
- Run time can be impractical with refined grid-blocks in a 3D heterogeneous field-scale model with a multi-component solvent.

Challenges

3. Challenges in mathematical modeling:

- Due to the complexity of the mechanisms involved, a purely analytical model may not be feasible for a co-injection process (a semi-analytical model seems more practical).
- Some of the main shortcomings/limitations of the available models in the literature:
    - Limited to a certain phase of the process
    - Inadequate phase behavior modeling
    - Neglecting convective mixing associated with gravity drainage
    - Neglecting the displacement efficiency improvement
    - Inadequate modeling of solvent retention and recovery
    - Inaccurate estimations on SOR

Note: Work (by M. Keshavarz) is in progress to develop a semi-analytical model for co-injection that can address some of the above challenges.

Challenges

4. Challenges in pilot/field applications:

- Solvent availability and supply.
- Compatibility of the co-injected solvent with surface facilities and costs of required modifications.
- Strong dependence of economics on solvent recovery which is a very uncertain and is not a very well understood topic.
- The need for frequent and reliable sampling/measurements to assess the performance of a pilot (e.g., compositions and flow rates of several streams need to be measured).
- Absence of a stable baseline production rate prior to co-injection and/or unforeseen variations/interruptions in operations during co-injection which make the assessment of solvent impacts more difficult.

Outline

- Background
- Solvent-Aided Processes
- Recent Industrial Solvent-Aided Pilots
- Lessons Learnt
- Challenges
- **Way Ahead**

Way Ahead

- A good understanding of the physics and chemistry of the co-injection process
- A good understanding of geology and rock/fluid properties of the reservoir
- A reliable simulation model that incorporates all important physics/chemistry occurring in the process
- A set of experimentally measured performance data under controlled conditions that can be used to validate the simulation model.

Way Ahead

An Evaluation Model will be needed to evaluate:

- **Technology**
- **Economics**
- **Energy intensity**
- **CO_2 intensity**
- **Co-injection strategy**
- **Solvent Wind Down**

Way Ahead

"Alone We Can Do So Little; Together We Can Do So Much" —Helen Keller

Success story: AOSTRA's UTF SAGD demonstration

Collaboration

Industry Initiatives
- R&D investment
- Timely adoption of new technologies
- Setting quantitative goals

Government Initiatives
- Environment
- Investments

Academia
- Focused research
- Practical research

Outline

Research Group

Research Collaborations

- **Collaboration with other labs**
  - Porous Media and Unconventional Oil Recovery Lab (Dr. M. Dong)
  - Energy High Bay (Dr. G. Moore and Dr. R. Mehta)
  - Hydrocarbon Upgrading Lab (Dr. P. Pereira)
  - Heavy Oil Properties Lab (Dr. H. Yarranton)
  - Solvent Enhanced SAGD Lab (Dr. B. Maini)
  - Solvent Enhanced Recovery Process Lab (Dr. J. Abedi)
  - **Simulation and Visualization Lab**
    - **Collaborator: Dr. Mario Costa Sousa (illustrares)**
    - **Collaborator: Dr. Ehud Sharlin (uTouch)**

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PhD (32) : Yi Pan, Mehdi Bahonar, Liping Zhu, Chao Dong, Amin Sharifi Haddad, Fan Liu, Seyed Ali Feizabadi, Ehsan Ranjbar, Seyed Reza (Shauheen) Etminan, Shaohua Gu, Wenchao Liu, Mojtaba Seifi, Yizheng Wei, Thanh Quy Cuong Dang, Arash Mirzabozorg, Vahid Hematfar, Jie Fan, Wisam Shaker, Loran Taabbodi, Mohammad Kyanpour, He (Mark) Zhong, Morteza Dejam, Mohamad Mojarab, Kevin Guo, Wenhao Chen, Dashuang He, Jian Yang, Jack (Hui) Deng, Jiangyong Hou, Mingjun Chen, Geoff Brown, and Kai Zhang

Post-docs (24): Hassan Hassanzadeh, Jian Li, Hongsen Chen, Xiaoping Liu, Kola Liadi Mudashiru, Karim Ghesmat, Ali Pourahmadi Laleh, Dharmeshkumar Gotawala, Nguyen Thi Bich Ngoc, Chenchen Wang, Ehsan Ranjbar, Majid Ahmadlouydarab, Hui Liu, Shanbo Mou, Jubran Akram, Xiaohu Dong, Xinfeng Jia, Guoxuan Ren, Keliu Wu, Kun Wang, Jia Luo, Mark Zhong, Roberta Cabral Mota, and Jing Li

Student Employment

UNIVERSITY OF CALGARY

- Devon
- Schlumberger
- Three Steam
- Suncor
- Nexen
- AMEC
- Surgutneftegas
- Sunshine
- ADCO, Abu Dhabi
- Laricina
- Alberta Innovates
- Canada Revenue Agency
- University of Calgary
- BP Canada
- Occidental Petroleum in Houston
- Many universities worldwide
- Sasol
- Cenovus Energy
- Penn West
- Husky Energy
- AJM-Deloitte
- Gushor
- Southern Pacific
- Weather Ford
- EnCana
- ConocoPhillips
- CMG Ltd.
- Jacobs
- Baker Hughes
- Apache
- CNR Ltd.
- Zonton Energy
- Koch

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HQP Global Dissemination

Current Research Group

UNIVERSITY OF CALGARY

Graduate Students : over 50 MSc and PhD

Post Docs and RAs: 11

Project Manager

Technical Managers

Administrative Assistants

Research Collaborators from Industry and Academia Globally

SCHULICH School of Engineering UNIVERSITY OF CALGARY

Multidisciplinary Program

Mathematics and Statistics

Computer Science

Geology (Geophysics)

Chemical and Petroleum Engineering

Electrical and Mechanical Engineering

Sponsors

5 Federal Funding Agencies

Natural Sciences and Engineering Research Council of Canada (NSERC)

Alberta Innovates Energy Environment Solutions (AIEES)

Alberta Innovates Technology Futures (AITF)
Informatics Circle of Research Excellence (iCORE)

Canada Foundation for Innovation (CFI)

Alberta Advanced Education and Technology (AET)

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- ConocoPhillips
- Devon Energy
- Husky Energy Ltd.
- IBM Canada
- Imperial Oil
- Kerui Group
- Laricina Energy Ltd.
- Shell
- Nexen
- PetroChina - RIPED
- Sherritt
- Statoil
- Suncor
- Swan Hill Synfuels Inc.
- IBM Alberta Centre for Advanced Studies

Research Resources

Advanced simulation (commercial and research) software

Computing hardware – EXAS IBM Cluster

CMG Simulation Laboratory

FCMG Frank and Sarah Meyer Collaboration Center for Simulation & Visualization Integration

Advanced oil/gas recovery laboratories

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Collaborator: Dr. Thomas G. Harding

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Linking Technology Development and Field Piloting

Haibo Huang

AACI Research Program

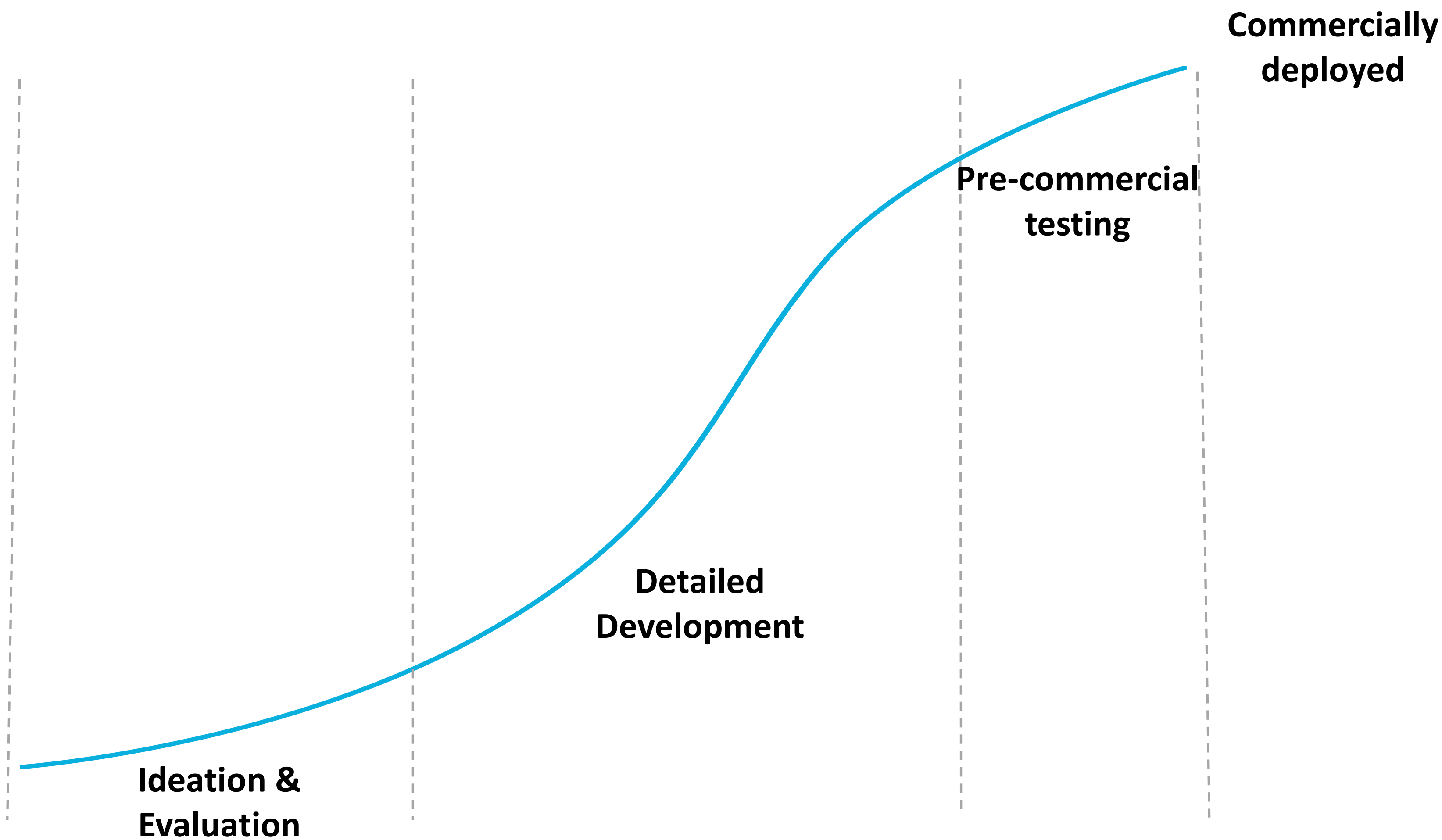
- Established R&D consortium in 1983, with AOSTRA (now AI Clean Energy), ARC (now InnoTech Alberta), and a number of industry participants
- Areas of R&D
  - ➢In-situ recovery processes for heavy oil and bitumen
  - ➢Reservoir and near wellbore phenomena (experimental & numerical simulation)
- Directed by the oil sands industry and managed by InnoTech Alberta (previously AITF/ARC)
- Renewed every 5 years with new strategic directions

AACI Research Efforts on in-situ Processes Involving Solvent

Technologies in Detailed Development Stage	Reservoir Type
▪ Steam-solvent co-injection processes (ES-SAGD, SBH, SAP) ▪ Vapor solvent assisted gravity drainage process (Vapex) ▪ Thermal solvent reflux process ▪ Solvent liquid alternating gas injection process (SLAG)	Immobile
▪ Cyclic solvent injection (CSI) process to follow up CHOPS	Mobile

AACI research in ES-SAGD, CSI, Vapex has direct involvement in pilot activities

Recovery Technology Development Path



AACI Technology Development Stage Gate Criteria

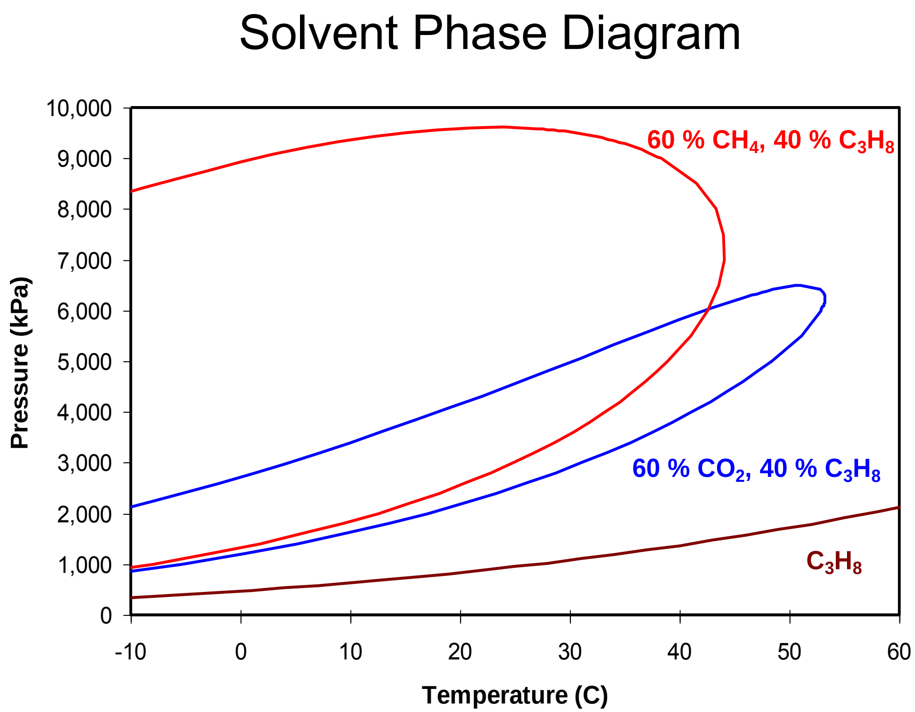
Knowledge category	Decision Gate Criteria – End of Detailed Development
Fundamentals	Comprehensive understanding of parameters defining technical performance of the technology
	Understanding of the target reservoir and all relevant formation and injected fluids
Mechanisms	Comprehensive understanding of mechanisms critical to the technology (all relevant physical and chemical processes)
Prediction	Documented understanding of extrapolation of lab results to field by scaling (scaling model)
	Credible basis to predict field performance (analytical, numerical models)
Commercial viability	Complete implementation scheme defined and documented
	Credible basis to quantify all key factors affecting economic and developmental performance
	Positive industry vetting

Recent AACI Research Efforts on Solvent Processes

Development stage technologies

- Early phase - Vapex
- Mid-phase - Steam-butane hybrid process (SBH)
- Piloting phase (determines viability)
  - Expanding solvent-SAGD (ES-SAGD)
  - Cyclic solvent injection (CSI)

Solvent Selection

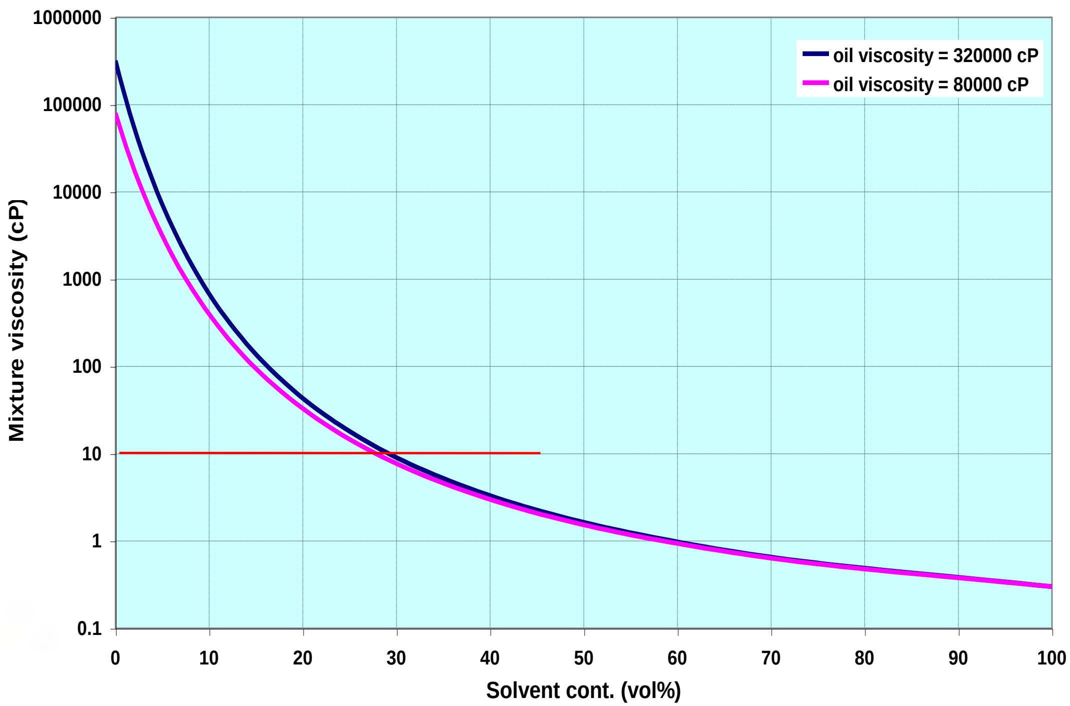


Important factors

- Reservoir conditions
  - Pay
  - Geophysics & geochemistry
  - Temperature
  - Pressure
- Oil properties
  - Density
  - Viscosity
  - Composition
- Solvent properties
  - Solubility in oil
  - Phase behaviour
  - Compatibility with oil

Fundamental Driver in Solvent Processes

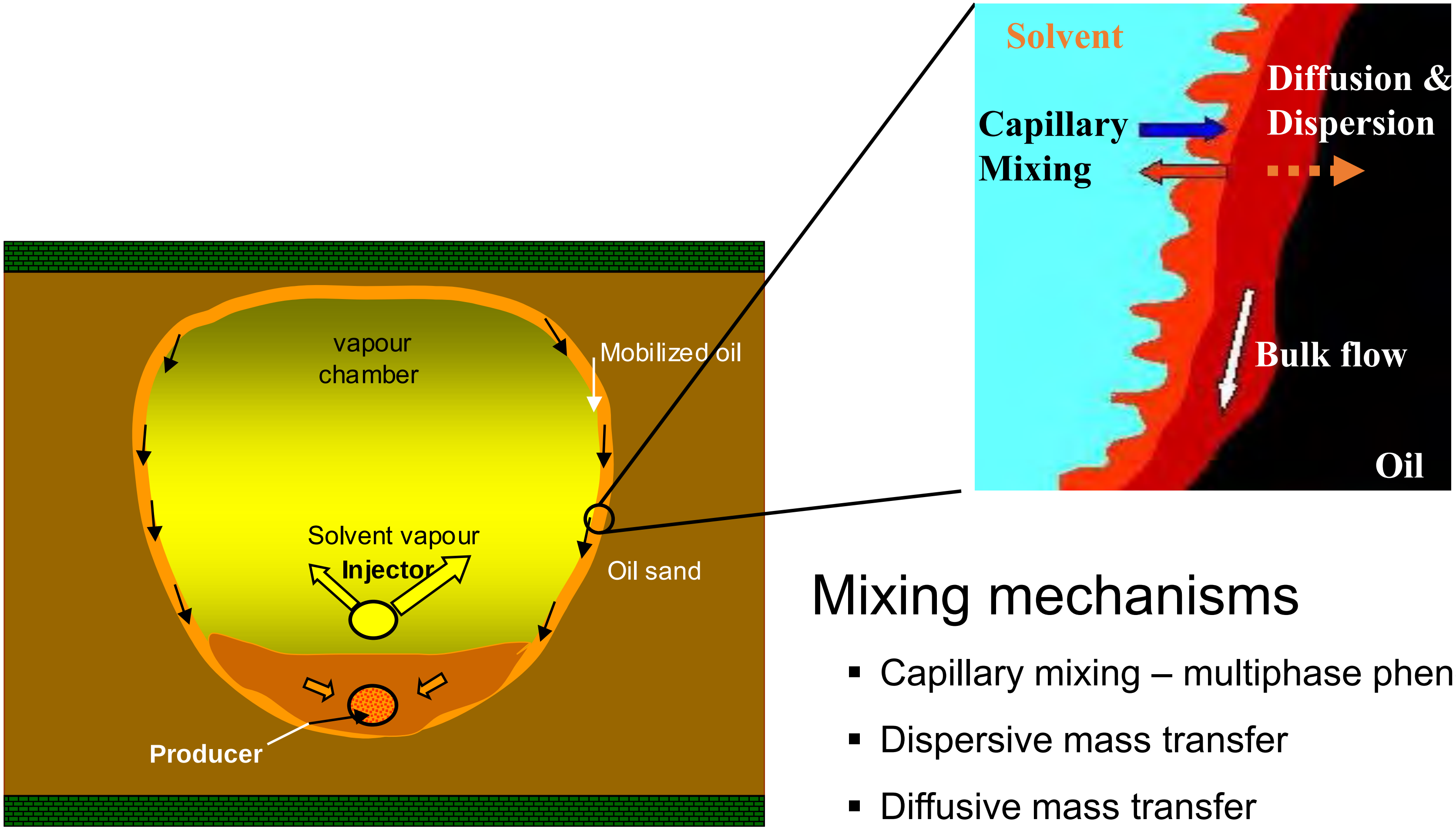
- Increasing oil mobility/transportability in porous media - reduced oil viscosity by solvent dilution



$$Q_{oil} = \frac{kA}{\mu_{oil}}\left(\frac{\Delta P}{\Delta L}\right)$$

$$\mu_{oil+solv} = f(c_{solv})$$

Vapex Process Scheme



Mixing mechanisms

- Capillary mixing – multiphase phenomenon
- Dispersive mass transfer
- Diffusive mass transfer

Drainage Characteristics in Vapex Process

Semi field scale 2D visual model (1.5m H x 2.5m W) Vapex experiment was conducted to study drainage characteristics in Vapex process

- Field condition sand
- Heavy oil
- N-butane

Simulation closely history matched the experiment when applying

- Heterogeneity effect
- Diff. mass transfer ($D = 4 \times 10^{-5}$ m^2/d)
- Disp. mass transfer (K ~ 10xD)
- Gas-oil capillary pressure (1~2 kPa)

Heterogeneity Impact in Vapex Process

- Significant heterogeneity effect on Vapex behaviour
  - Subtle permeability condition (packing variability)
  - Low permeability barriers
- Strong chamber growth in the horizontal direction

Impact of Asphaltene Behaviour in Vapex

Asphaltene/asphalts precipitate could deposit in reservoir

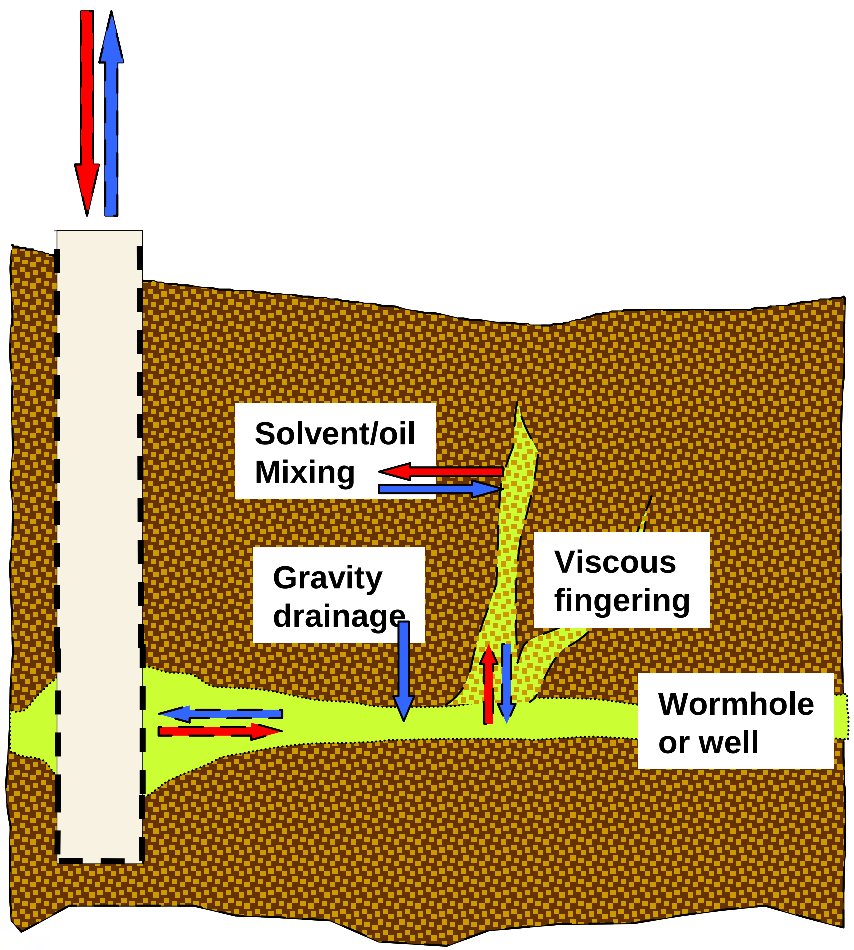
- Benefits
  - Additional viscosity reduction – higher mobility
  - Selective production of oil – better quality
- Problems
  - Plugging in reservoir – reducing permeability
  - Plugging facilities – increasing operating cost

- Asphaltene precipitation occurs in oil when solvent content exceeds the pptn. onset point, which varies with solvent
- Flow of oil-solvent fluid with low quantity precipitate
  - Slow build up of deposition in porous media
  - No strong plugging with high volume flowed
- Flow of oil-solvent fluid with high quantity precipitate
  - Strong deposition in porous media
  - Gradual increase of resistance to flow, leads to plugging
- Asphaltene precipitate potentially causes plugging

Vapex Process Summary

- **Advantages**
  - High recovery ~ 60 %
  - Low water, energy, completion and facility costs
  - Reduced GHG and potential for upgraded oil
  - In reservoirs with some oil mobility may use staggered well configurations with existing wells
- **Disadvantages**
  - Low rates
  - Start-up is a challenging operation
  - As viscosity increases pay thickness must increase
  - Potential asphaltene issues
  - Solvent cost and availability
- **Current Status**
  - Classic Vapex has been piloted with mixed results

CSI Process Scheme



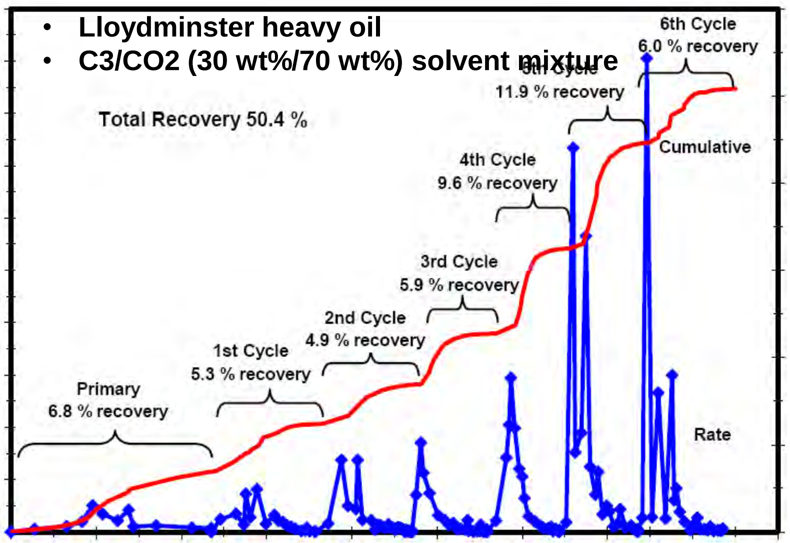
Solvent injection cycle

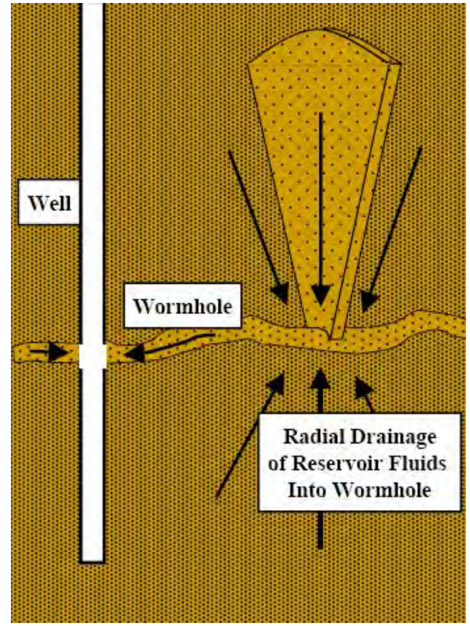
- Increasing pressure
- Viscous fingering
- Solvent dissolution in oil
  - Convective dispersion
  - Molecular diffusion
- Solvent phase change (gas →liquid)
- Oil redistribution
  - Oil swelling
  - Gravity drainage

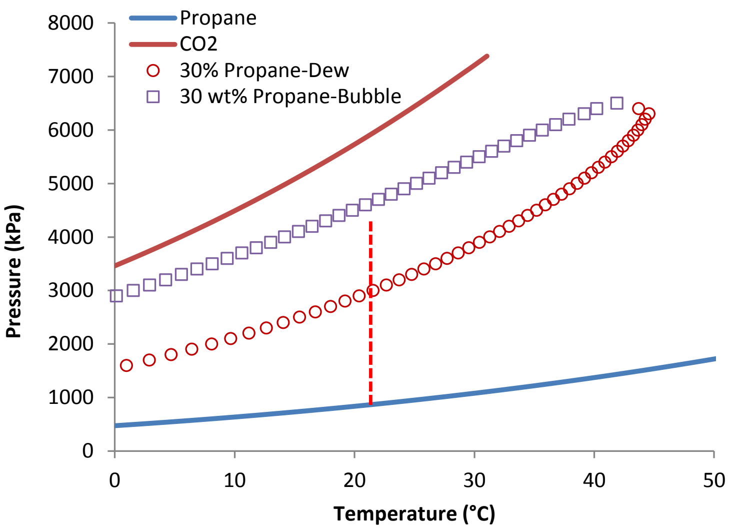
Fluid production cycle

- Decreasing pressure
- Solvent exsolution from oil
  - Foamy oil drive
- Solvent phase change (liquid → gas)
  - Gas expansion drive
- Gravity drainage

CSI Laboratory Model Expt.







Radial drainage experiment to mimic CSI process – represents drainage into wormhole

CSI Development Focuses

- Main CSI application target - thin post-CHOPS heavy oil reservoirs
- Solvent systems – C_2, C_1/C_3, C_3/CO_2, CO_2
- Improvement to CSI modelling - multi-well field scale numerical simulation incorporated with important mechanisms determined from experiments and measured fluid properties

CSI Process Behaviour

- Process characteristics
  - Foamy oil drive has strong impact on oil production in CSI
  - In applying pressure support from an offset well
    - Require low offset gas injection rate to avoid gravity over-ride
    - A CO_2/C_3 mixture performs better than either C_1 or CO_2 (solubility effect)
- Process fundamentals – solvent dissolution in oil
  - C_3 and a C_3/CO_2 mixture dissolve faster in dead oil
  - CO_2 dissolves 2-3 times faster in lived heavy oil than in dead oil
  - Non-equilibrium behaviour plays a significant role in processes using gas mixtures

CSI Process Behaviour

- Process modeling
  - Improved CSI simulation models with the quantified process mechanisms
  - Sensitivity study of CSI performance by field scale CSI simulation
    - Oil production is more dependent on pay thickness than on dead oil viscosity
    - Oil production has little dependence on the layer where dominant wormholes are located
- Process economics (preliminary)
  - CSI could be economic for 50 – 75 CAD/bbl oil with process optimization
  - Only marginally affected by C_3 price

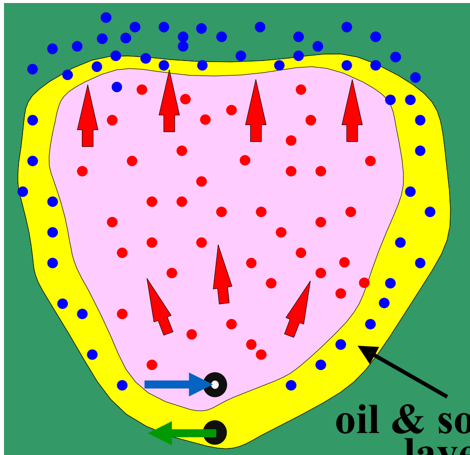
Gaps in CSI Development

- Understanding and characterization of wormholes
  - Wormhole location and distribution
  - Effective ways of utilizing them for CSI
- Solvent systems that increases oil mobility and facilitates/sustain foamy oil behaviour
- Reduce solvent retention
- Reservoir containment

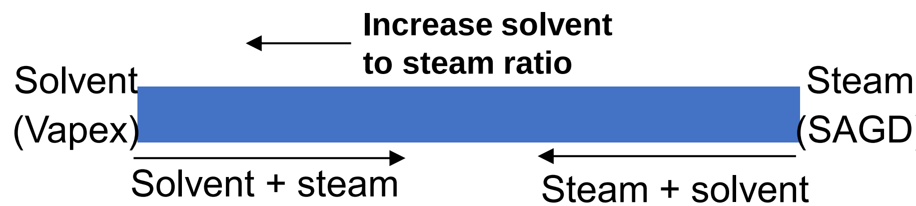
CSI Process Summary

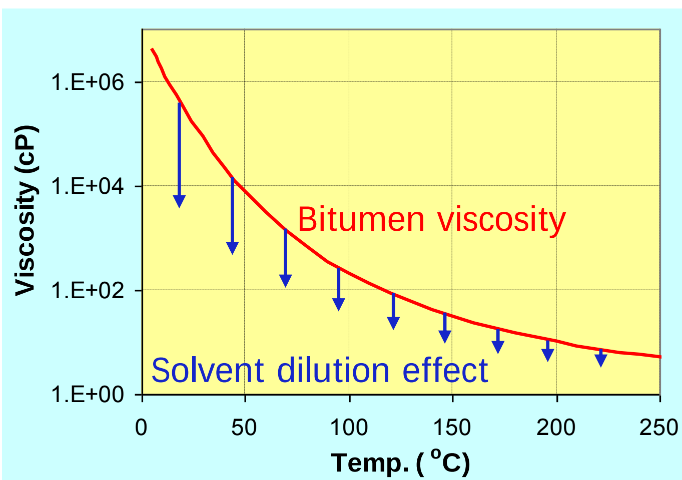
- **Advantages**
  - Test results demonstrated CSI potential as a follow-up process
  - Use existing wells for injection of solvents
- **Disadvantages**
  - Cannot be used in reservoir with gas cap or bottom water
  - Solvent cost and availability
- **Current Status**
  - Pilot tested, incremental RF not yet determined/established

Steam-Solvent Co-injection Process Schematic



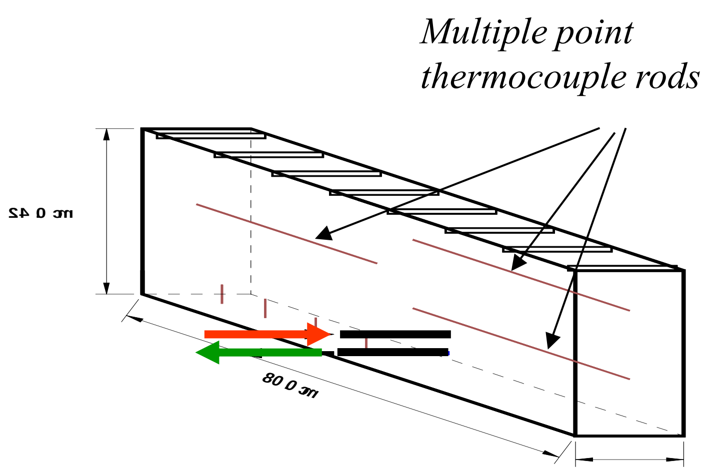
Hybrid co-injection spectrum



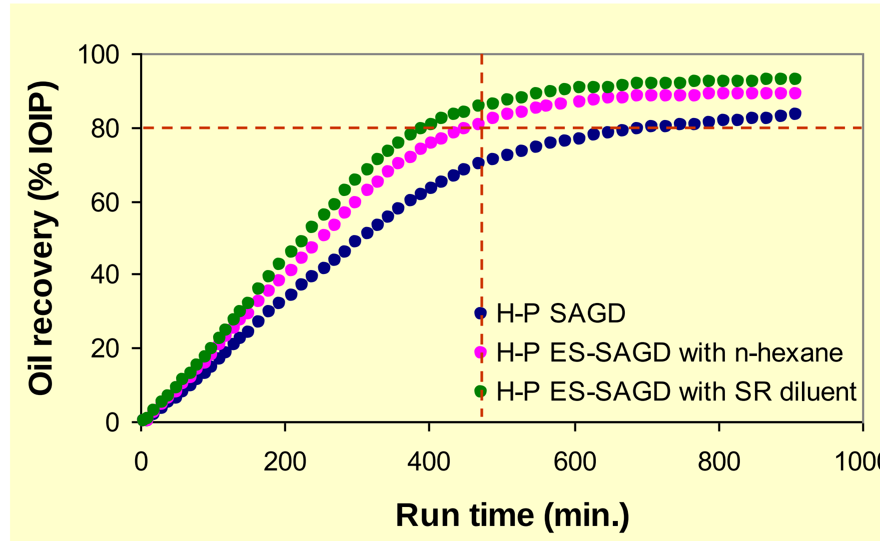


- Utilize heat and solvent-dilution to mobilize high viscosity oil (bitumen/heavy oil) in reservoir

Parametric Study of ES-SAGD



80cm (L) × 24 cm (H) × 10cm (D)



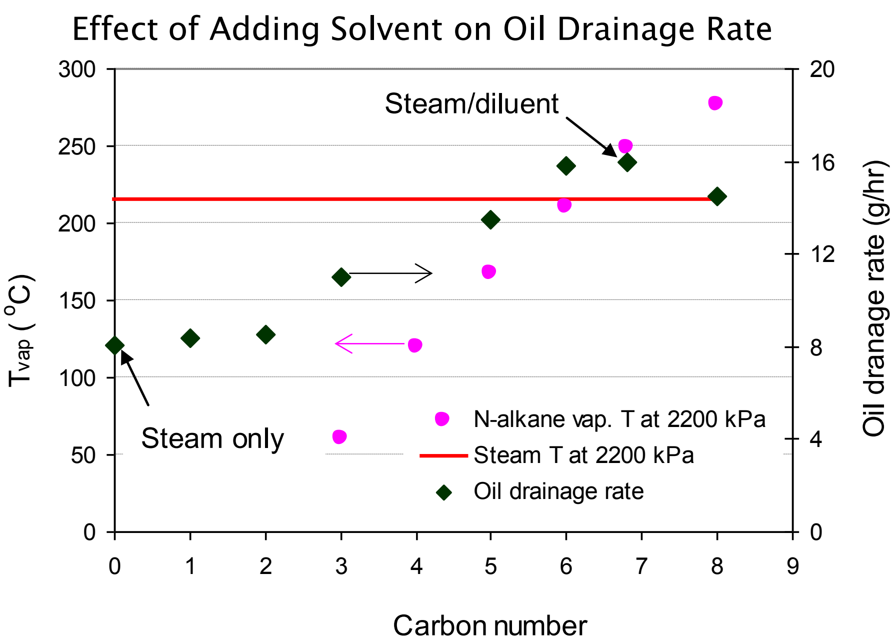
Adding intermediate hydrocarbon solvent to steam improved process performance

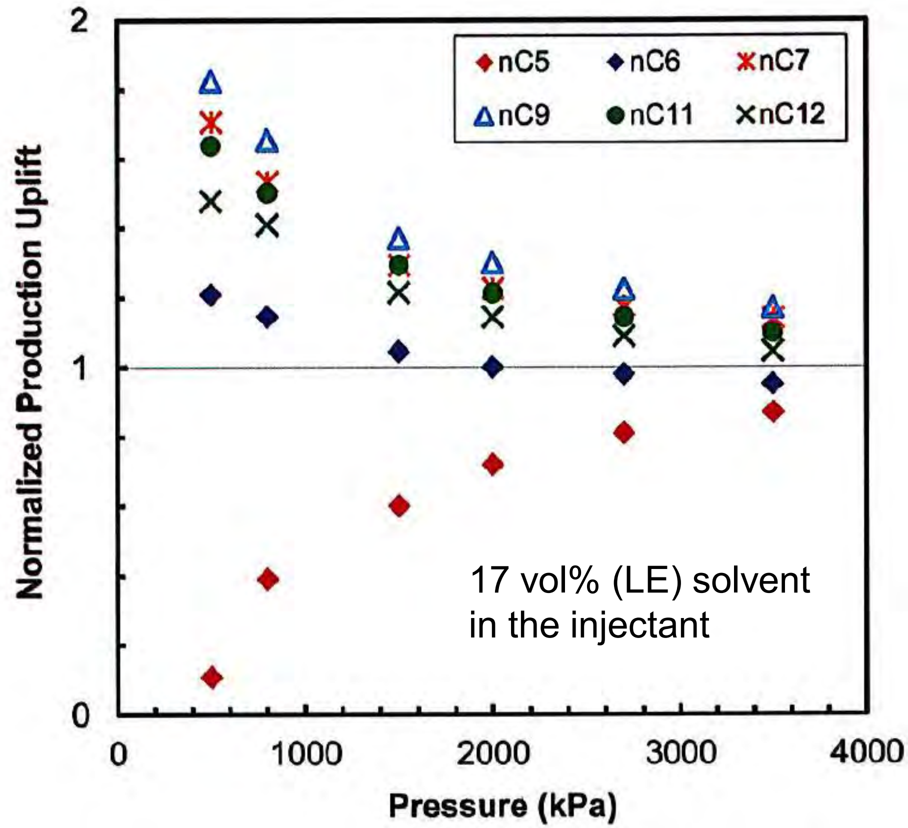
- Oil rate increased in early stage of operation (reduces operation time for the same RF)
- Increased oil recovery (10~14% increase in RF)

Hybrid Process Development Focuses

- Main hybrid processes application target – thick bitumen and heavy oil reservoirs
- Close the gaps in the fundamentals and mechanisms of ES-SAGD process (relatively low solvent loading)
- Develop a credible numerical tool for ES-SAGD field performance prediction
- Determine & quantify the high solvent loading SBH process mechanisms

Co-injection Process Solvent Selection Guideline





R. Khaledi, "Optimized Solvent Assisted-Steam Assisted Gravity Drainage (SA-SAGD) Recovery Processes", 2015, SPE 174429

Advancement in ES-SAGD Development

Process fundamentals

- Solvent behaviour in the chamber
  - Solvent vapor accumulates/condenses along the boundary of the chamber thus forming a zone with high solvent content (experiment)

Three distinct zones in ES-SAGD reservoir

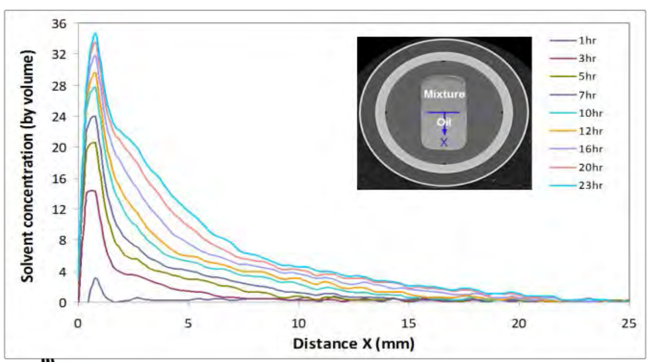
- High bitumen content – undepleted area
- Very low bitumen content and high solvent content – drainage front
- Low bitumen content – depletion area

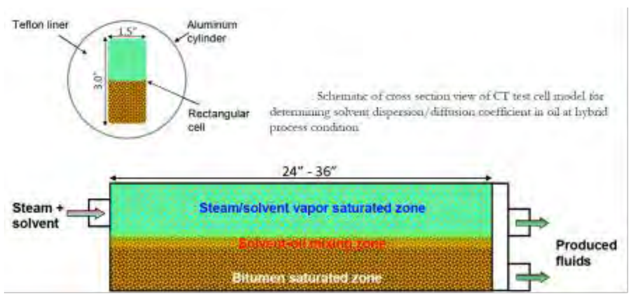
Process fundamentals

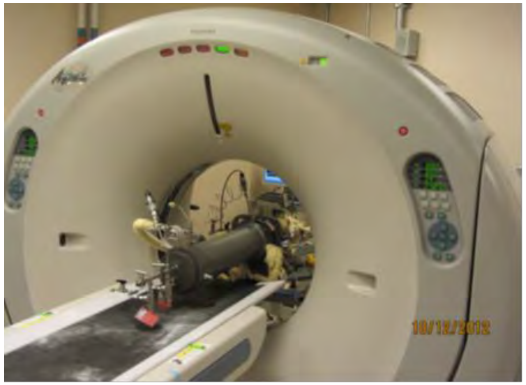
- Fluid properties & phase behaviour
  - A fluid model of the Athabasca bitumen/solvent fluid system with different solvent (C_4 – C_8) for ES-SAGD process (solvent solubility & viscosity reduction correlation)
  - Low solubility of hydrocarbons (C_4 – C_8) in water under ES-SAGD condition – solvent loss through dissolving in water will be low

Process fundamentals

- Key solvent mass transfer mechanisms in field condition porous medium at ES-SAGD process temp.
  - Solvent diffusivity in bitumen
  - Solvent dispersivity in bitumen at realistic oil phase flow velocity
  - Capillary pressure of vapor solvent-oil
  - Solvent penetration depth in porous media

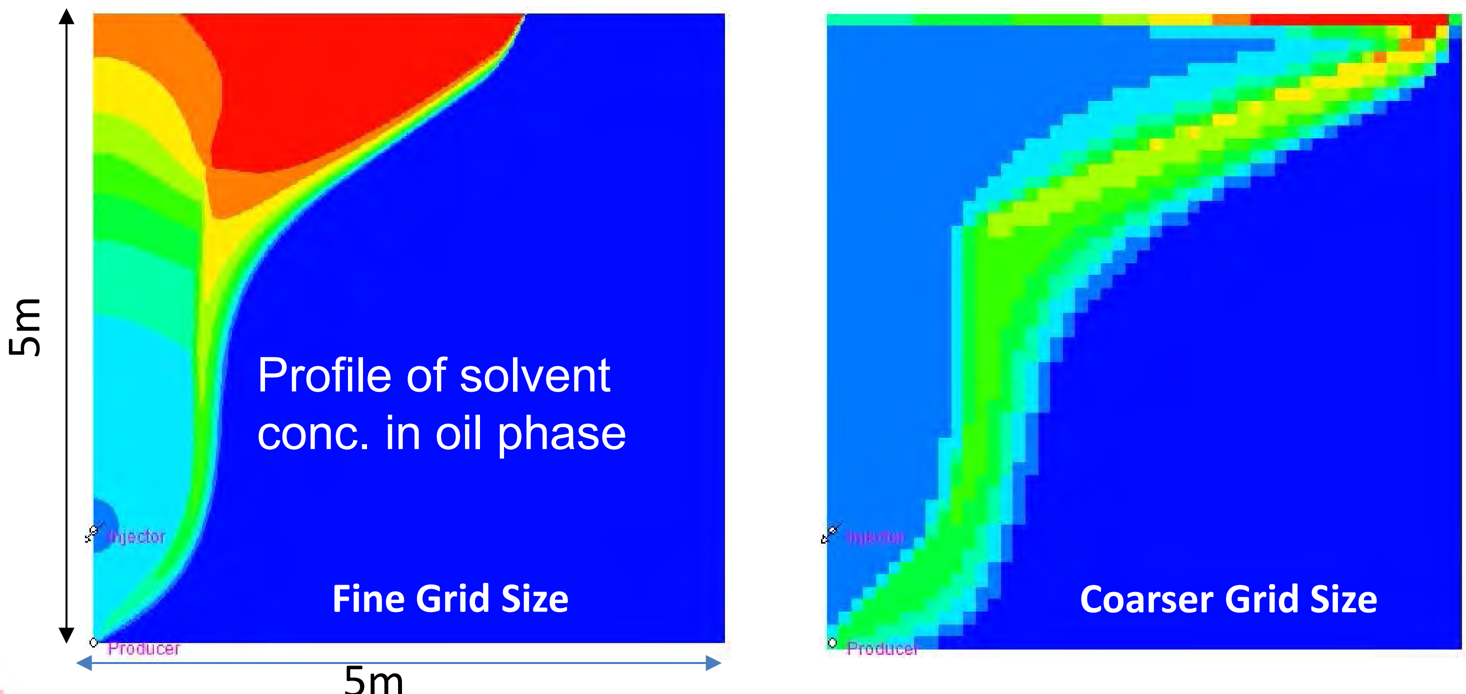






Process modeling

- History matching of semi field ES-SAGD experiments (inj./prod., T, solvent conc., water saturation) with implementing the quantified mechanisms, using different grid size (1cm - 10cm)
- Good match between expt. extrapolation and simulation with grid size of < 10 cm, significant discrepancy with 10cm grid size



Advancement in SBH Development

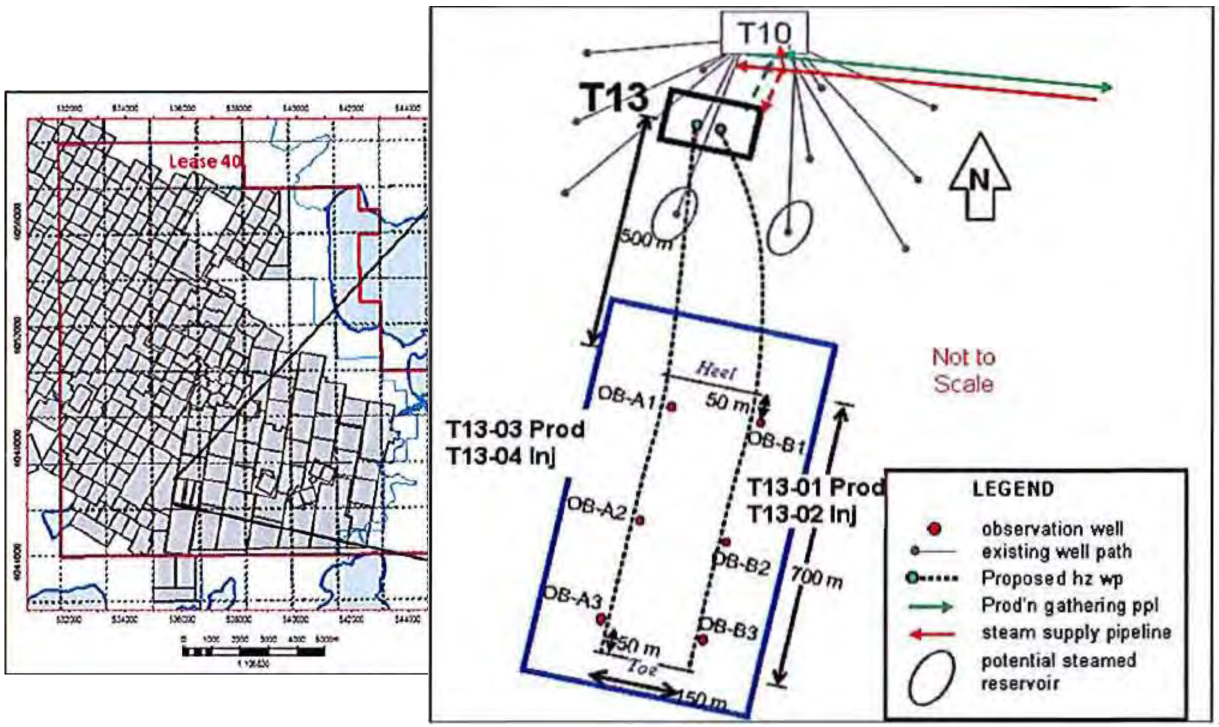
- Process characteristics
  - High solvent loading SBH process has a competitive advantage over SAGD when reservoir heat losses are significant
  - Has the potential to operate more efficiently at lower tem. than SAGD
  - Solvent penetration depth in porous media is greater than in ES-SAGD
- Process fundamentals
  - Fluid properties & phase behaviour - PVT meas. on Athabasca bitumen/nC4 fluid system at relevant T/P
  - Key solvent mass transfer mechanisms in field condition porous medium at process T (150 °C) - dispersivity and diffusivity in bitumen

Summary of Some Co-injection Pilots

Operator	Process Scheme	Location	Solvent	$P_{operating}$ (kPa)	Piloting Status
Suncor	ES-SAGD	Firebag/Athabasca	C7-C9	~2500	2006-2008
Cenovus	SAP	Senlac/Lloydminster	C4	2200 ~ 3000	2002
Cenovus	SAP	Christina Lake/Athabasca	C5-C6	4500 -> 2500	2009-2014
Statoil	SCI	Leismer/Athabasca	C5-C6	~3200	2013-2014
Imperial Oil	SA-SAGD	Mahkeses/Cold Lake	C7-C8	~3600	2011 - to date
Devon	Solvent Injection	Jackfish/Athabasca	C6	~2800	2013
Nexen	SCI	Long Lake/Athabasca	C5-C7	~2000	2014-2015
COP	ES-SAGD	Surmont/Athabasca	C3, C4, C6 blend	~3500	2012-2013
Connacher	SAGD+	Algar/Athabasca	C5-C6	~4000	2011-2015

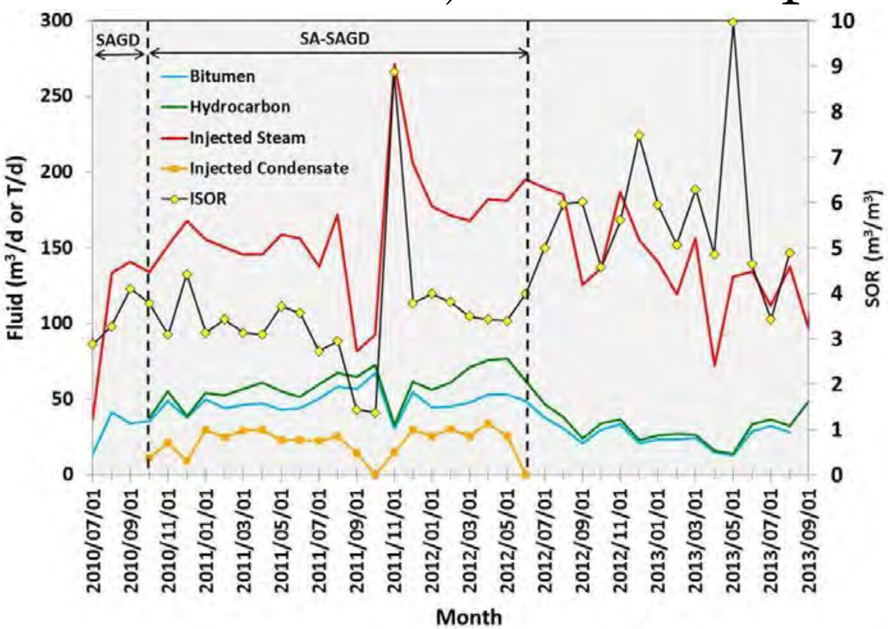
Co-injection Pilot – IOL Cold Lake

- Located in the Imperial Oil Cold Lake Lease 40 at Pad T13
- Two wellpairs: well length ~ 700m, wellpair spacing ~150m

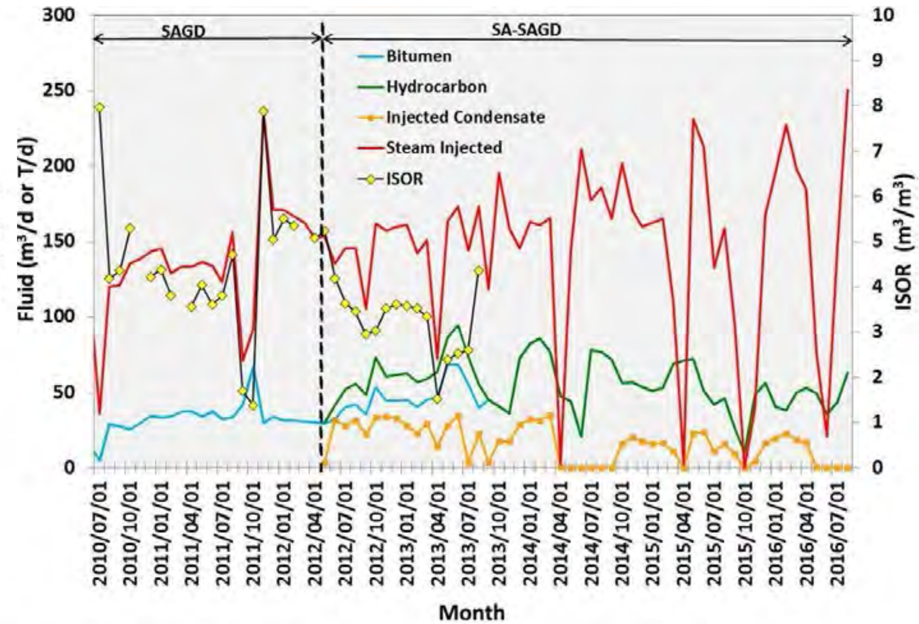


Co-injection Pilot – IOL Cold Lake

Injection and production rates, SOR

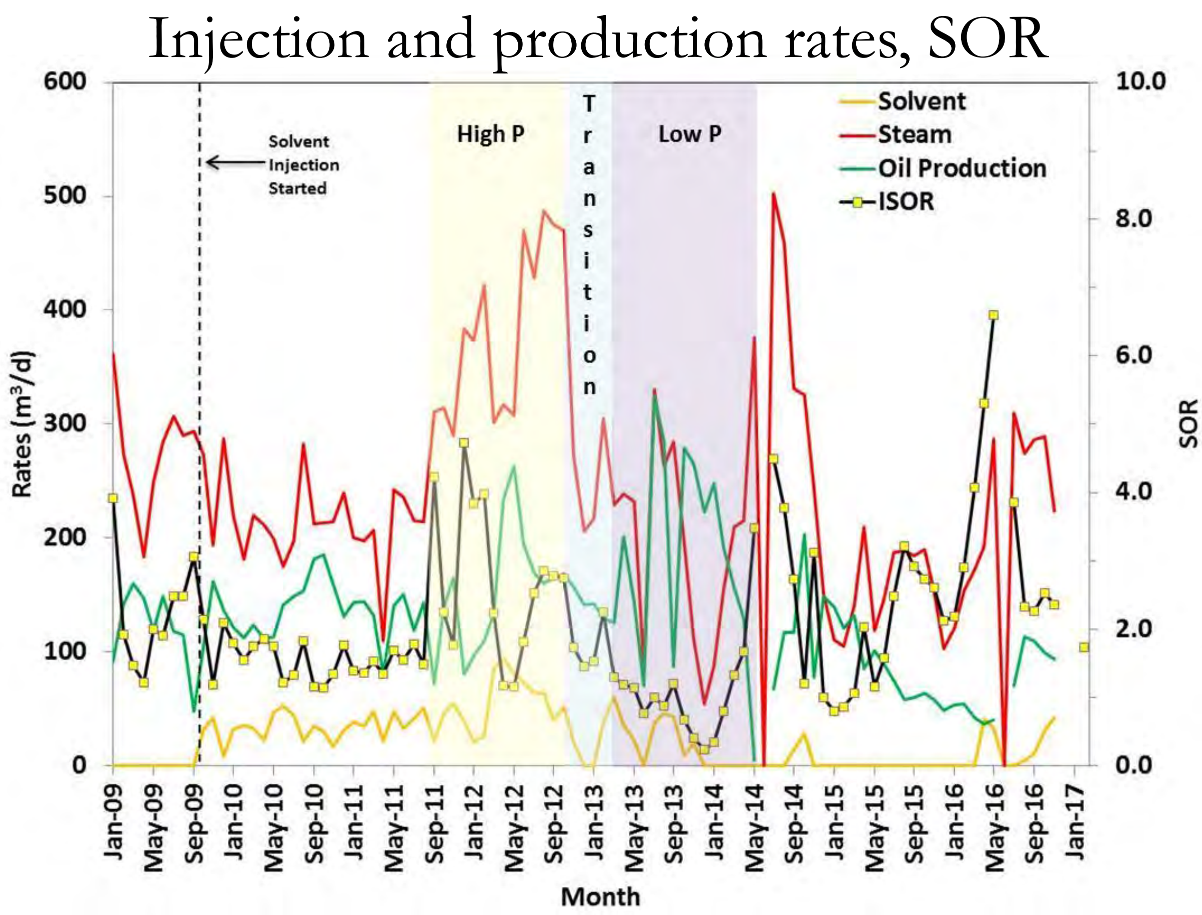


WP2

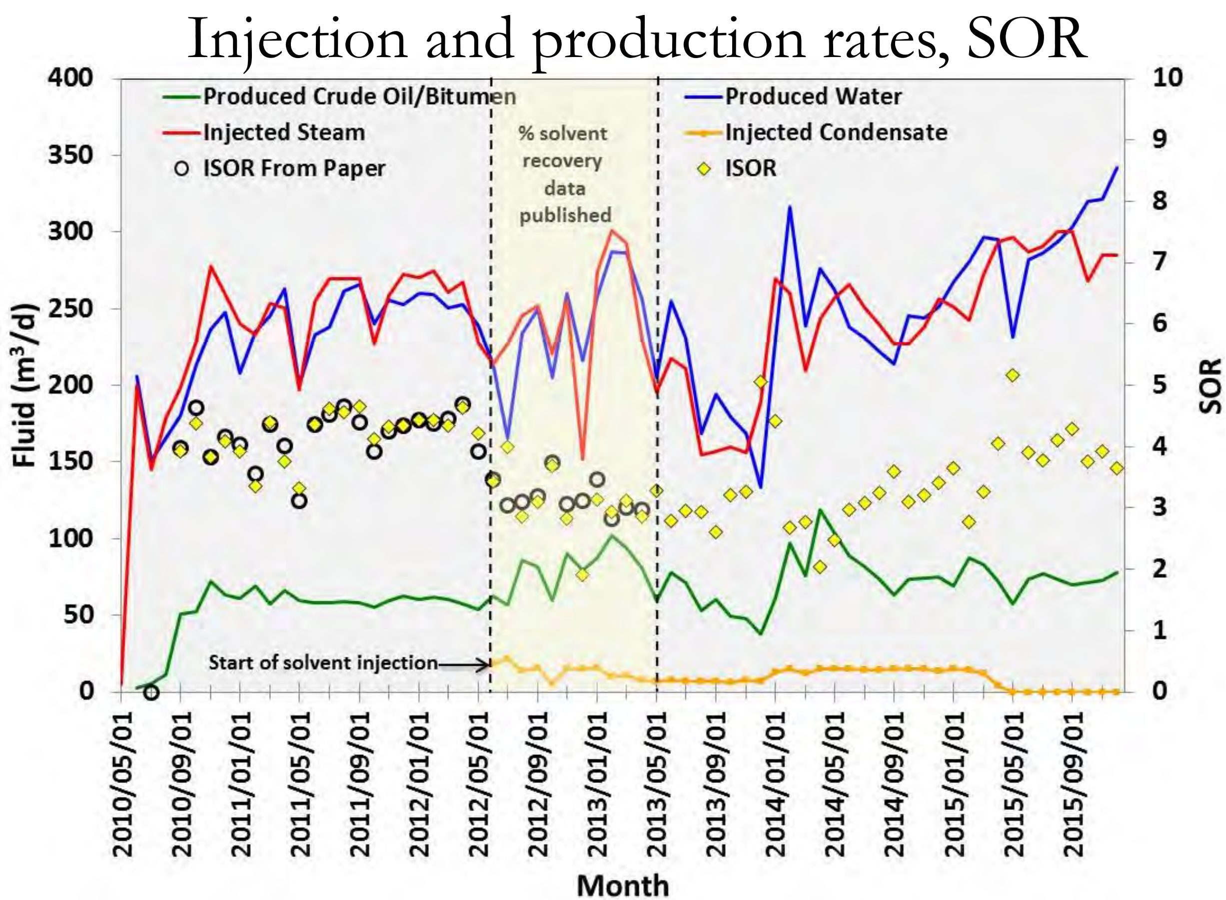


WP1

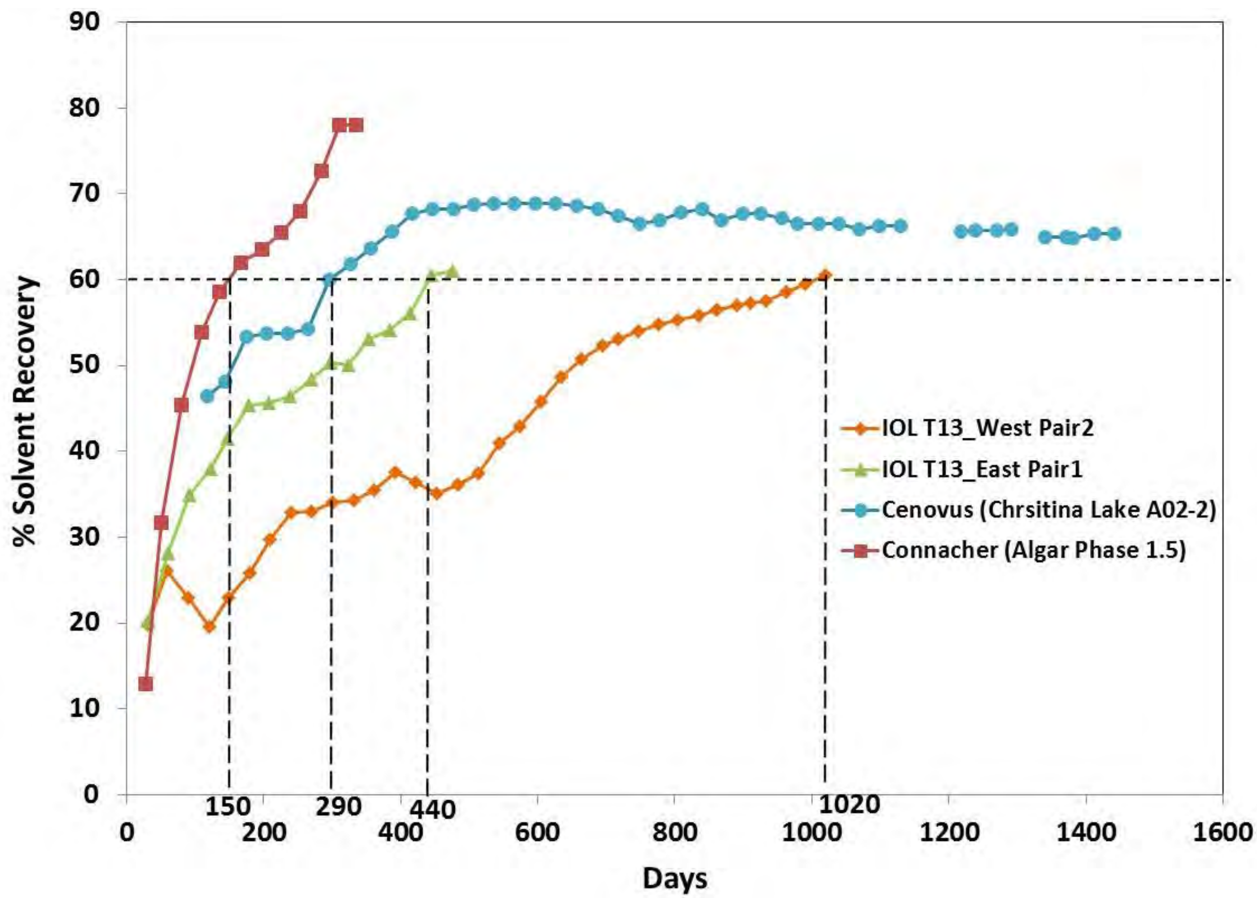
Co-injection Pilot – Cenovus Christina Lake A02-2



Co-injection Pilot – Connacher Algar Project – Phase 1.5



Co-injection Pilots – Solvent Recovery Behaviour



Learning from the Pilots

On Steam-Solvent Co-injection Technology

- Oil production rate lifting demonstrated: viscosity reduction of solvent along the boundary, near well
- SOR reduction demonstrated: oil production rate lifting, near well, and/or NCG effect
- Generally low solvent recovery, though solvent recovery continues after solvent injection stopped
- Improvement of recovery factor: not demonstrated
- Bitumen upgrading: not demonstrated

Detailed evaluations of solvent's impact in these pilots are required to distinguish the contribution factors

- Commercialization – up to the interpretation of individual company on the economics of co-injection project: cost of solvent, NPV of oil production lifting, etc.

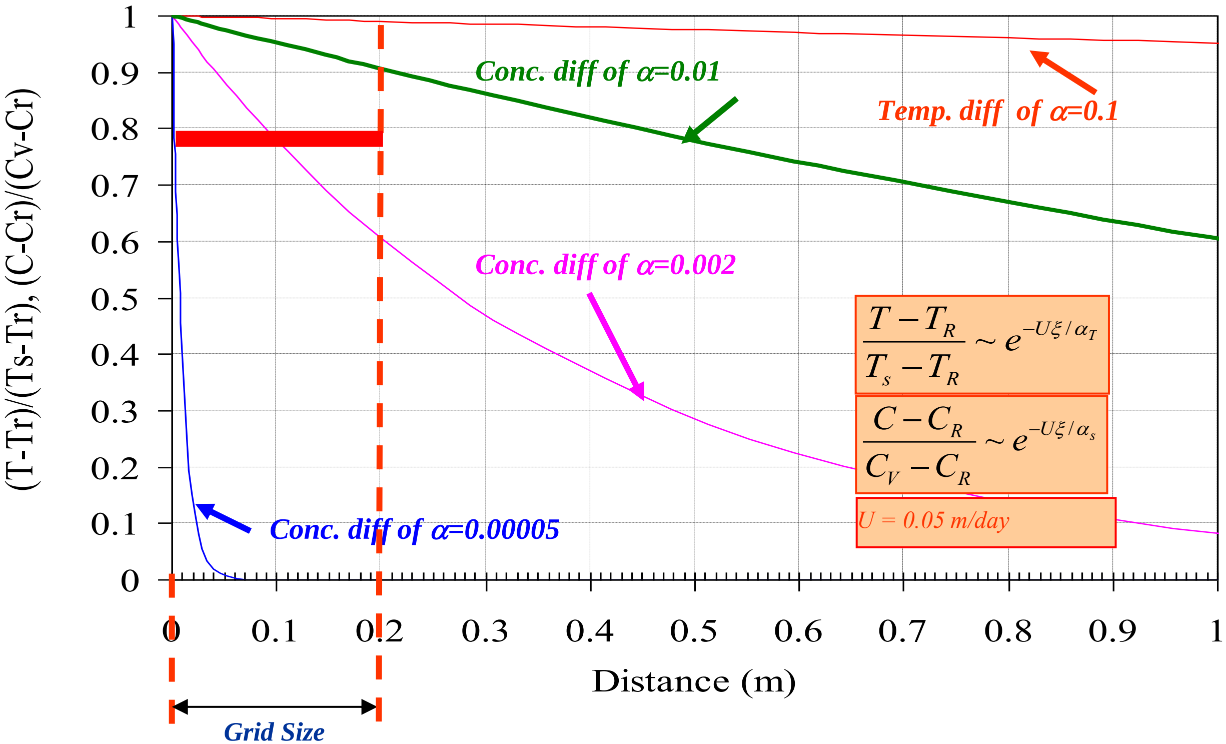
Field Scale Simulation – Grid Size Effect

1. Reservoir heterogeneity
2. Numerical dispersion – effect of grid size

- Reservoir heterogeneity has different impacts to thermal heat transfer and solvent mass transfer
  - Heat transfer via solids (even barriers) and fluids, bulk of reservoir is solids
  - Mass transfer only via fluids (diffusion, dispersion, convection)
- Mass transfer by diffusion/dispersion maybe much slower than heat transfer by diffusion

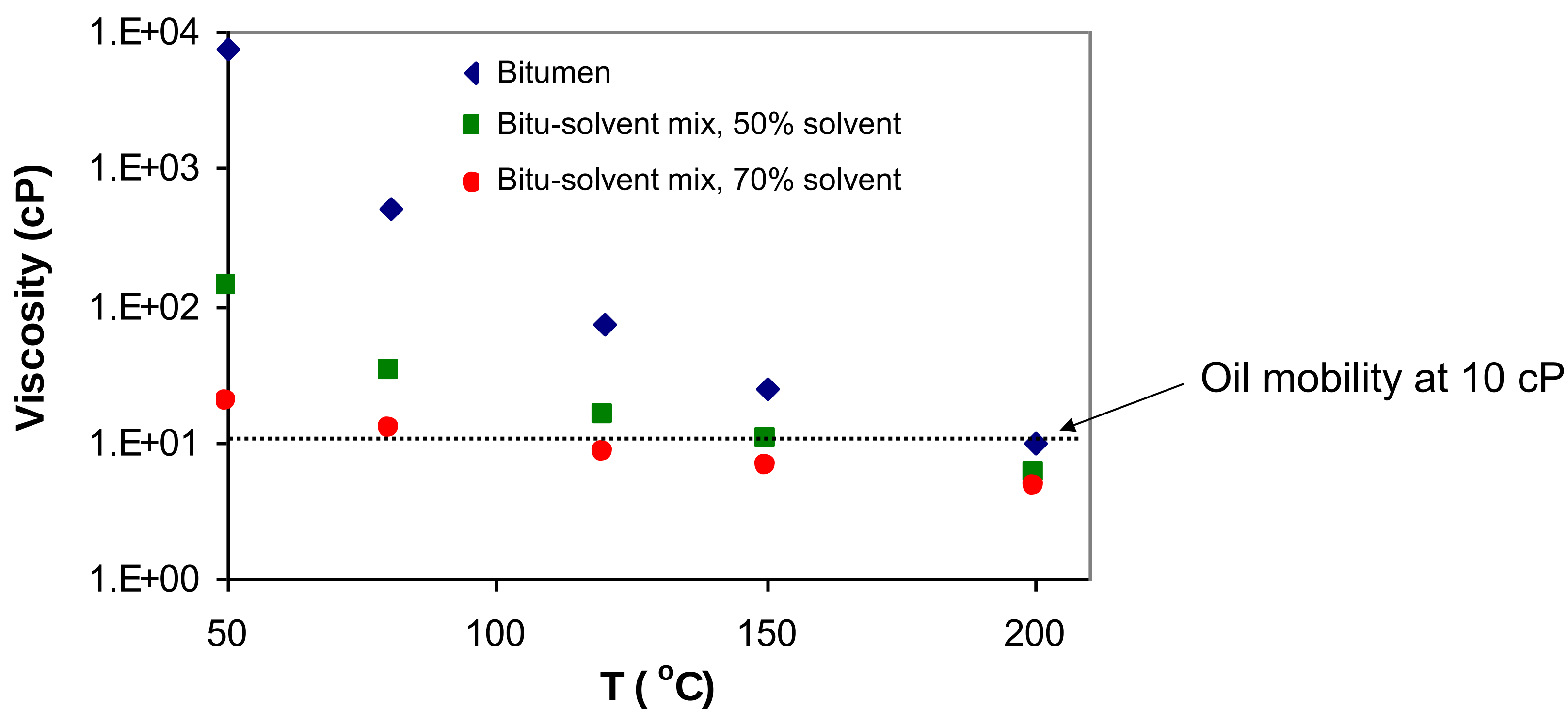
Numerical Dispersion – Grid Size Effect

Relative concentration/temperature profiles within penetration length



Modification to Co-injection Scheme

- Increasing solvent loading to achieve desired oil mobility at low temperatures – lower energy intensity



Status of Co-injection Application

- Fundamentals of the process – reasonably understood
- Mechanisms of the solvent mass transfer in the co-injection process - quantified
- Methods to measure and model the phase behaviour and viscosity of the solvent-bitumen-water - established
- Field pilots demonstrated:
  - oil production rate lifting
  - SOR reduction
  - generally low solvent recovery although solvent recovery continues after solvent injection stopped
  - not the improvement of recovery factor

Status of Co-injection Application

- Analytical solution of the co-injection process - not available
- Up-scaling from lab scale physical model test to field scale - not available
- Simulation approaches to predict the co-injection process in field - reasonably established, needs further improvement
- Issues to address in commercial field application
  - Operating strategies to maximize the economics of co-injection project under the field reservoir constraints
  - Co-injection facility design - heating solvent, mixing steam and solvent, etc.
  - Down-hole production control - subcool, solvent gas production, etc.
  - Surface separation facility - gas separation, liquid separation, etc.
  - Measurement and monitoring

Acknowledgments

- AACI Program & Researchers - research work
- Colleagues from O&G companies – interactions on the relevant subjects
- AI Clean Energy – opportunity to share the ideas/learning with Workshop participants