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Additional support provided by AIME

A New Heavy Oil Recovery Technology to Maximize Performance and Minimize Environmental Impact

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Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl

Outline

- Global perspective of heavy oil
- Overview of recovery processes
  - Steam-based thermal processes
- Environmental impacts from current heavy oil recovery
- Technology development to meet environmental challenges
  - Hybrid steam-solvent process: from research concept to field pilots
- Conclusions

Heavy Oil

Heavy Oil: Crude Oil with API < 22.3° (*sp. gr.* = 0.92)

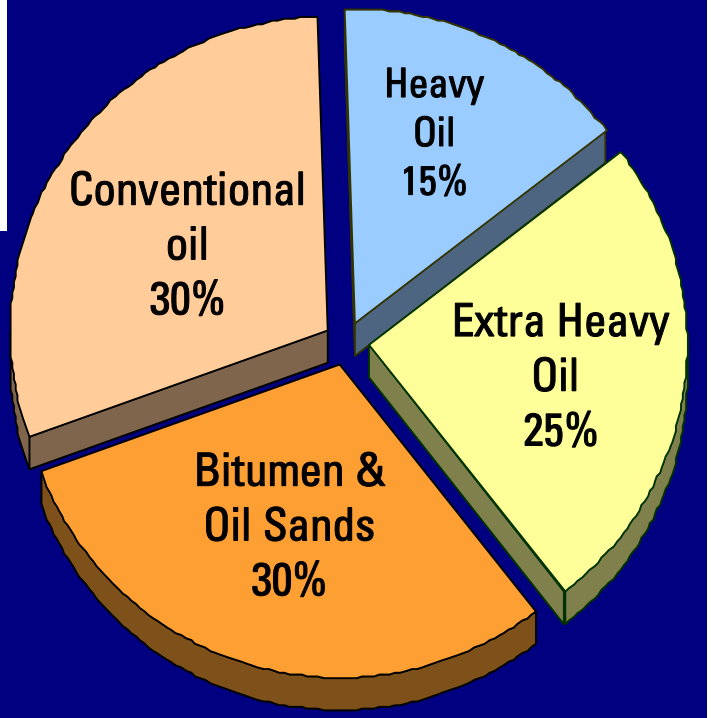
	API Gravity	Viscosity (cp)
Heavy Oil	10º – 22.3º	100 – 10,000
Extra Heavy Oil	< 10º	100 – 10,000
Bitumen	< 10º	> 10,000

Source: 12th World Petroleum Congress (WPC), 1987

Total World Crude Oil Resources: 9 – 13 trillion bbls

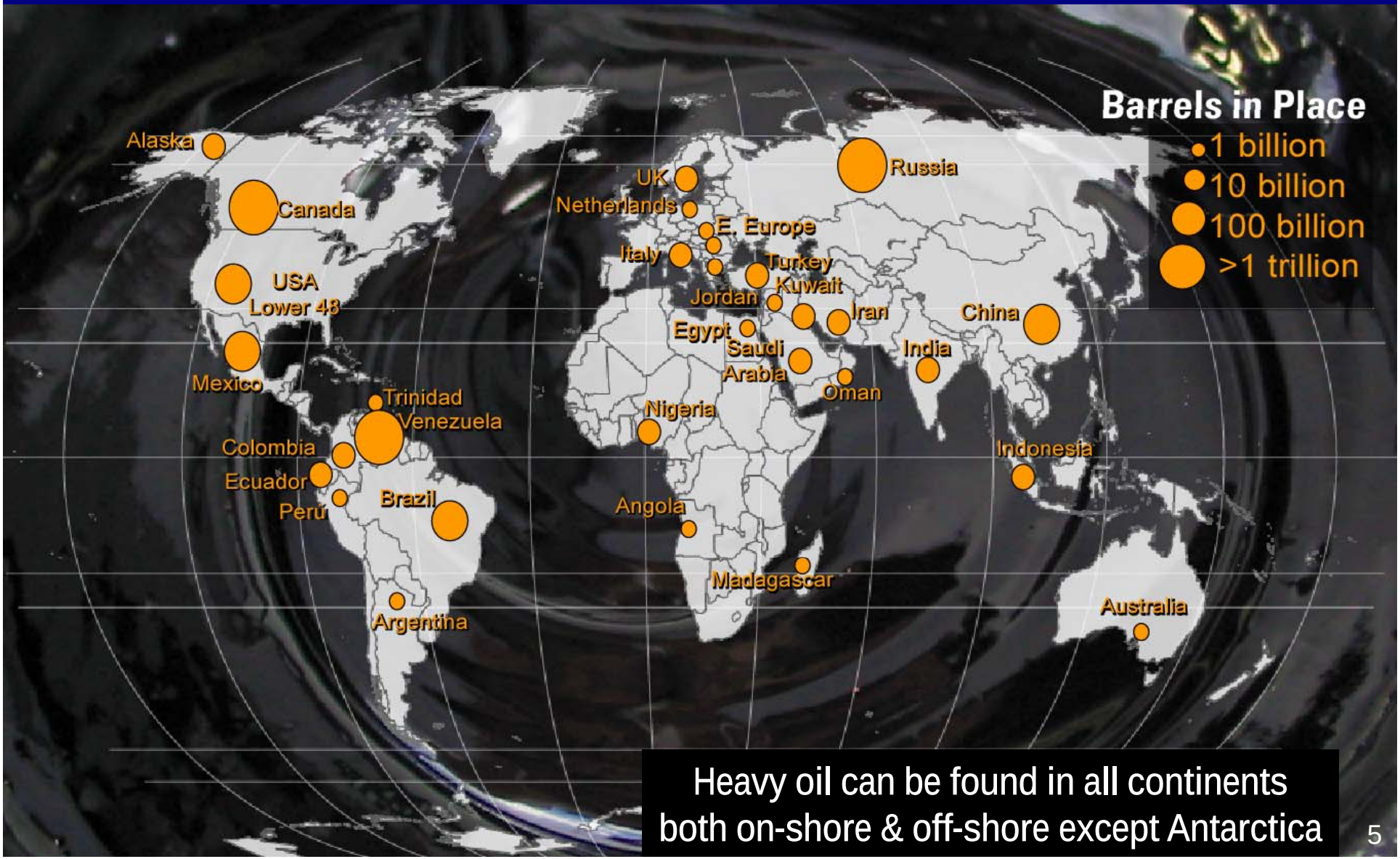
More than 2/3 of total oil resources are heavy oil and bitumen

Oil Resources



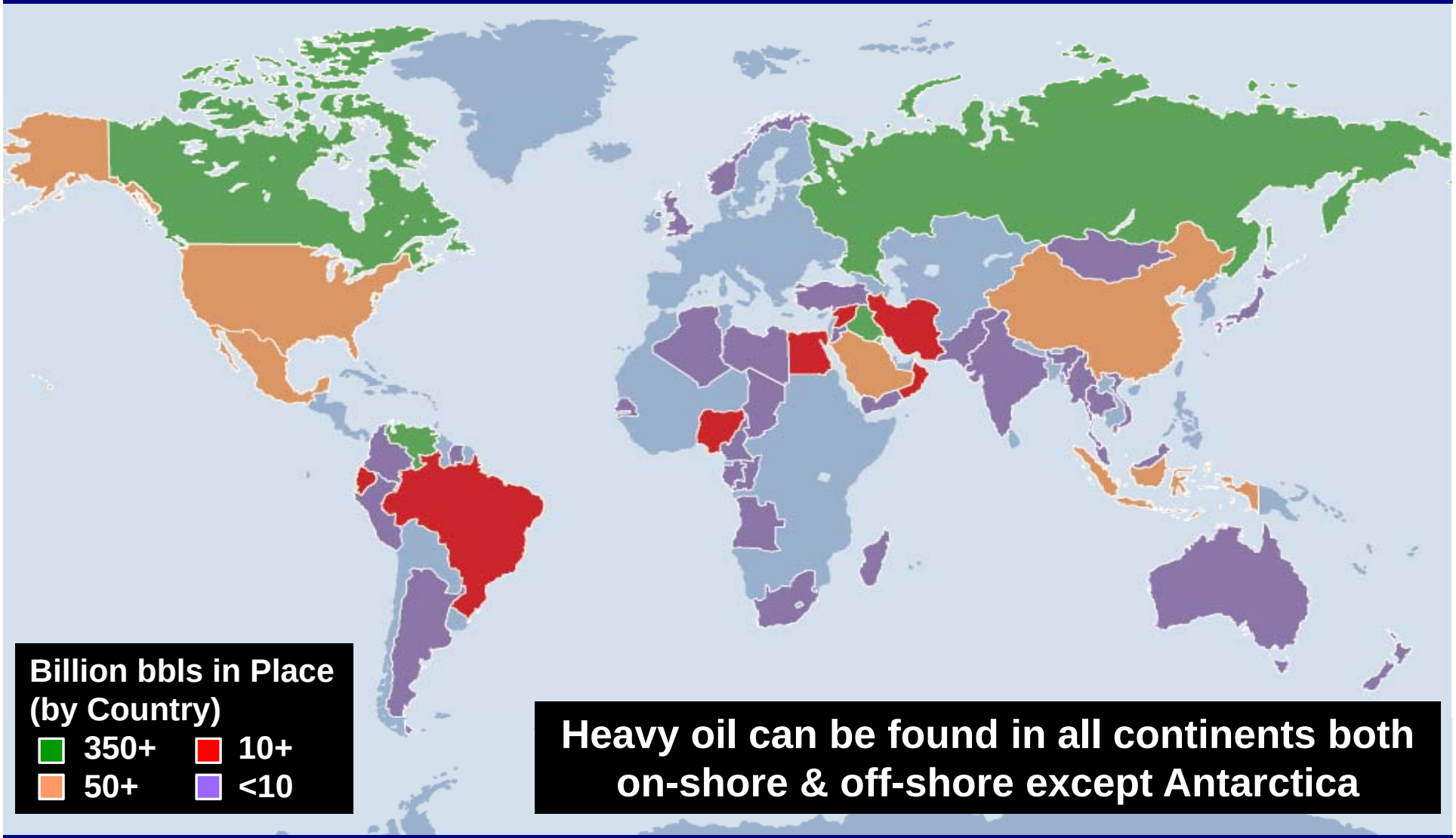
Source: International Energy Agency (IEA)

Global Heavy Oil Resources



Heavy oil can be found in all continents both on-shore & off-shore except Antarctica

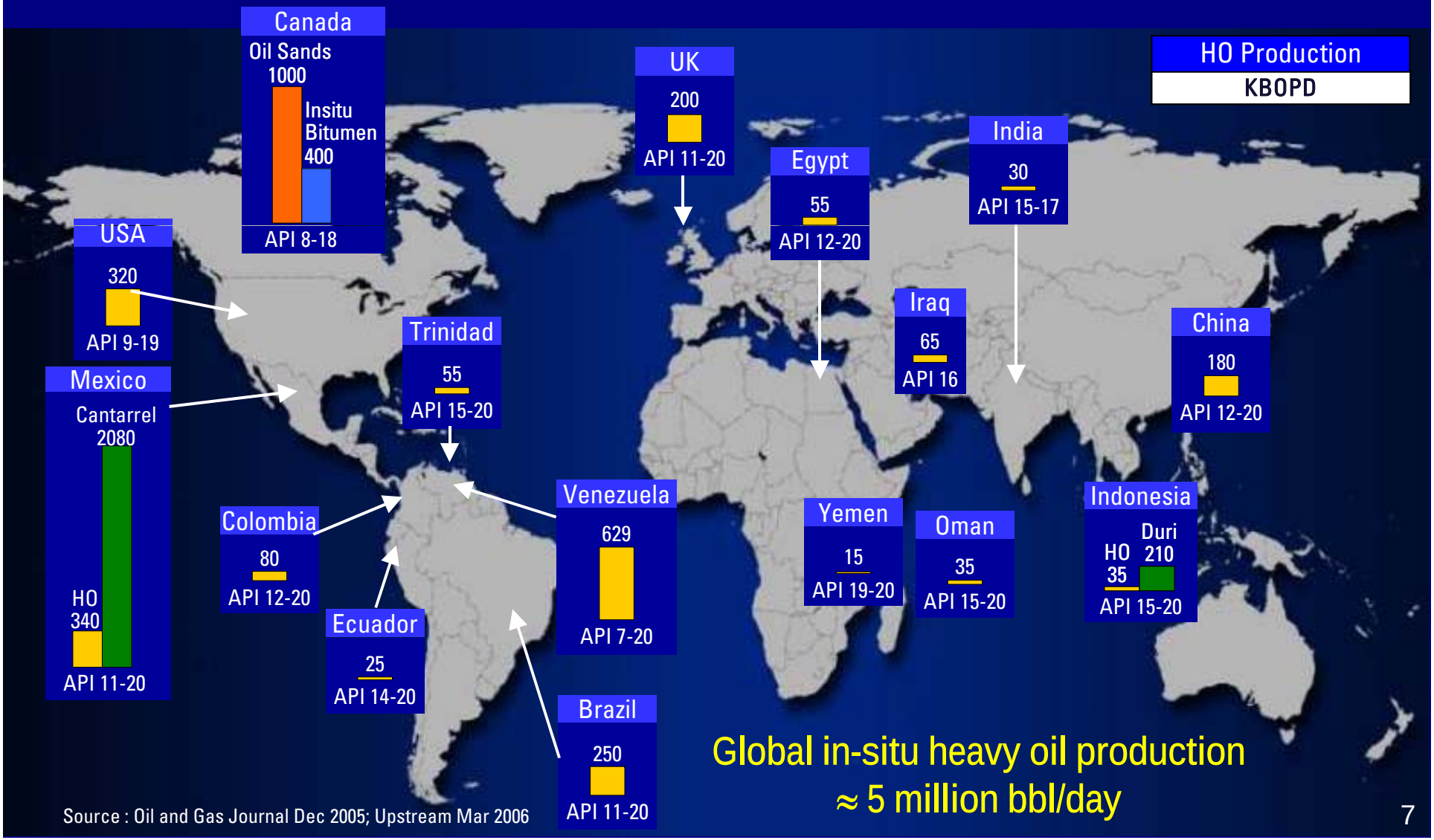
Global Heavy Oil Reserves



Heavy oil can be found in all continents both on-shore & off-shore except Antarctica

Source: http://www.HeavyOil*info*.com

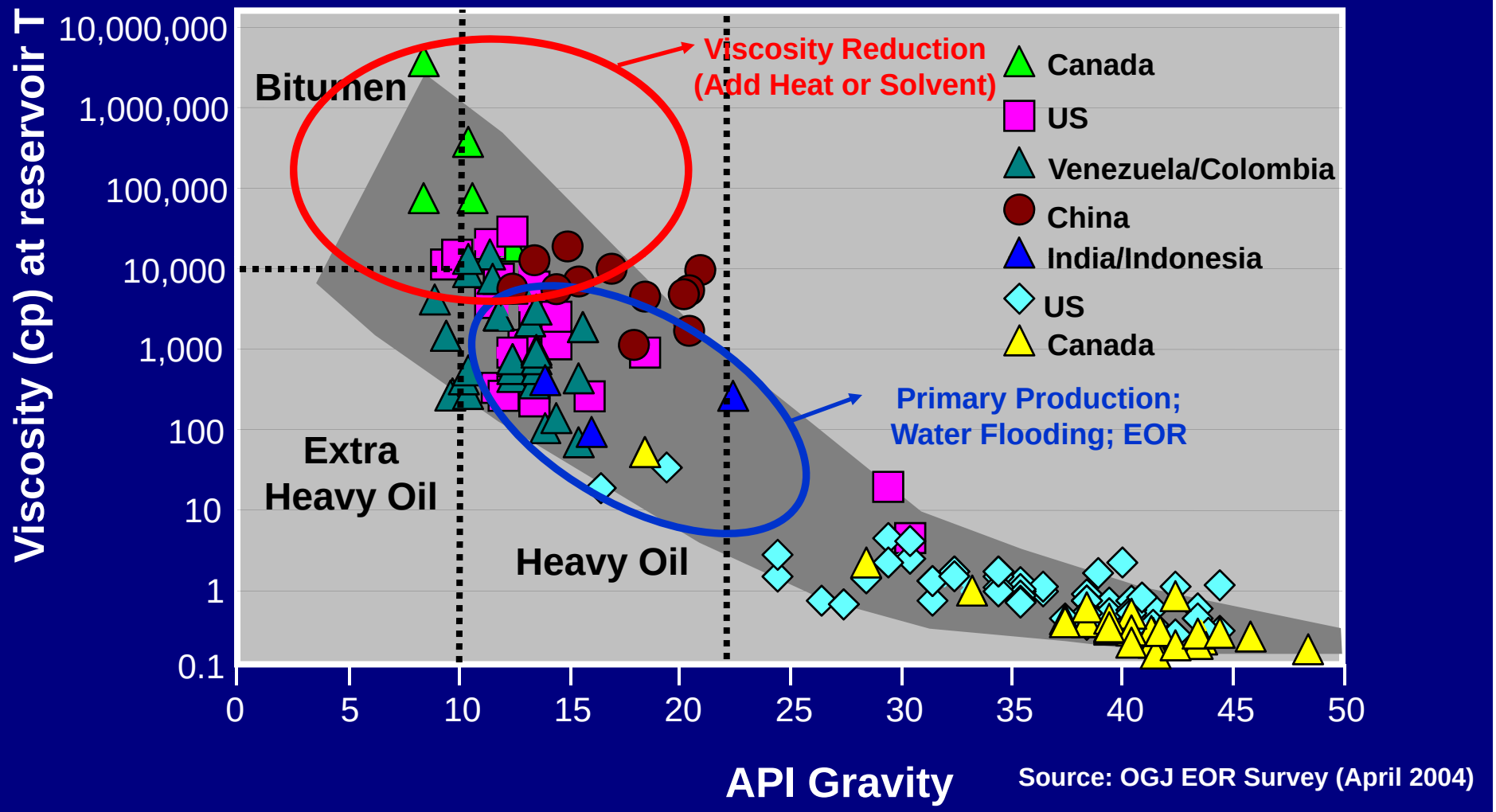
Global Heavy Oil Production



Global in-situ heavy oil production
≈ 5 million bbl/day

Source : Oil and Gas Journal Dec 2005; Upstream Mar 2006

Variety of Viscous Oils



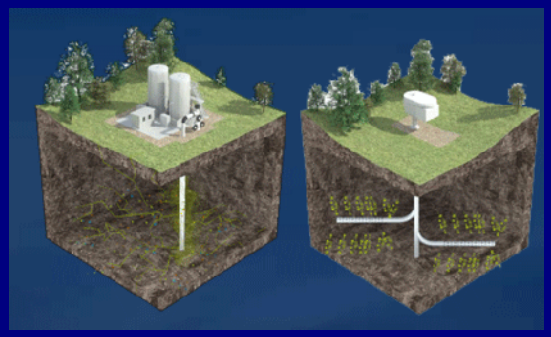
Source: OGJ EOR Survey (April 2004)

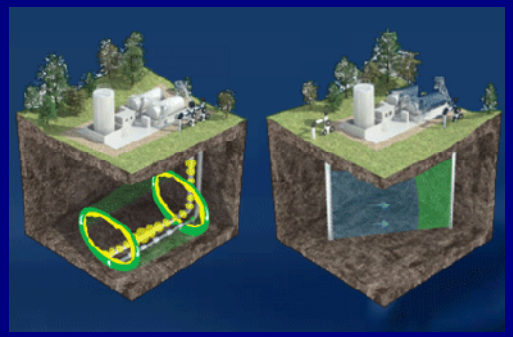
There are many ways to recover heavy oil

Heavy Oil Recovery Processes

Recovery Processes

- **Surface Mining**
- **Primary**
  - Cold Production
  - CHOPS
- **Thermal**
  - **Steam-Based**
    - CSS
    - Flooding
    - SAGD
  - **Combustion**
    - Fire Flooding
    - THAI
- **Non-Thermal**
  - Water Flooding
  - Chemical Flooding
  - VAPEX





CHOPS: Cold Heavy Oil Production with Sands
CSS: Cyclic Steam Stimulation
SAGD: Steam Assisted Gravity Drainage
THAI: Toe-to-Heel Air Injection
VAPEX: Vapour Extraction

Steam-based thermal recovery processes are most extensively used

Cyclic Steam Stimulation (CSS)

- Single well operation
- Injection/production cycle:
  - Steam injection
  - shut-in (soak)
  - Oil production
- Recovery factor (RF) ≈ 15% OOIP (original oil-in-place)

CSS

Source: http://www.HeavyOil*info*.com

Steamflooding

- Multi-well operation in regular pattern
- Inject steam into one or more wells
- Drive oil to separate producers
- Recovery factor (RF) ≈ 50% OOIP

Steamflooding

Source: http://www.HeavyOil*info*.com

Steam-Assisted Gravity Drainage (SAGD)

- Horizontal well pair near bottom of pay
  - Upper steam injector
  - Lower oil producer
- Steam chamber rises upward, then, spreads sideway
- Oil drains downward to producer
- Recovery factor (RF) > 50% OOIP

SAGD

Source: http://www.HeavyOil*info*.com

Steam-Based Thermal Recovery Processes

- Very energy intensive and inefficient

Thermal Efficiency for Each Stage:

Steam Generator	→	Transmission to Well	→	Well to Reservoir	→	Flow in Reservoir
(75 – 85%)		(75 – 95%)		(80 – 95%)		(25 – 75%)

Source: Butler, "GravDrain's Blackbook", (1998)

Final Efficiency: *11% - 58%*

- Significant environmental impacts
  - Land: Surface footprint
  - Air: Greenhouse gas (GHG) emission
  - Water: Water usage and disposal

Surface Footprint

- Small well spacing for heavy oil
  - less than 10 acres pattern for CSS and Steam flooding

Chevron Steamflooding Operation
Kern River, California, USA

>15,000 wells in ~60 km^2 (~23 mile^2)

Surface Footprint

- Reduce surface footprint with horizontal or multi-lateral wells (e.g., SAGD)

Sources: Google Satellite Map

CNRL CSS Operation with Horizontal Wells
Primrose, Alberta, Canada
(62,000 bbl/d)

Reduce Surface Footprint

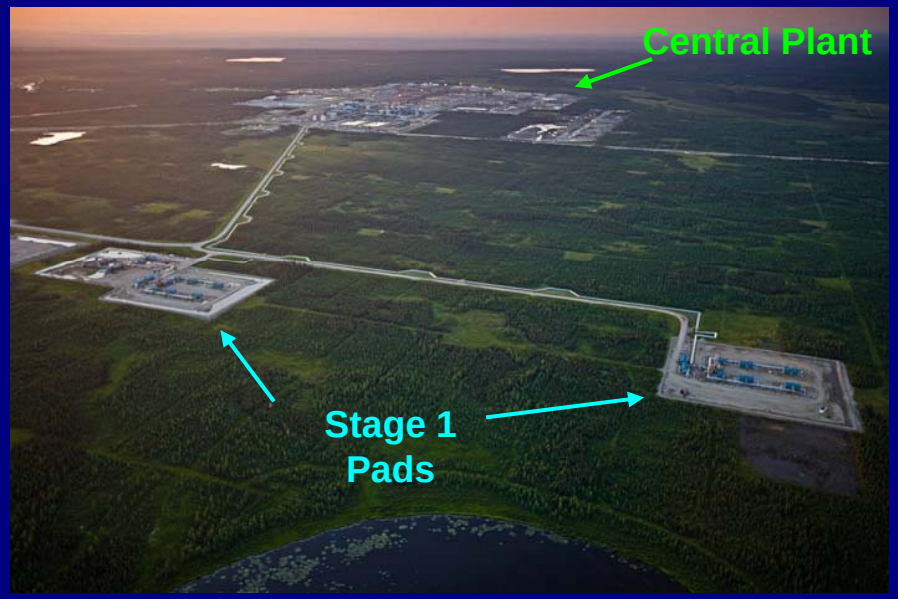
ESSO CSS Operation with Vertical Wells
Cold Lake, Alberta, Canada
(140,000 bbl/d)

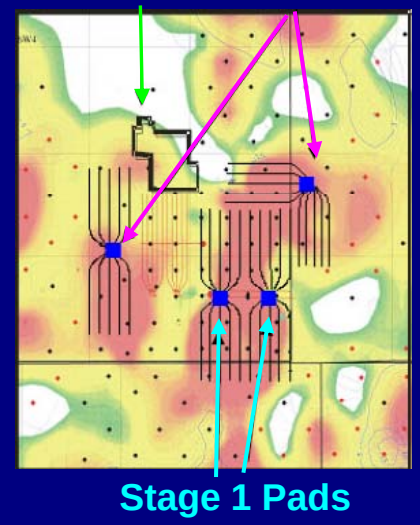
Sources: Energy Resources Conservation Board (ERCB) of Alberta

Surface Footprint

- Reduce surface footprint (further) with SAGD well pairs

Suncor Firebag SAGD Operation with Horizontal Well-Pairs, Athabasca, Alberta, Canada (35,000 bbl/day/Stage)

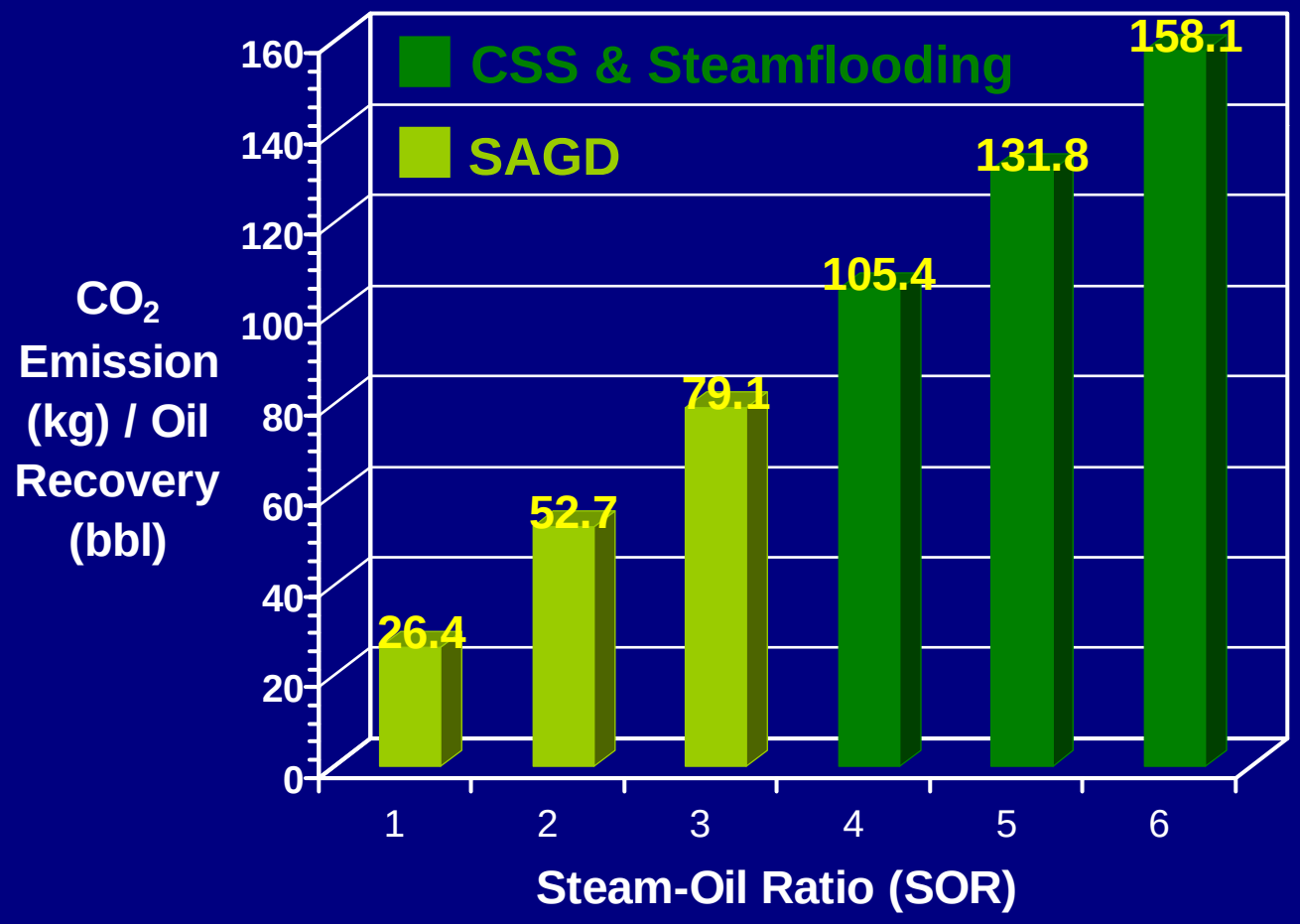




Greenhouse Gas Emission

- GHG emission from steam generation at 250° C
  - Burning natural gas (CO_2 emission = 0.532 tonne/Mscf)

Environmental Canada Data

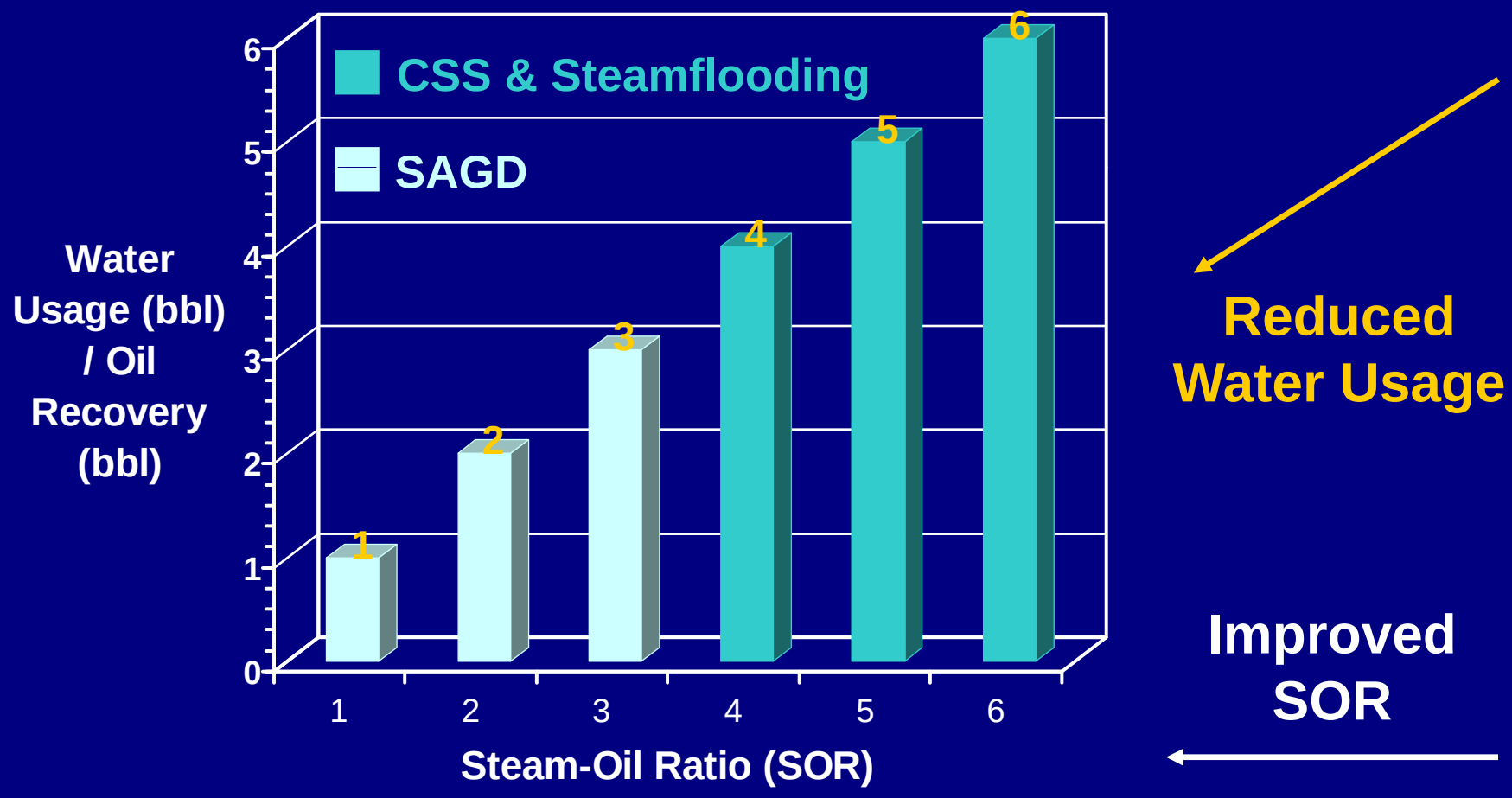


Reduced GHG Emission

Improved SOR

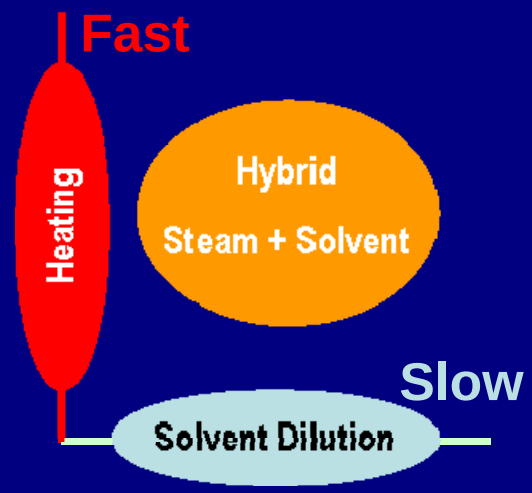
Water Usage and Disposal

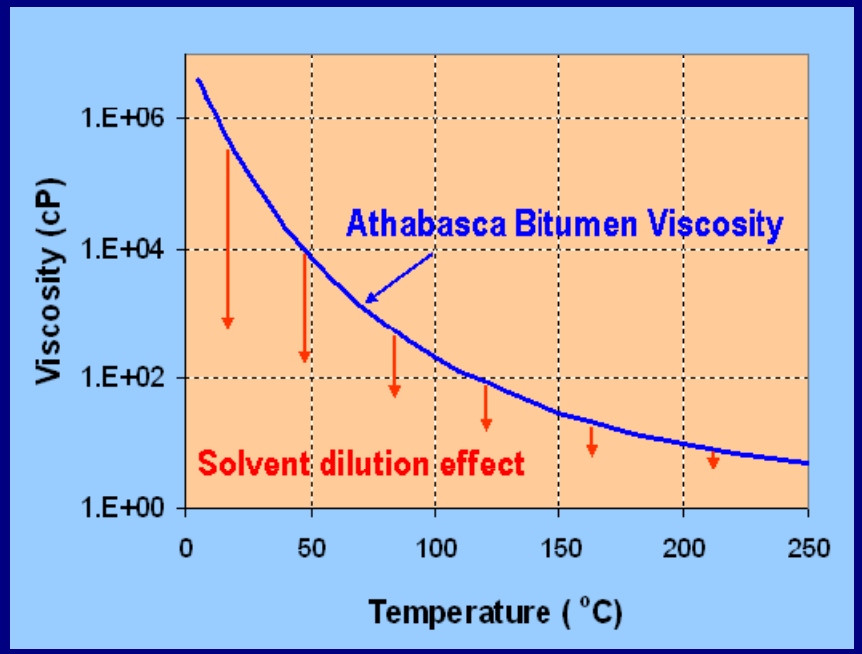
- Water usage for steam generation



Concept for New Technology

Methods to Reduce Viscosity:



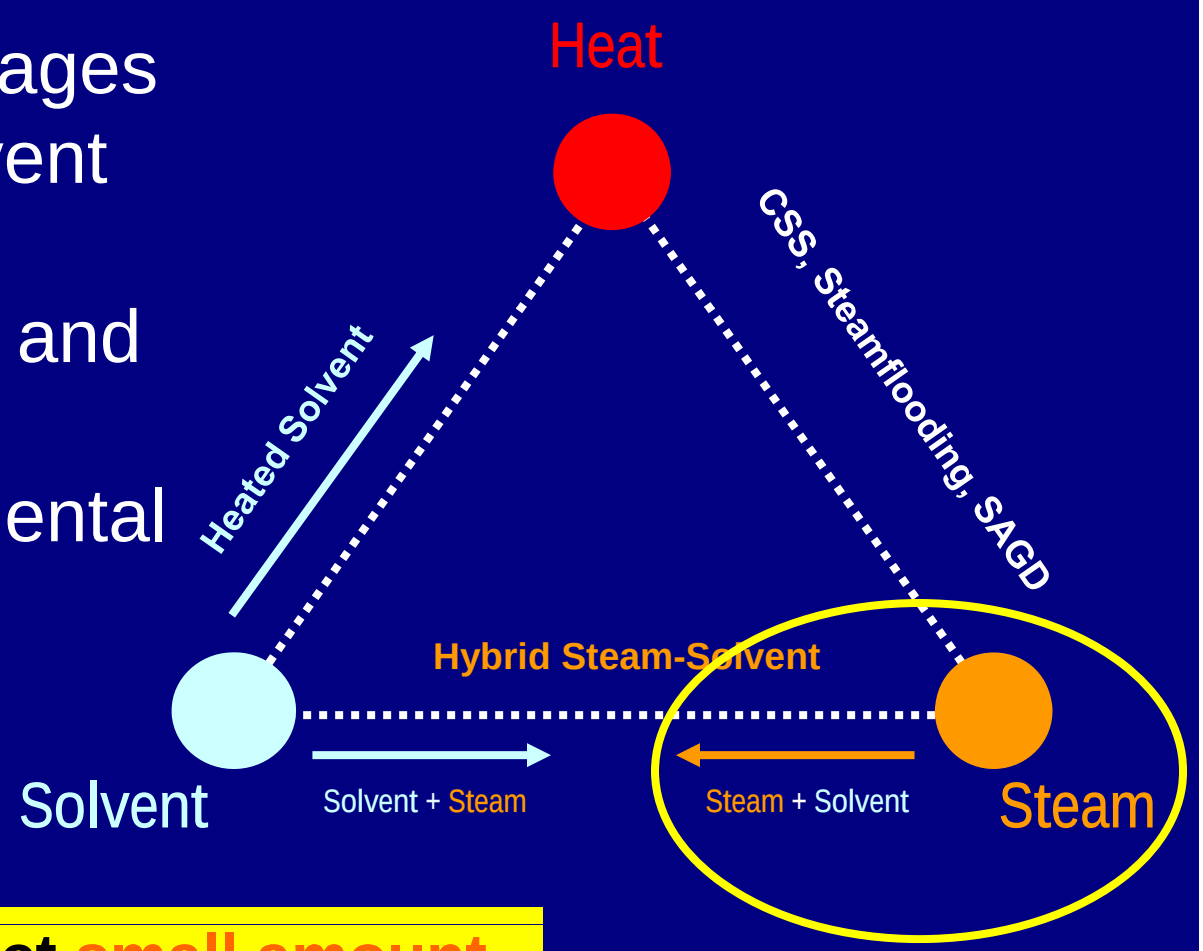


- **Steam-only**
  - Heat transfer controlled
  - High oil rate
  - High energy and water requirements
  - Commercial applications
- **Solvent-only**
  - Diffusion/dispersion controlled
  - Low oil rate
  - Low energy and water requirements
  - Field pilot stage

Courtesy of Alberta Research Council (ARC)

Hybrid Steam-Solvent Processes

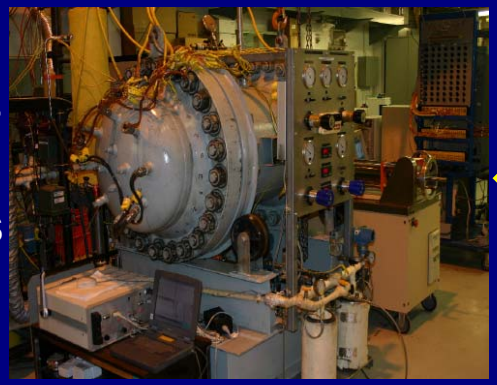
- Synergize advantages of steam and solvent processes
- Enhance oil rates and lower SOR
- Reduce environmental impact



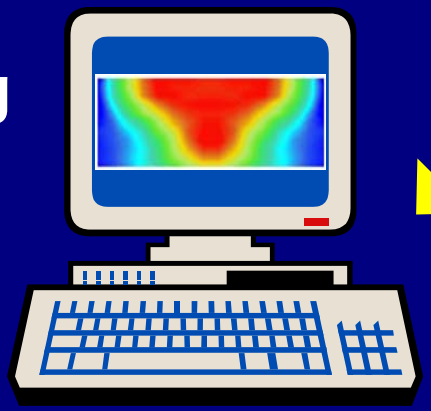
Co-inject small amount of solvent with steam

Technology Development
Hybrid Steam-Solvent Processes

Laboratory Studies
- Proof of concept
- Property measurements
- Scale-up



Workflow



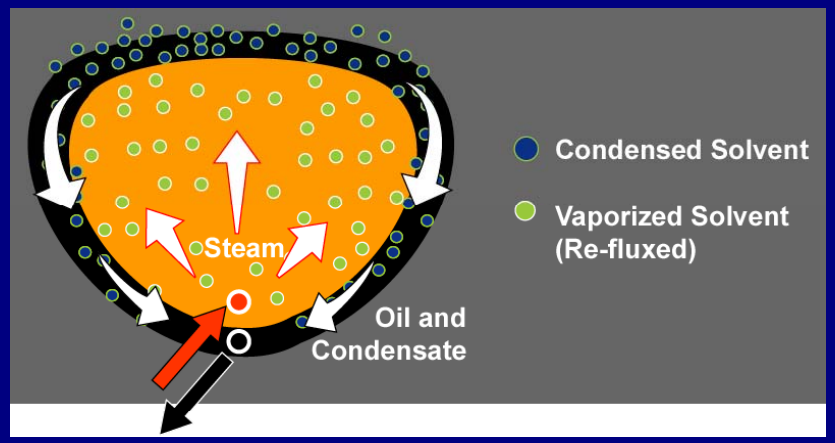
Numerical Modelling
- Model validation
- Mechanistic Analysis
- Field-scale prediction

Field Application
- Pilot tests
- Commercial Operation

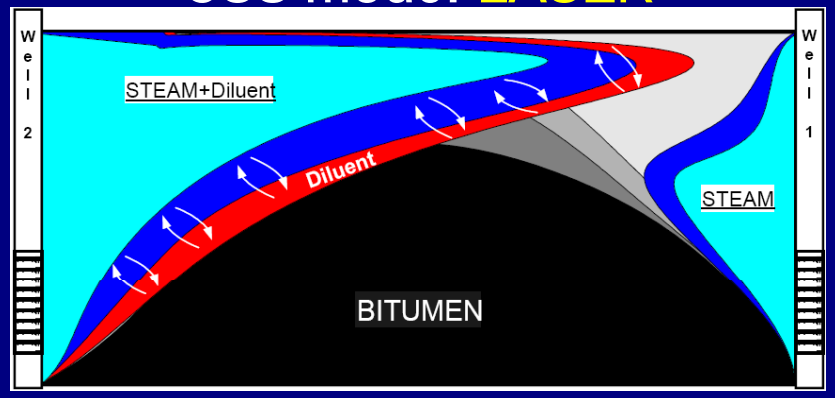
Hybrid Steam-Solvent Processes

- Nomenclature
  - Expanding Solvent-SAGD (**ES-SAGD**)
  - Solvent Aided-Process (**SAP**)
  - Liquid Addition to Steam for Enhancing Recovery (**LASER**)
  - Many more ….
- Different strategies:
  - Solvent selection
  - Steam - solvent ratio
  - Continuous or cyclic

SAGD mode: ES-SAGD and SAP



CSS mode: LASER

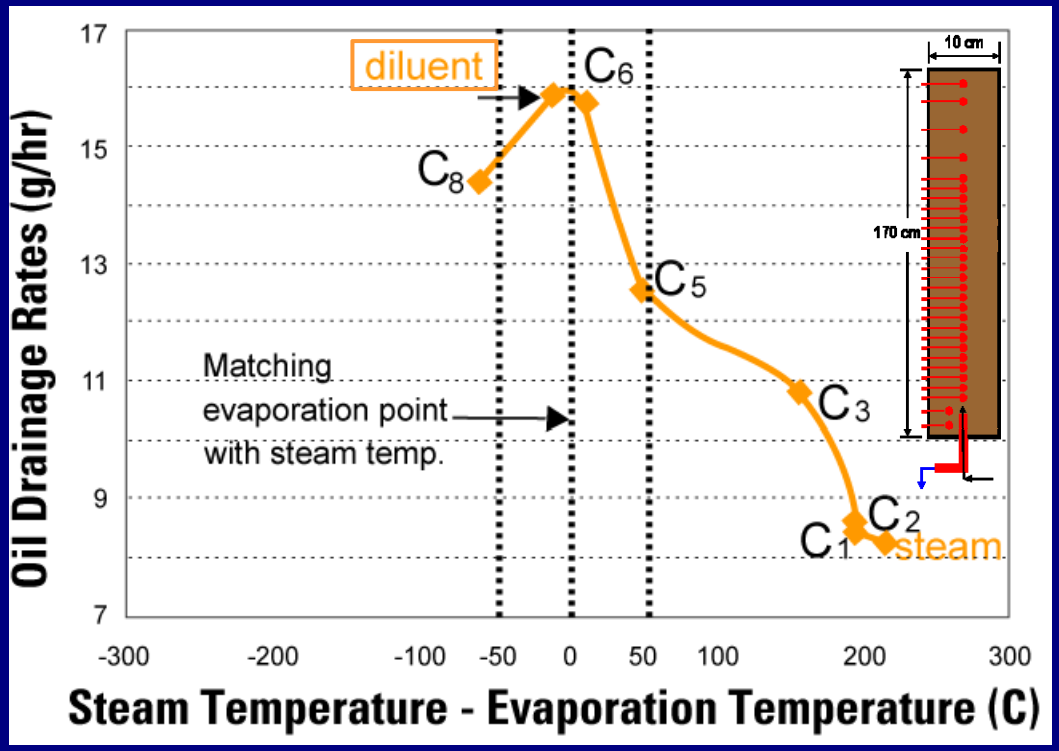


Laboratory Studies
Solvent Selection

- Hexane and diluents (a solvent mixture)
  - Evaporation temperatures closest to steam temperature
  - Steam-solvent ratio = 64 (by vol.)

"1-D" ES-SAGD Experiments

Courtesy of Alberta Research Council (ARC), Canada



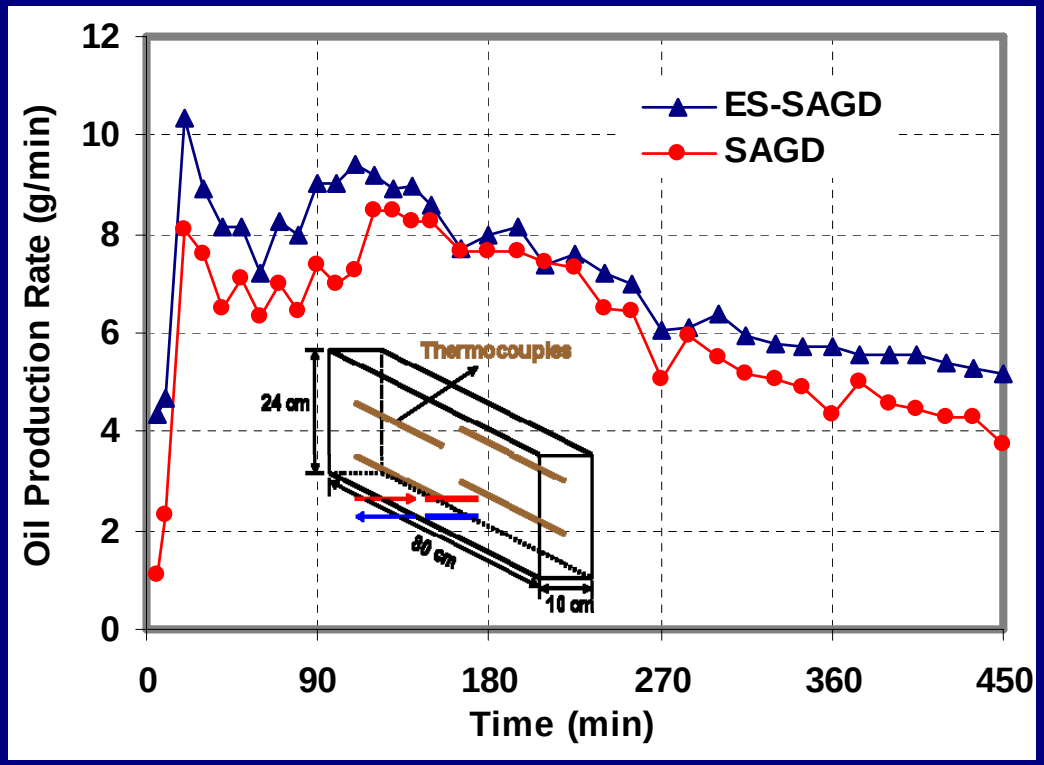
ES-SAGD: Nasr, *et al*., *JCPT* (2003)

Laboratory Studies
Proof of Concept

- ES-SAGD versus steam-only
- Continuous diluents co-injected with steam
  - Steam-solvent ratio = 6.9 (by vol.)

"2-D" Scale-Model Experiments

Courtesy of Alberta Research Council (ARC), Canada

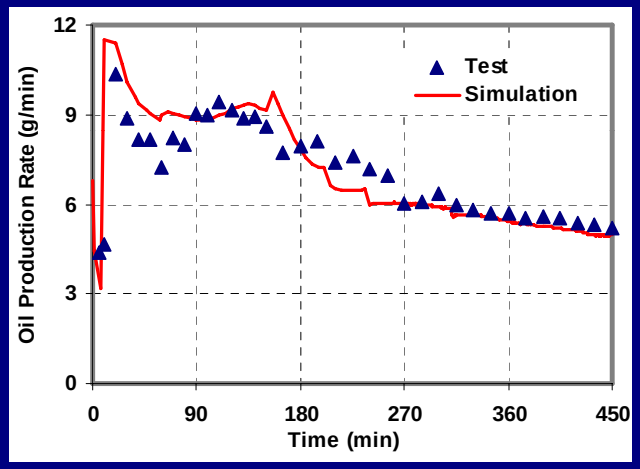


ES-SAGD: Nasr and Ayodele, *SPE 101717* (2006)
Deng, *et al.*, *WHOC* (2006)

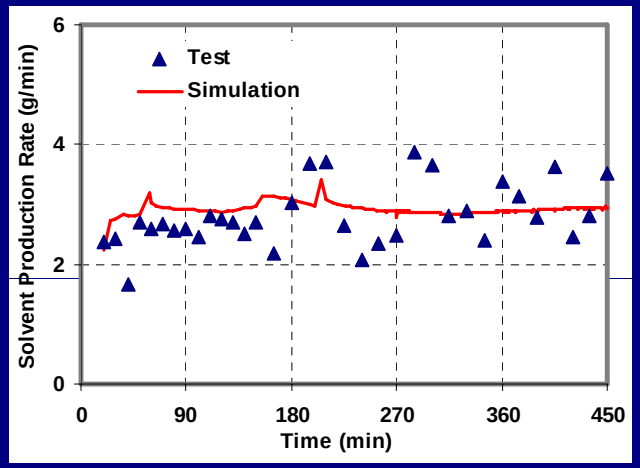
Numerical Modeling
Model Validation

- History match of 2-D scale-model experiments

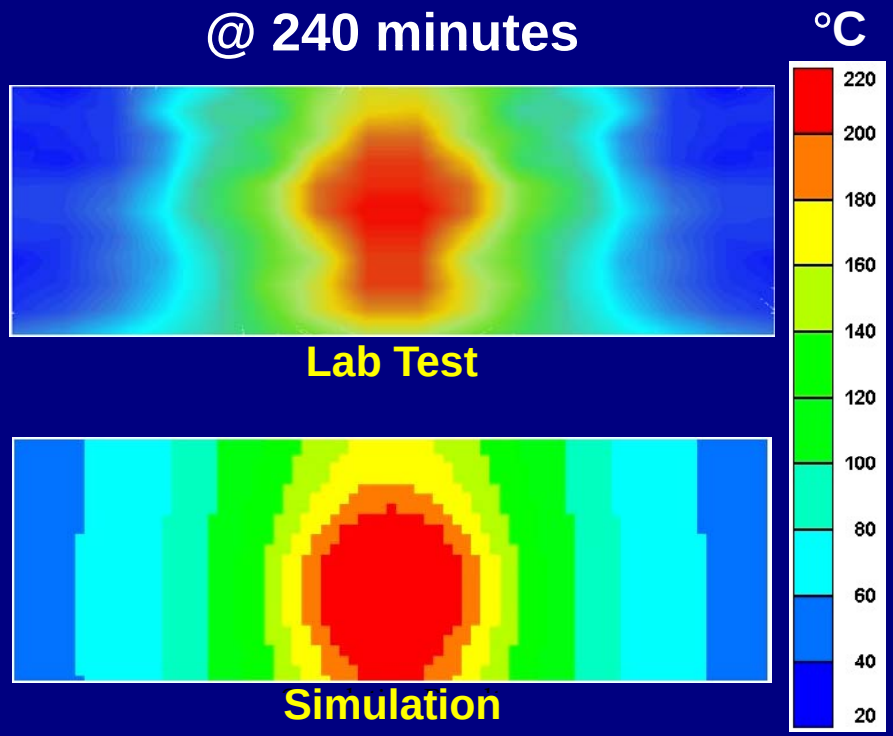
Oil Production Rate



Solvent Production Rate (85% Recovery)



Temperature Profile @ 240 minutes

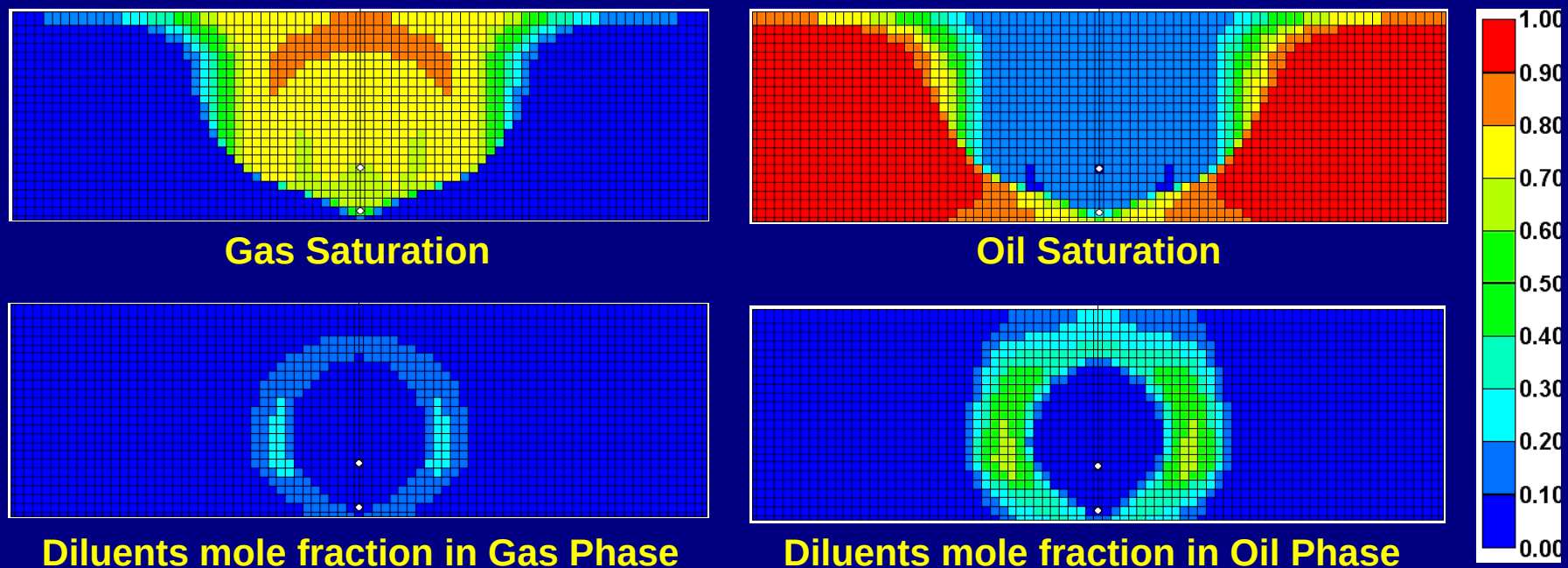


ES-SAGD: Deng, *et al.*, *WHOC* (2006)

Numerical Modeling
Mechanistic Analysis

- Understand ES-SAGD process mechanisms
  - Solvent appears along slope of steam chamber
  - Observation not available from experiments

Profile @ 240 minutes



Gas Saturation

Oil Saturation

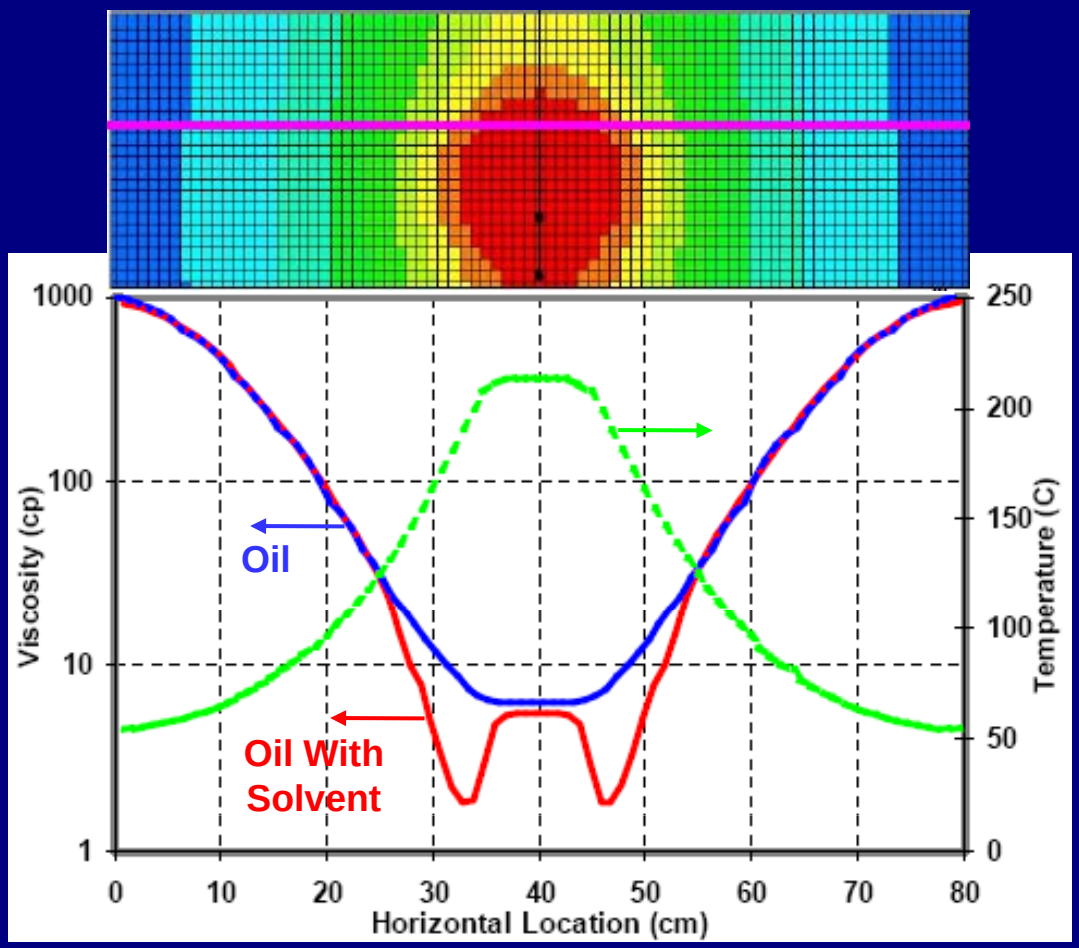
Diluents mole fraction in Gas Phase

Diluents mole fraction in Oil Phase

ES-SAGD: Deng, *et al.*, *WHOC* (2006)

Numerical Modeling
Mechanistic Analysis

Temperature Profile @ 240 minutes

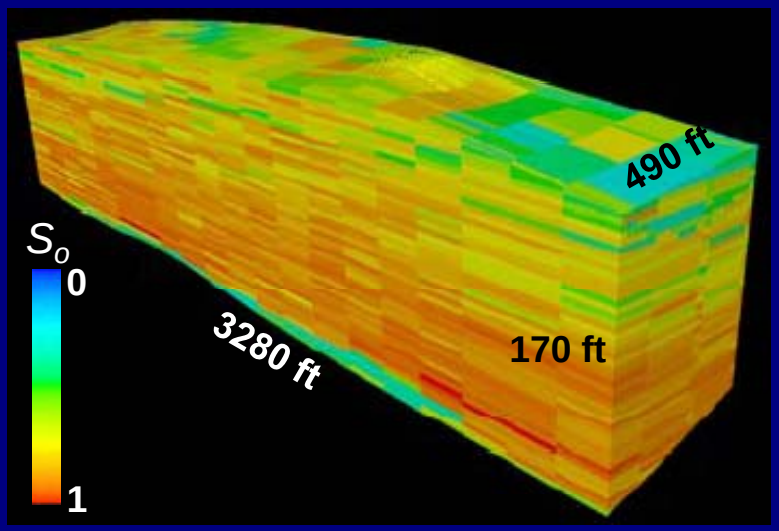


- Understand ES-SAGD process mechanisms
  - Solvent further reduces oil viscosity along the slope of steam chamber

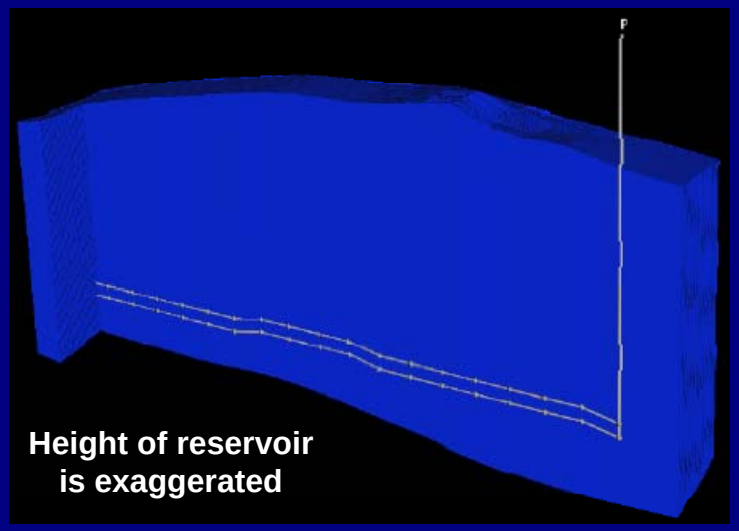
ES-SAGD: Deng, *et al.*, *WHOC* (2006)

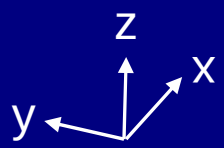
Numerical Modeling
Field-Scale Prediction

- A bitumen asset in Western Canada
  - Preheat: 100 days; SAGD: 150 days
  - ES-SAGD: after 250 days
  - Solvent composition: 98% C_4 & 2% C_1



Saturation Distribution



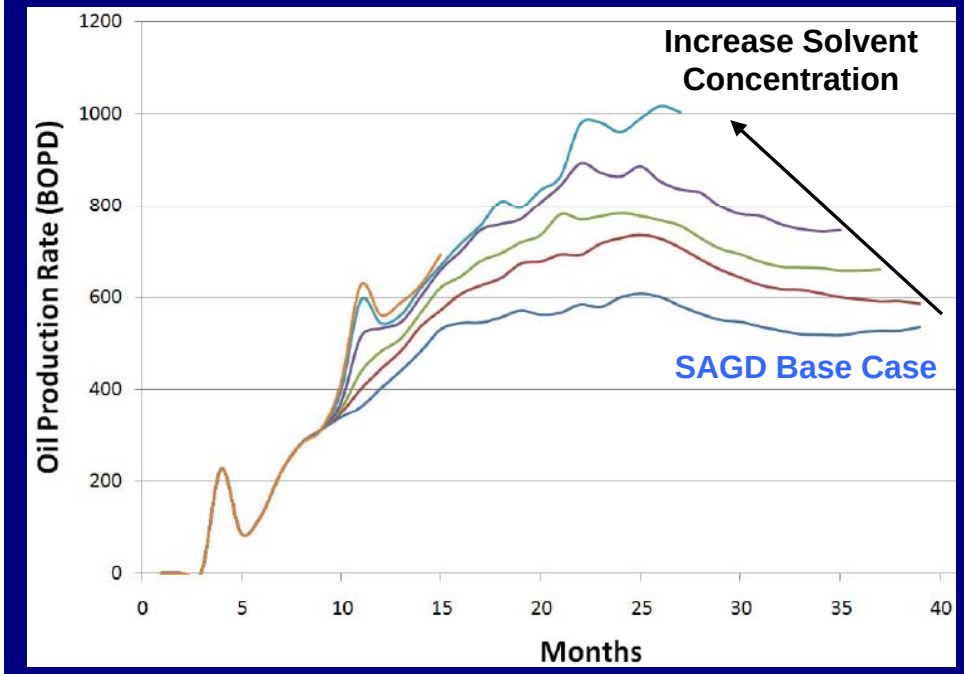


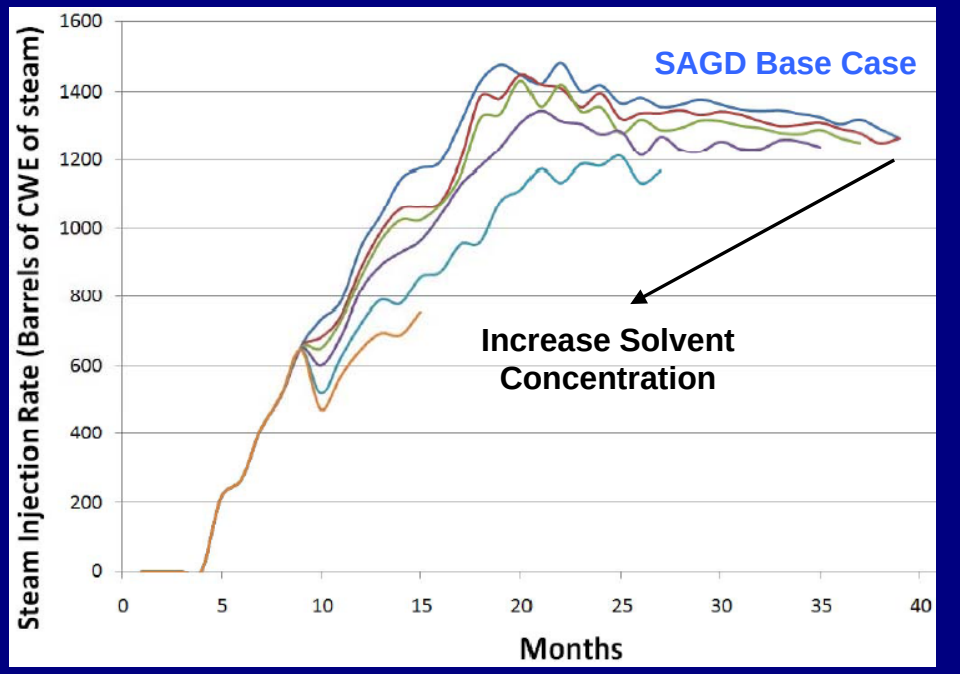
SAGD Well Pair Location

ES-SAGD: Akinboyewa, *et al.*, *SPE 129963* (2010)

Numerical Modeling
Field-Scale Prediction

Oil Production and Steam Injection





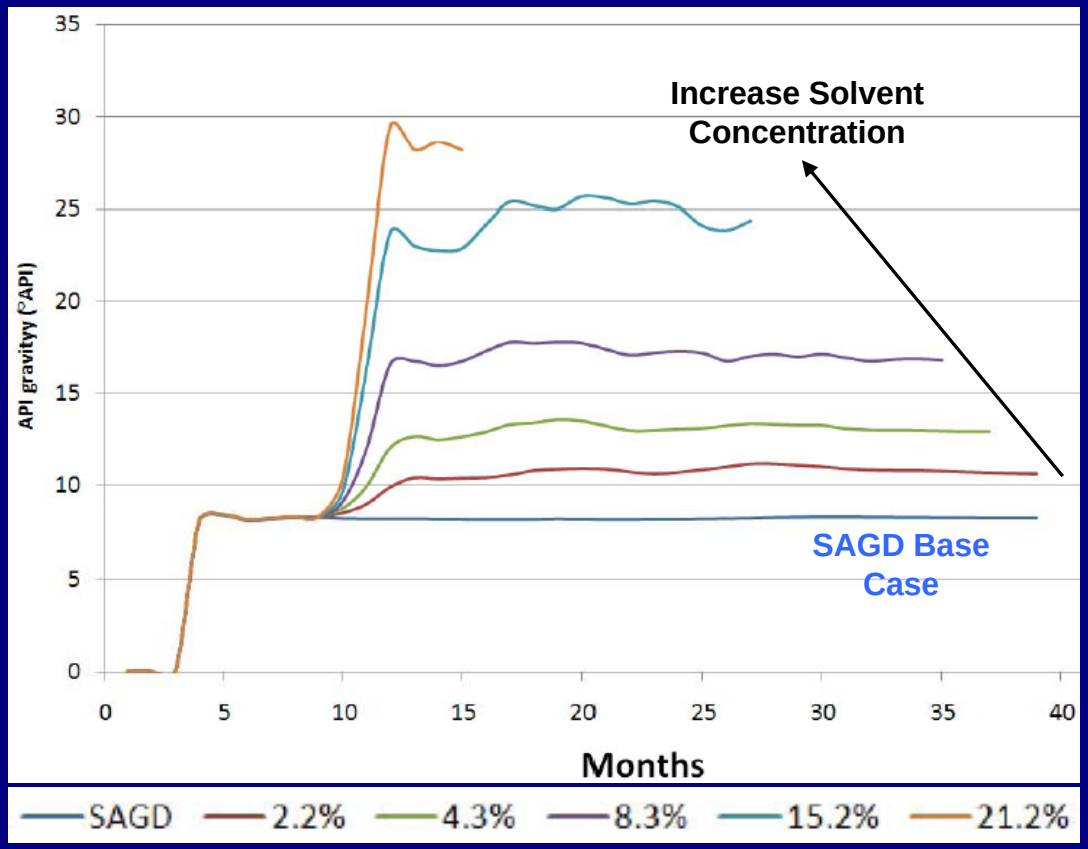
SAGD 2.2% 4.3% 8.3% 15.2% 21.2% **% Solvent in Steam (by vol.)**

- Improve oil production with solvent
- Reduce steam injection with solvent

ES-SAGD: Akinboyewa, *et al.*, *SPE 129963* (2010)

Numerical Modeling
Field-Scale Prediction

In-Situ Upgrading

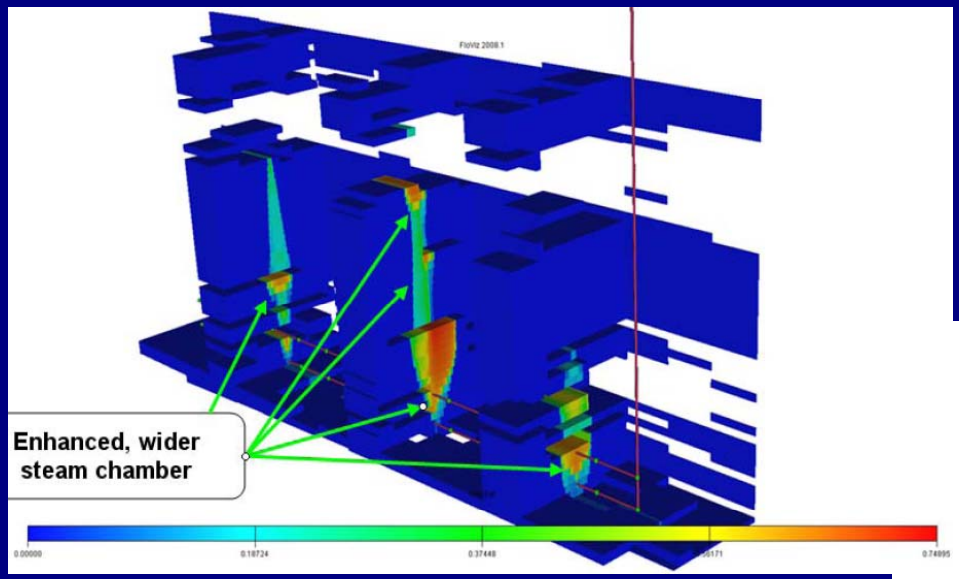


- The presence of solvent in produced oil improves its API
  - API is calculated based on composition of produced oil

ES-SAGD: Akinboyewa, *et al.*, *SPE 129963* (2010)

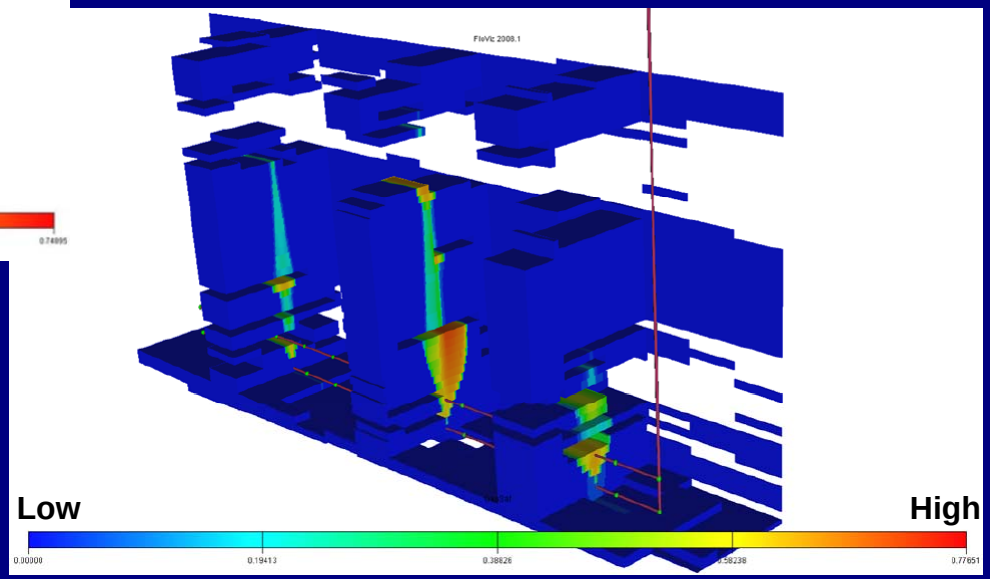
Numerical Modeling
Field-Scale Prediction

Gas Saturation Distribution



Steam Chamber with 5% Solvent Injection

Steam Chamber with SAGD Base Case



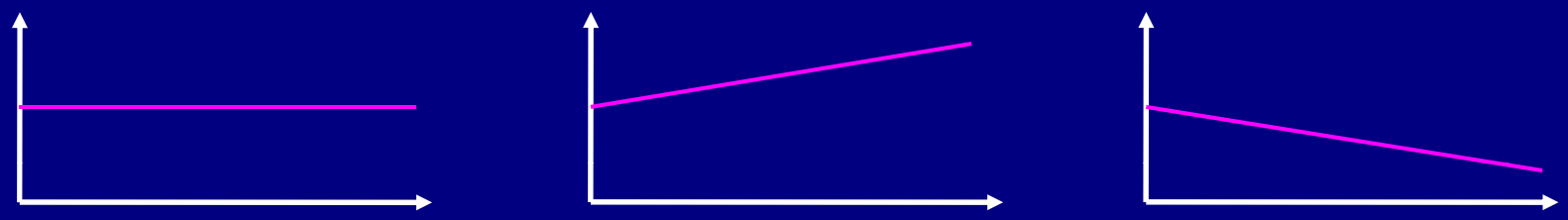
- Solvent slows vertical growth of steam chamber (reduces heat loss) and allows it to grow more laterally

ES-SAGD: Akinboyewa, *et al.*, *SPE 129963* (2010)

Challenges from Lab to Field

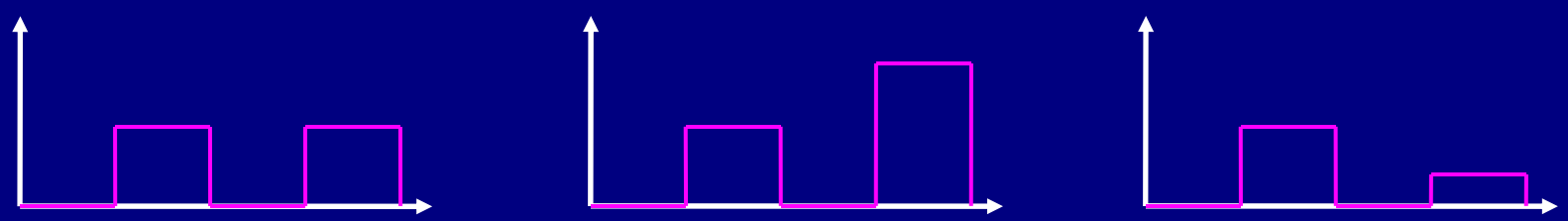
Optimal Solvent Injection Strategy

Continuous solvent injection



Constant Rate **Ramp-Up** **Ramp-Down**

Cyclic solvent injection

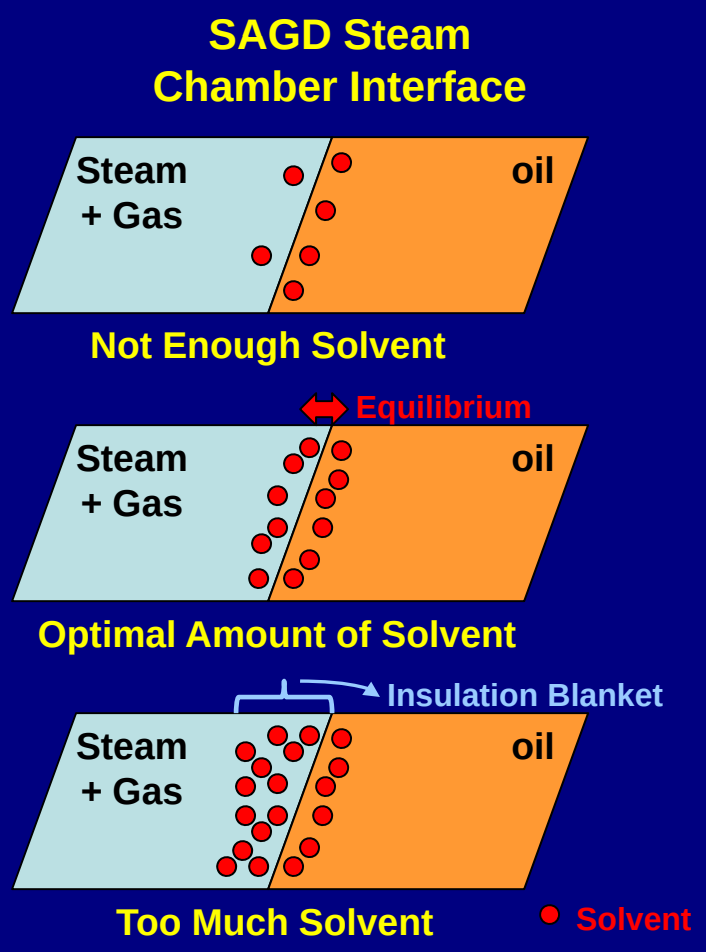


Constant Rate **Ramp-Up** **Ramp-Down**

- Unrealistic to test all strategies in the field
- Lab experiments and numerical studies can be useful

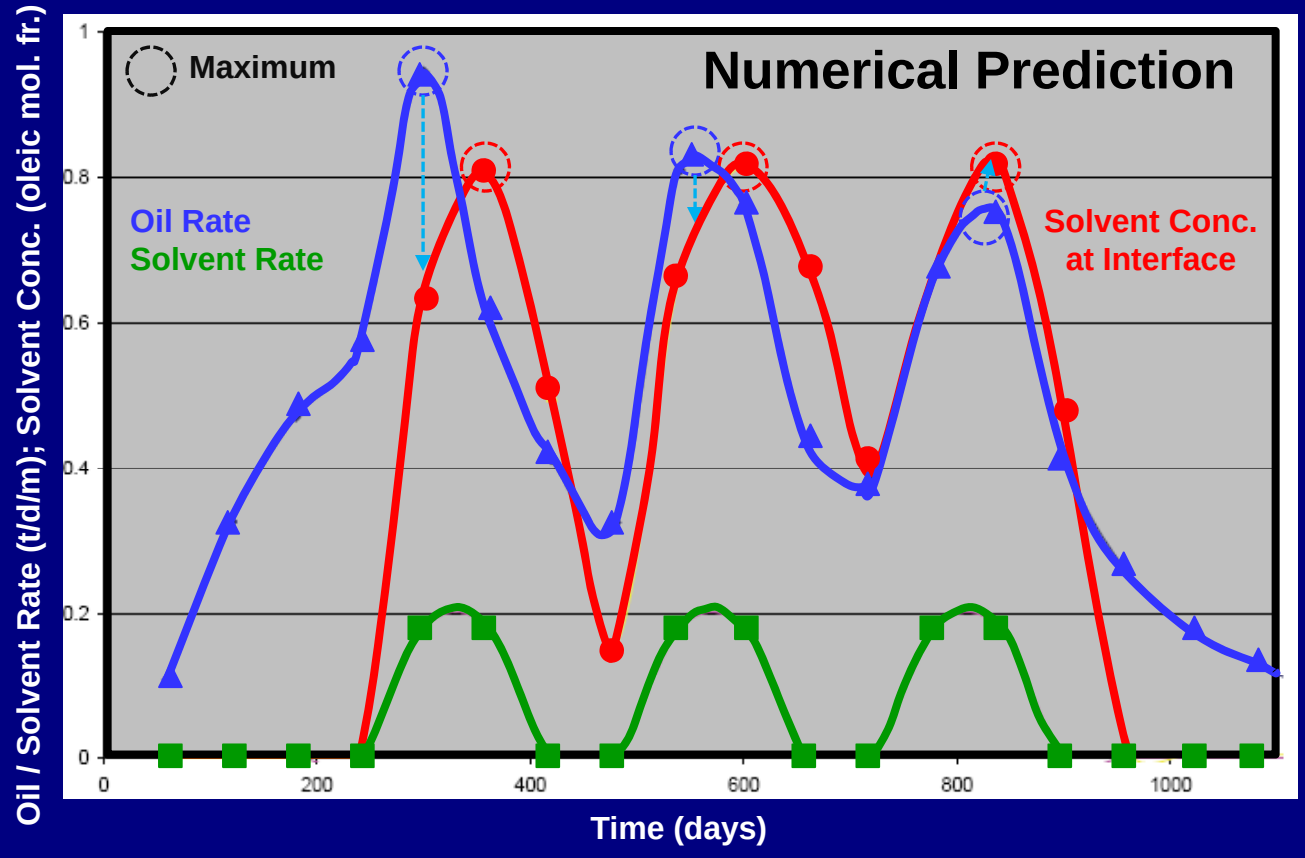
Challenges from Lab to Field
Optimal Amount of Solvent

- Not enough solvent
  - Less solvent dissolution in oleic phase
  - Less oil viscosity reduction
- Too much solvent
  - Excessive solvent in gaseous phase that forms an insulation blanket near steam chamber interface
  - Hinder propagation of steam front

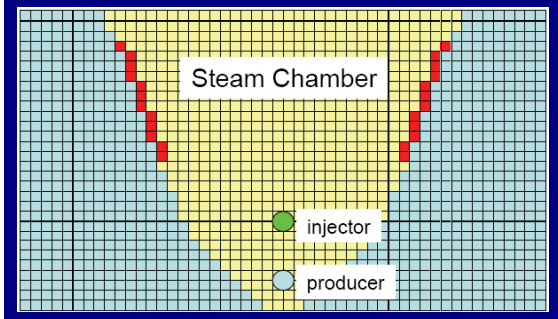


SAP: Gupta, *et al.*, *SPE 137543* (2010)

Challenges from Lab to Field
Optimal Amount of Solvent



SAGD Steam Chamber

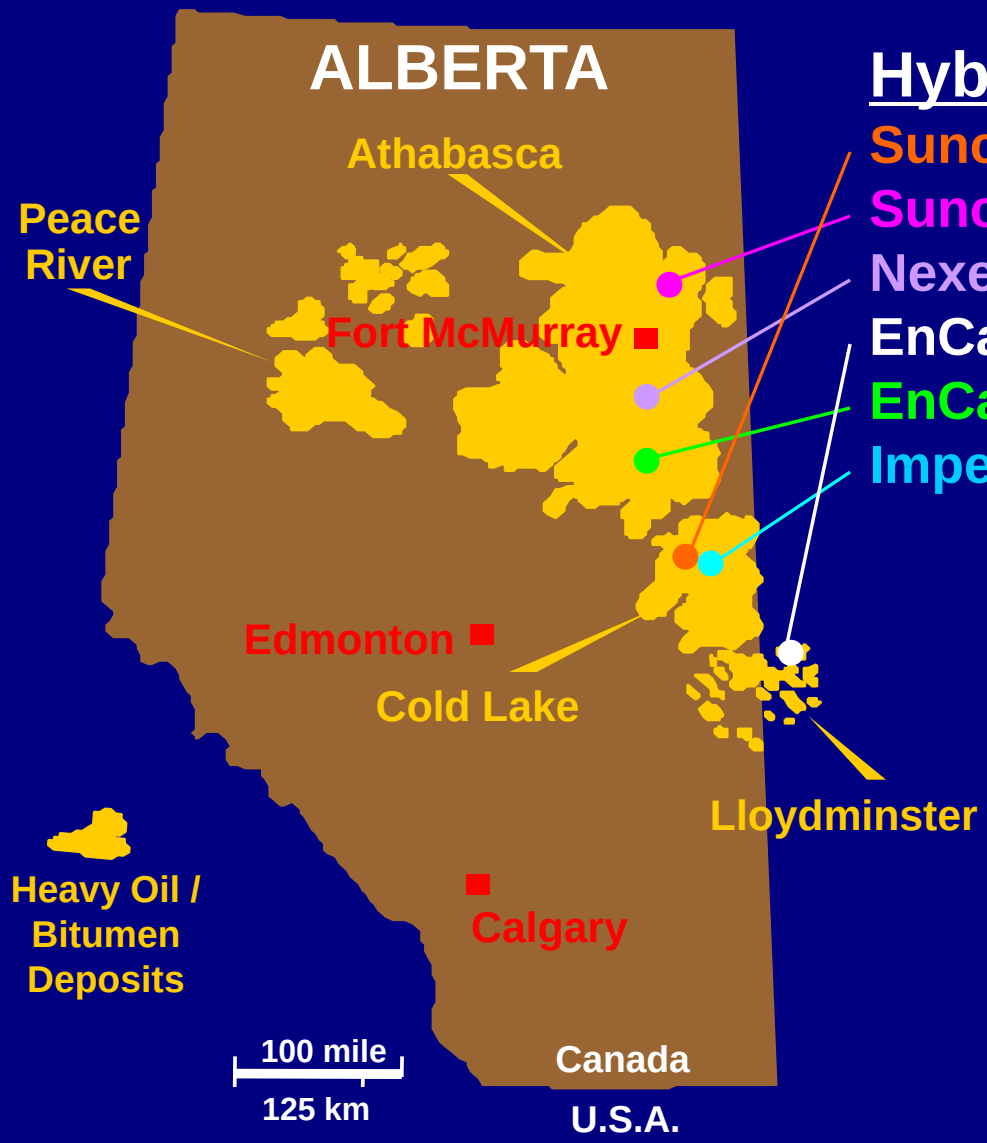


Solvent at steam chamber interface

- Optimal amount of solvent varies throughout lifetime of process

SAP: Gupta, *et al.*, *SPE 137543* (2010)

Field Pilot Tests in Canada



Hybrid Process Field Pilots:

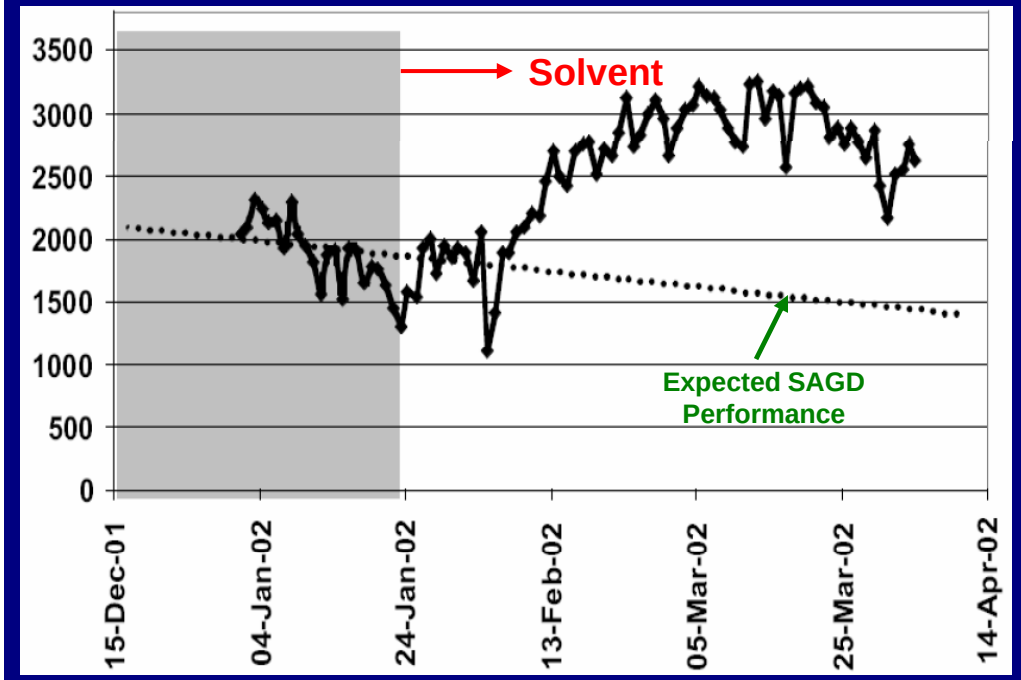
- Suncor / CNRL Burnt Lake – ES-SAGD
- Suncor Firebag – ES-SAGD
- Nexen Long Lake – ES-SAGD
- EnCana Senlac – SAP
- EnCana Christina Lake – SAP
- Imperial Oil Cold Lake – LASER

Field Pilot Test

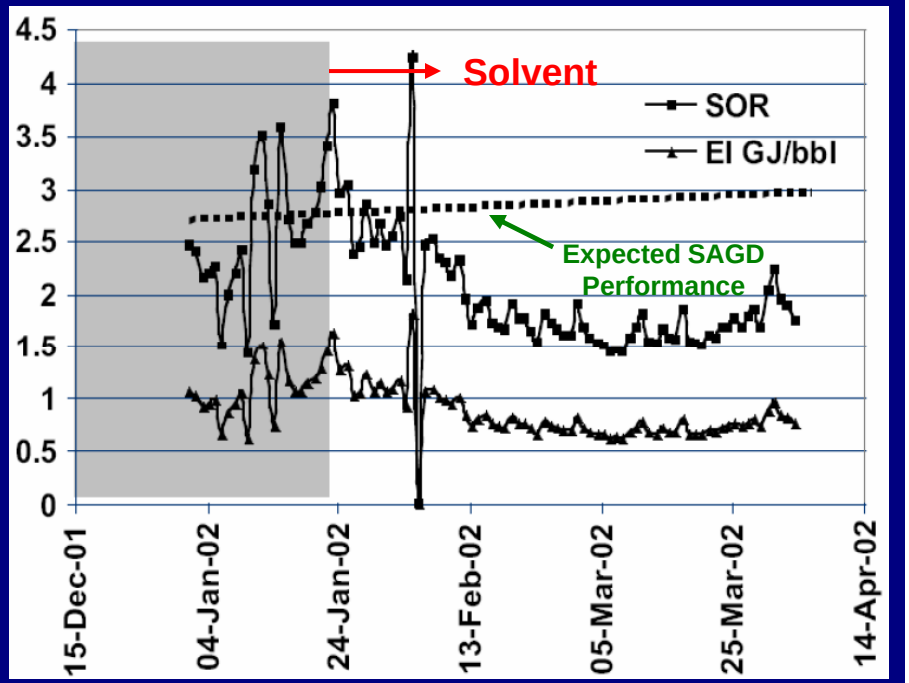
EnCana Senlac (January 2002)

- One well pair already in SAGD operation
  - Achieved peak rate
- Butane (C_4) was used as solvent

Oil Production Rate (bbl/d)



SOR and Energy Intensity (EI)



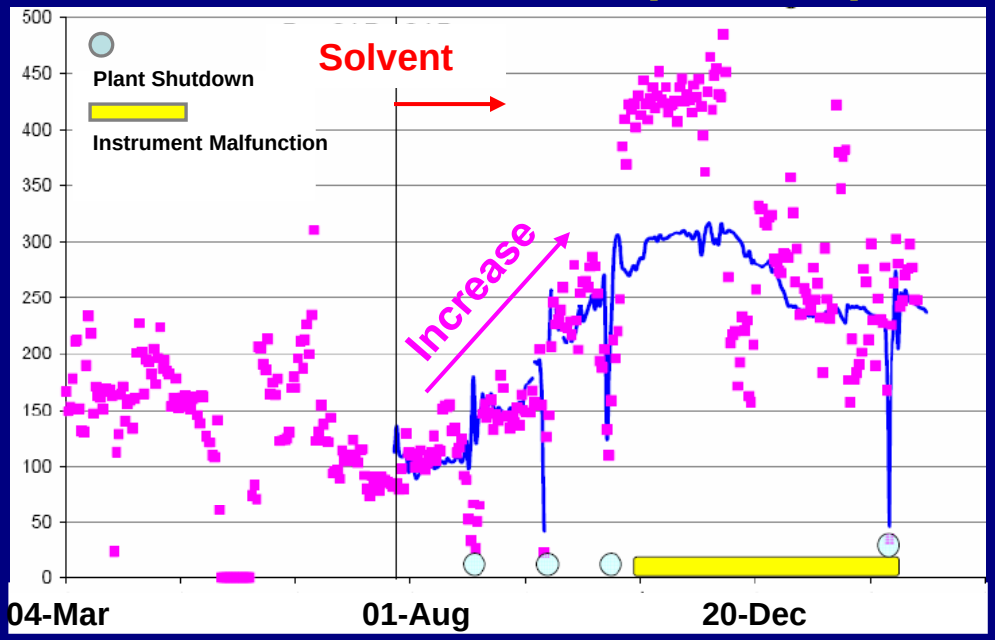
SAP: Gupta, *et al.*, *CIPC* (2002) & Gupta, *et al.*, *JCPT* (2005)

Field Pilot Test

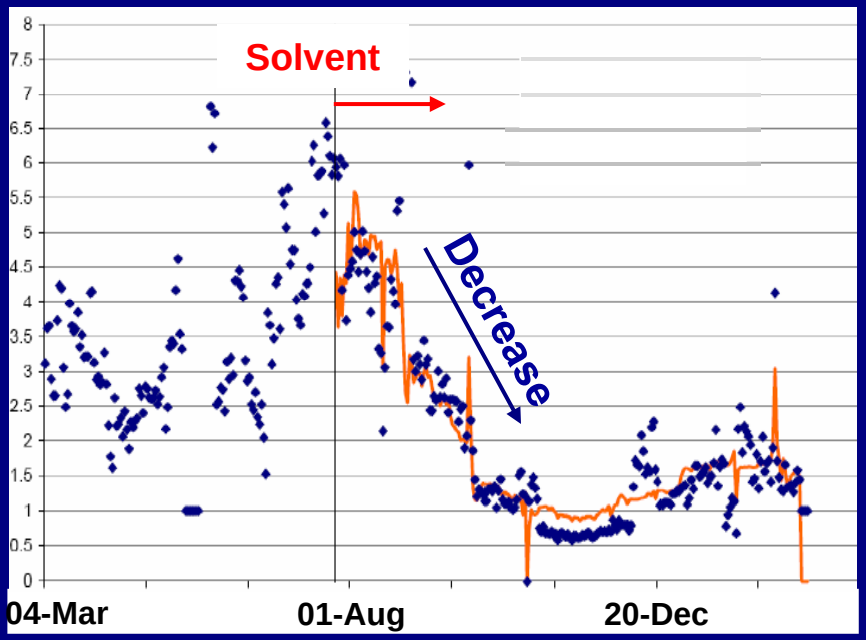
EnCana Christina Lake (April 2004)

- One well pair already in SAGD operation
  - Achieved peak rate (after two years)
  - Worst performance in 4 side-by-side well pairs
- Butane (C_4) was used as solvent

Oil Production Rate (tonne/d)



SOR



SAP: Gupta and Gittins, *CIPC* (2005) & Gupta and Gittins, *JCPT* (2006)

Field Pilot Test Performance
EnCana Senlac & Christina Lake

- Very encouraging pilot results
  - Improved initial oil rate over 50% in Senlac and 150% in Christina Lake
  - Reduced SOR
  - Improved API° gravity of produced oil over a range of 0.7° - 1°
- Economic improvement – Senlac

SAP: **Gupta, *et al*., *CIPC* (2002) & Gupta, *et al*., *JCPT* (2005)**
Gupta and Gittins, *CIPC* (2005) & Gupta and Gittins, *JCPT* (2006)

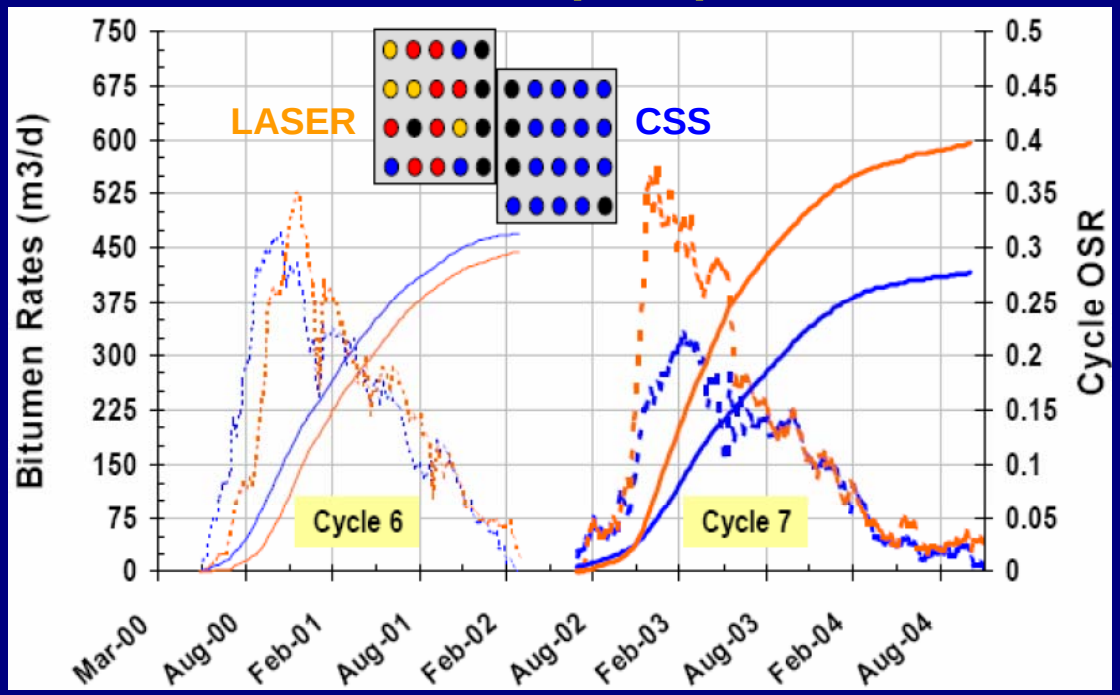
- Cenovus (previously EnCana) is planning SAP commercialization near Christina Lake

Field Pilot Test

Imperial Oil Cold Lake (March 2002)

- One CSS pad chosen from two adjacent identically performed pads considered
  - Cycle 6 – CSS; Cycle 7 - LASER
- Diluent (C_{5+} condensate) was used as solvent

Oil Production Rate (m^3/d) & Cumulative



- **Base CSS wells**
- **LASER Injection wells**
- **CCS wells influenced by other operations**
- **CSS wells produced substantial diluent**

LASER: Leaute and Carey, *CIPC* (2005)

Field Pilot Test Performance
Imperial Oil Cold Lake

- Very encouraging first LASER cycle (cycle 7) results
  - Recovered 80% of injected diluent
  - OSR declined for CSS pad but increased for LASER pad
  - Achieved an incremental "oil-to-solvent storage ratio*" of 10

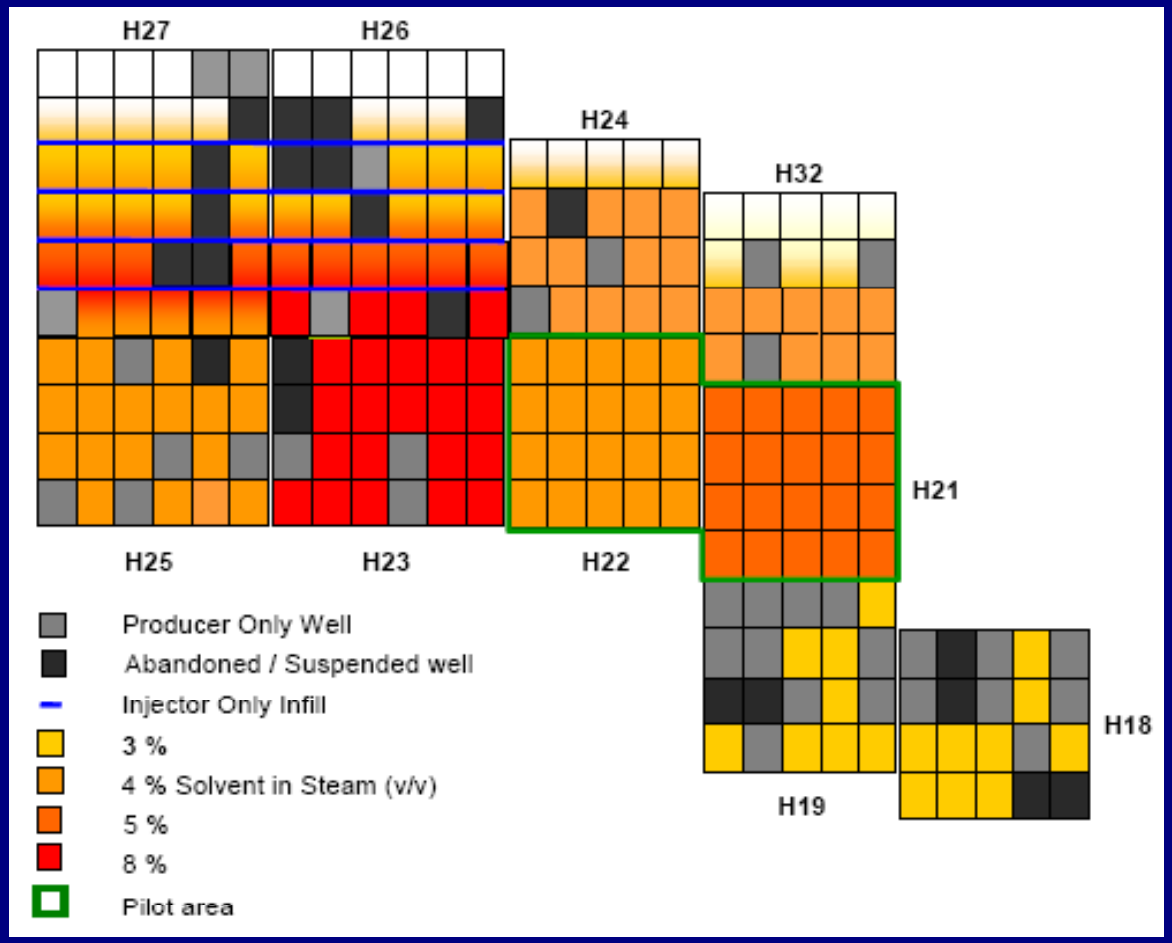
* m^3 oil produced / m^3 solvent retained in reservoir

LASER: Leaute and Carey, *CIPC* (2005)

LASER Commercialization

Imperial Oil Cold Lake

- 10 pads
- Diluent injection (Q3 2007 – April 2009) in 10 pads
- Production is expected to reach peak rate in late 2010 to early 2011



LASER: Energy Resources Conservation Board (ERCB) of Alberta **(2010)**

Hybrid Steam-Solvent Processes
Reduction of Environmental Impacts

- Reduce surface footprint
  - Use horizontal wells (e.g., SAGD)
- Reduce GHG and water usage
  - Reduce SOR by 1 in a 100,000 bbl/day project
    - Reduce ~1 million tonnes/year of CO_2 emission
    - Reduce 100,000 bbl/day of water usage for steam generation
- Reduce water disposal
  - Recycle significant amount of produced water

Conclusions

- Hybrid steam-solvent process is a feasible heavy oil recovery technology
  - Concept proven - lab and numerical results
  - Technically successful field pilot tests
- Hybrid steam-solvent processes can:
  - Improved oil rate and SOR
  - Reduce environmental impacts
  - Improve quality of produced oil

There is continuous improvement on heavy oil recovery technologies to meet the challenges of environmental issues