# $CO_2$ Flooding in Southeast Saskatchewan — Proven Success Leads to Another Boom Era

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**for**
**19th Williston Basin Petroleum Conference**

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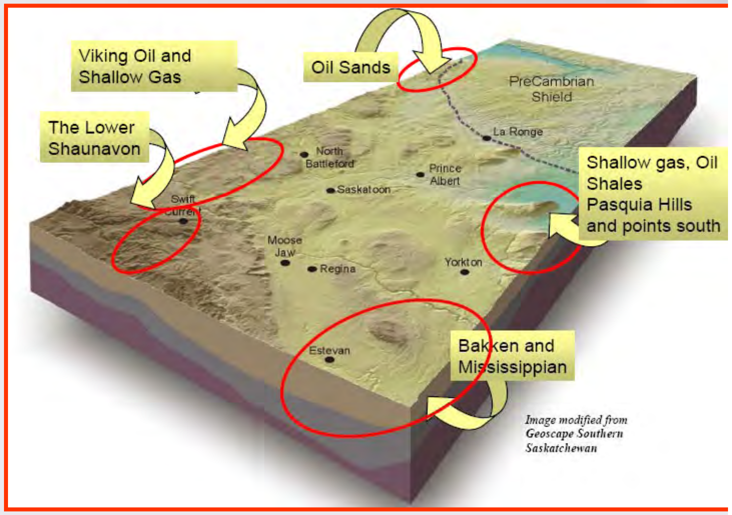
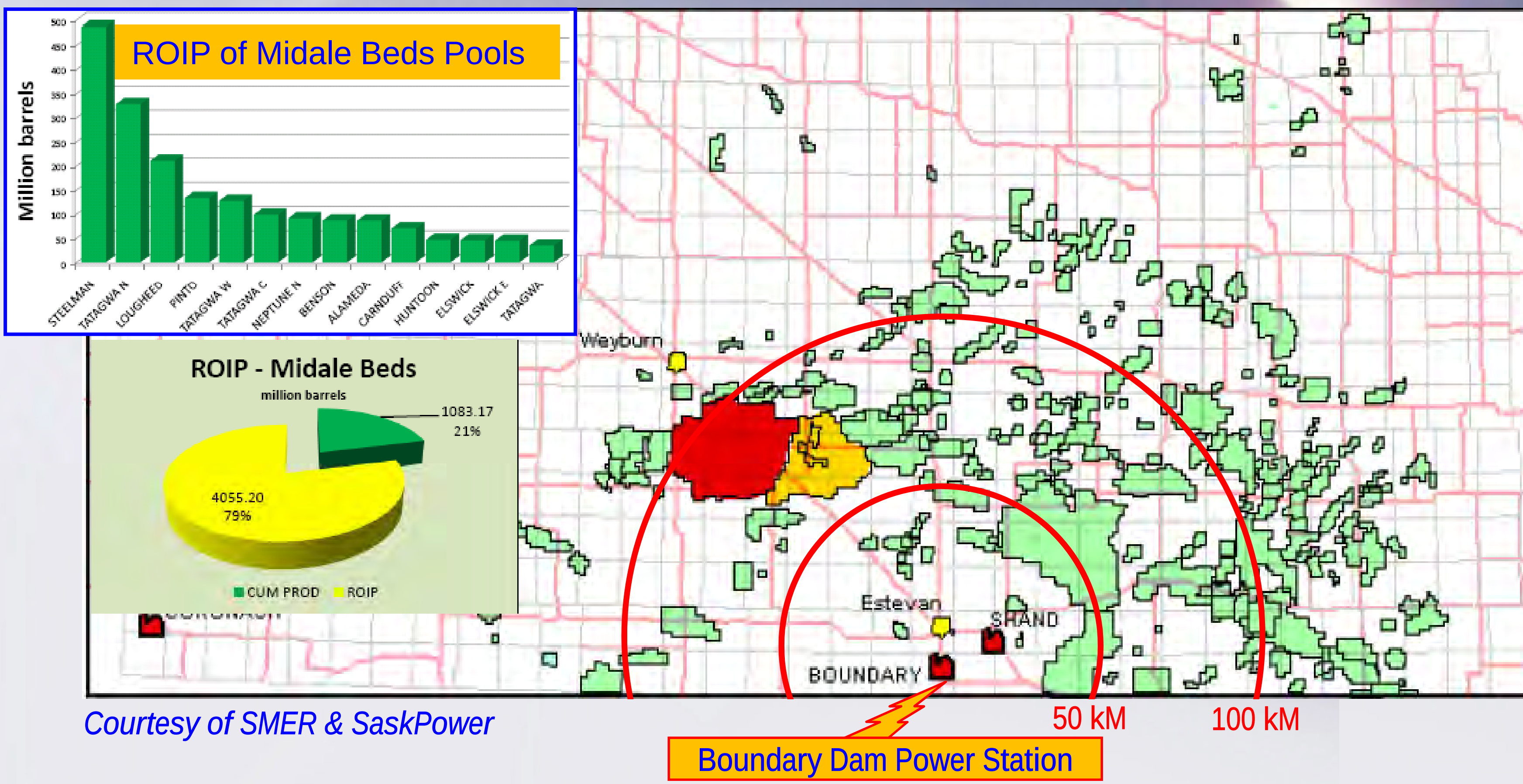
# $CO_2$ Flooding in Saskatchewan

- Saskatchewan's initial established L/M oil reserves: ~3.9 billion barrels (2008)
- Many reservoirs are at economic limit
- EOR process is imperative
- $CO_2$ flooding is a proven process
  - Can recover up to 25% additional IOIP
  - Will triple existing reserves
  - Extend producing life by over 20 years
  - Success stories at Weyburn and Midale
  - Carbon Capture and Storage (CCS)




Courtesy of Saskatchewan Ministry of Energy and Resources

# Reservoirs of Interest in SE Sask.




*Courtesy of SMER & SaskPower*

# Research Conducted on SE Sask.

## — Multi-Client Programs:

Brought industry and government clients together in a consortium, focusing on providing/applying $CO_2$ injection in SE Sask. and other LMH oil reservoirs.

1988 – 1993

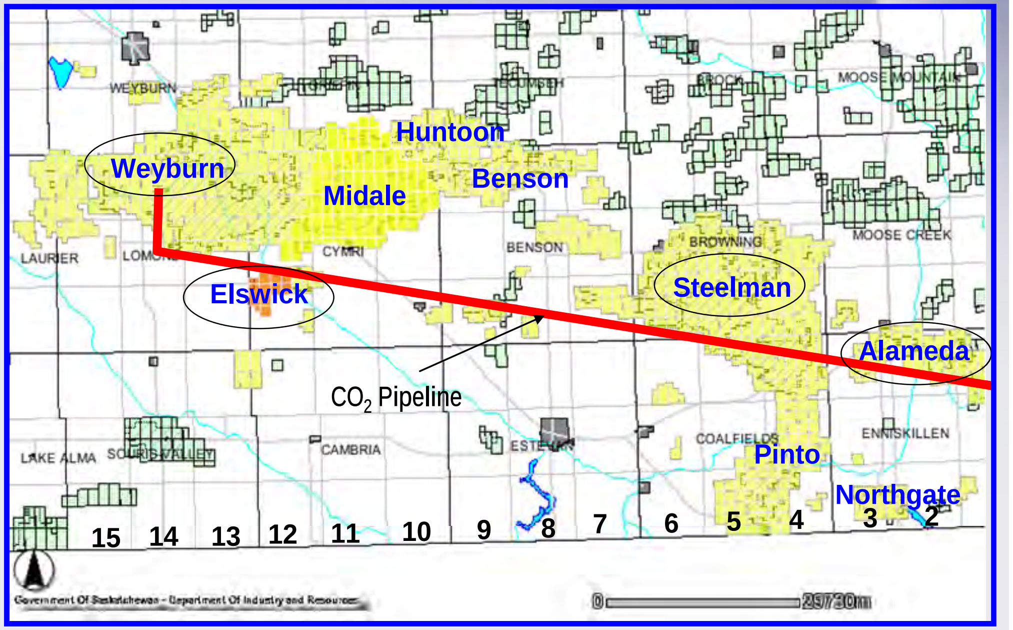
$CO_2$ miscible flooding feasibility for the Weyburn pool

1993 – 1996

$CO_2$ miscible flooding feasibility for the Steelman and Alameda pools

1996 – 2000

$CO_2$ immiscible/near-miscible flooding feasibility for other light/medium oil reservoirs in SE Sask.



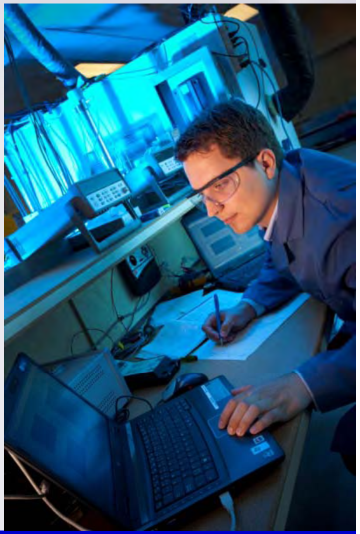
# Research Conducted on SE Sask.

## — IEA Weyburn $CO_2$ Monitoring & Storage Project

- Fluid Properties and Phase Behaviour Study of Weyburn Oil–$CO_2$ System
- Influence of $CO_2$/Brine Interfacial Properties on the Long-Term Fate of $CO_2$ Injected into Weyburn Reservoir
- Re-injection of Recycled $CO_2$: Changes to $CO_2$-Oil Miscibility over the Year 2002
- Laboratory Dynamic Fluid Testing — Reservoir Fluid Property Changes over the Year 2002
- Re-injection of Recycled $CO_2$: Changes to $CO_2$-Oil Miscibility over the Year 2001
- Baseline Study of Oil Recovery Parameters at Pre-$CO_2$-Injection Conditions

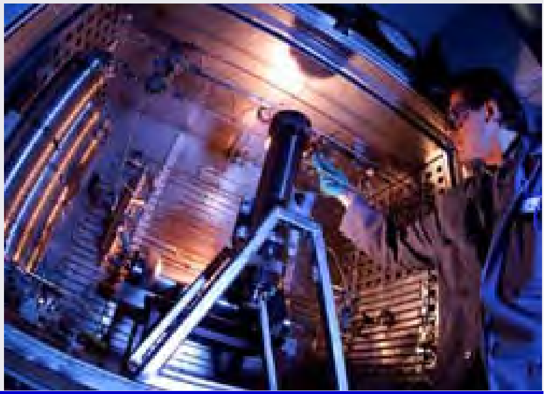
# Technical Questions

- Minimum miscibility pressure (MMP)
- Effects of impurities in $CO_2$ on MMP
- Asphaltene precipitation
- $CO_2$ injection strategy
- Reservoir heterogeneity
- Wettability alteration and acidic effect
- Water blocking of oil
- Viscous fingering & gravity override



# Technical Approaches

- Measure PVT properties of oil–solvent system
  - ✓ PVT properties, EOS modeling
- Determine oil–$CO_2$ MMP
  - ✓ Slim tube, rising bubble apparatus, vanishing IFT
- Quantify asphaltene flocculation/precipitation
  - ✓ Formation damage, precipitation inhibition
- Study oil recovery efficiency in coreflooding
  - ✓ Injection scheme, solvent
- Conduct numerical simulation
  - ✓ Coreflood history match and field-scale prediction



# Weyburn $CO_2$ Miscible Flooding
## — Laboratory Engineering Design

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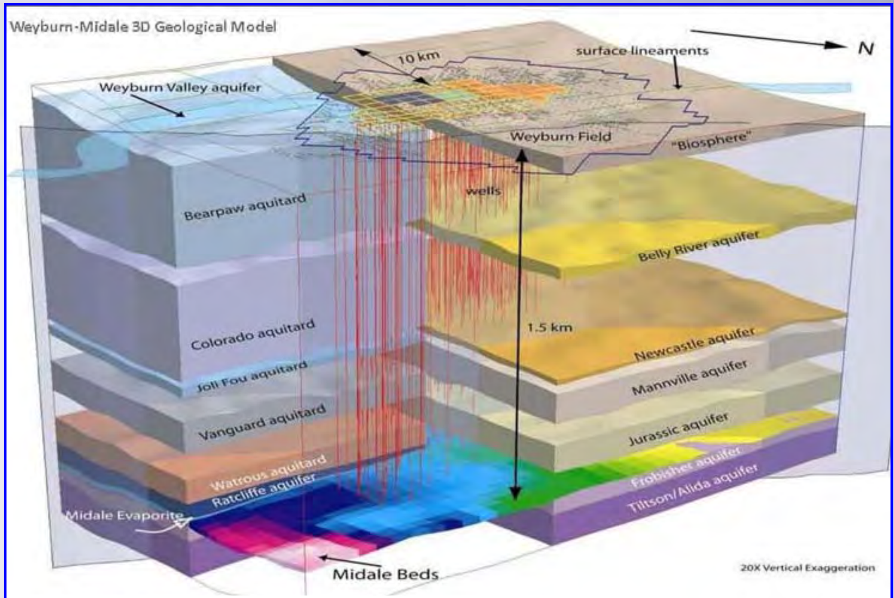
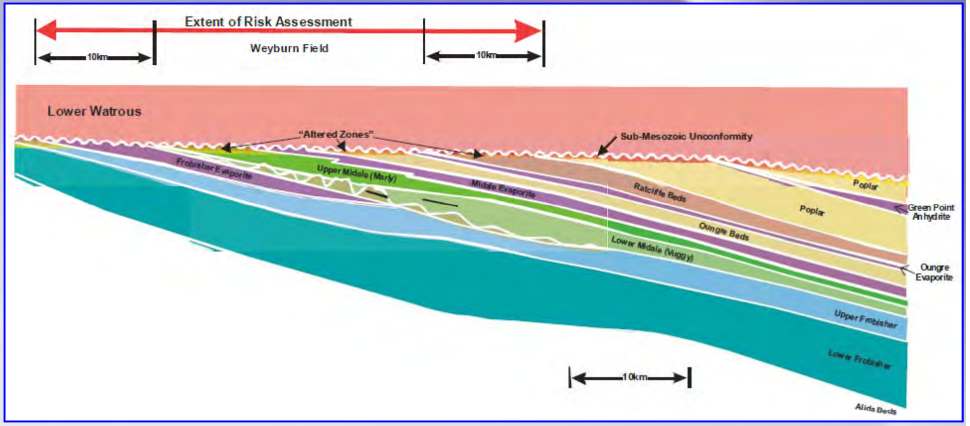
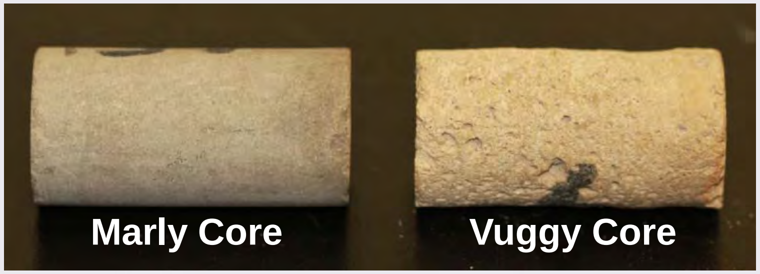
### Weyburn 3-D Geological Model




*Courtesy of Petroleum Technology Research Centre*

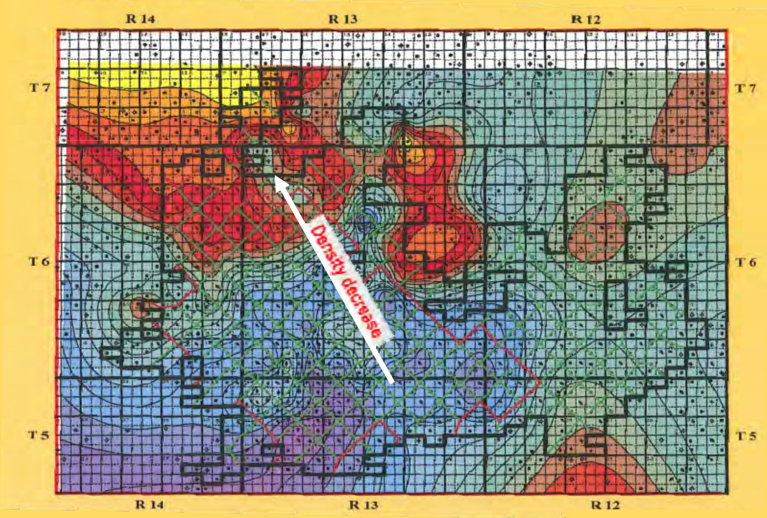
### Weyburn Geology



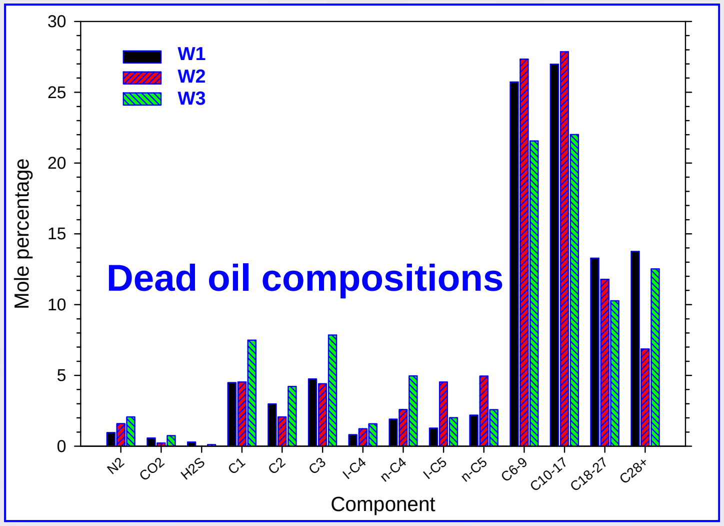




| Properties | Marly Zone | Vuggy Zone |
|---|---|---|
| Zone Depth | 1450 m | 1460 m |
| Porosity | 16 - 38% | 3 - 18% |
| Permeability, | 1 – 100 mD | 0.01 – 500 mD |
| Mineralogy | Chalky dolostone with occasional limestone interbeds | Heterogeneous, subtidal limestone |

# Physical Properties of Weyburn Reservoir Fluids

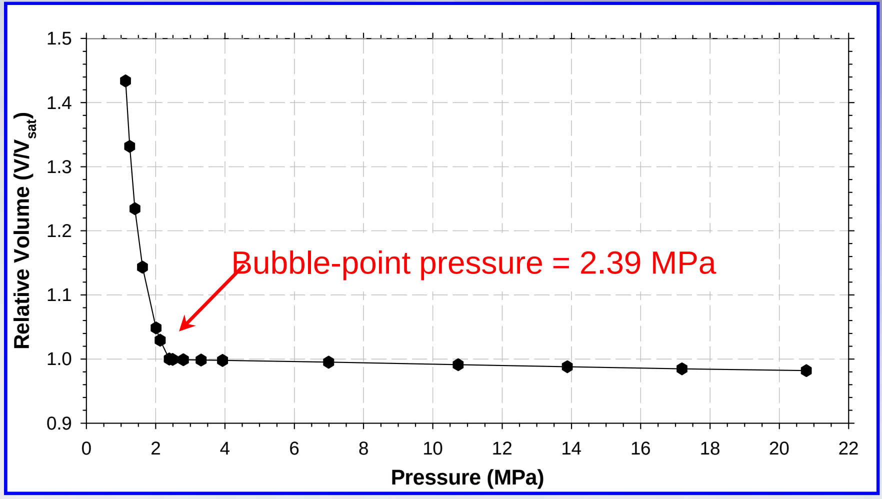



API gravity variations in Weyburn pool

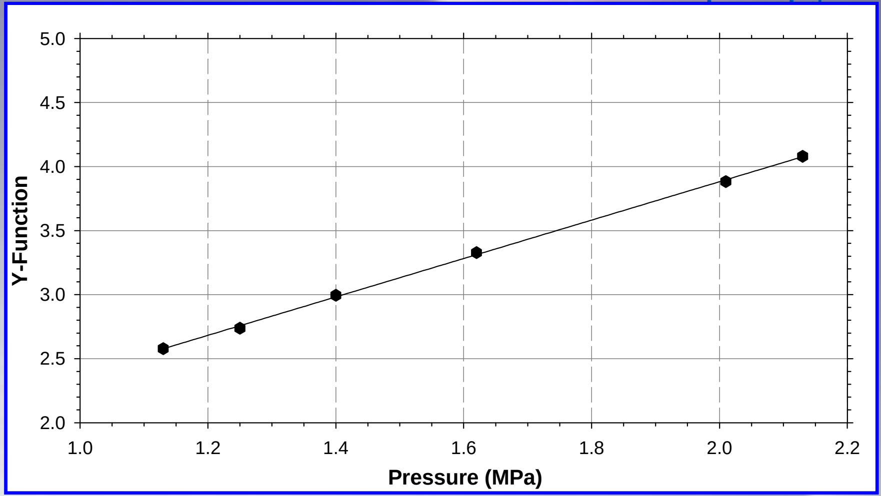



| Dead Oil Properties | | | |
|---|---|---|---|
| Properties | W1 | W2 | W3 |
| Well Number | 14-17-6-13W2M | 3-11-7-13W2M | 12-18-6-13W2M |
| API Gravity | 29.5 | 34.0 | 31.2 |
| Viscosity @ 1 atm, 20°C | 11.3 | 4.6 | 9.4 |
| MW, kg/kmol | 232 | 203 | 215 |
| Saturates, wt% | 39.5 | 55.3 | 48.4 |
| Aromatics, wt% | 45.4 | 31.1 | 33.5 |
| Resins, wt% | 8.4 | 9.6 | 13.2 |
| Asphaltenes, wt% | 6.7 | 4.0 | 4.9 |
| **Live Oil Properties** | | | |
| $P_{sat}$, MPa | 2.39 | 3.47 | 4.92 |
| Viscosity, mPa·s | 2.70 | 1.45 | 1.76 |
| Density, kg/m$^3$ | 833.5 | 797.2 | 806.4 |
| FVF, m$^3$/m$^3$ | 1.088 | 1.102 | 1.124 |
| Swelling Factor, m$^3$/m$^3$ | 1.076 | 1.060 | 1.085 |
| GOR, sm$^3$/m$^3$ | 19 | 23 | 32 |

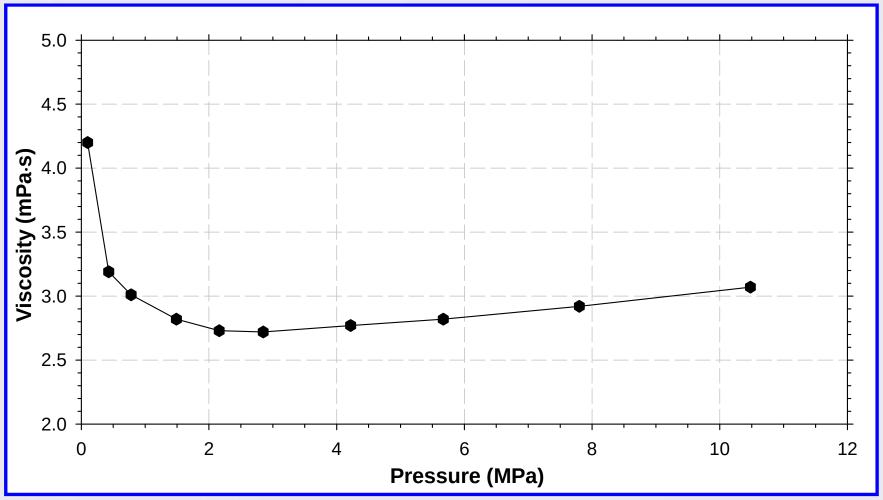
# PVT Properties of Reservoir Fluid



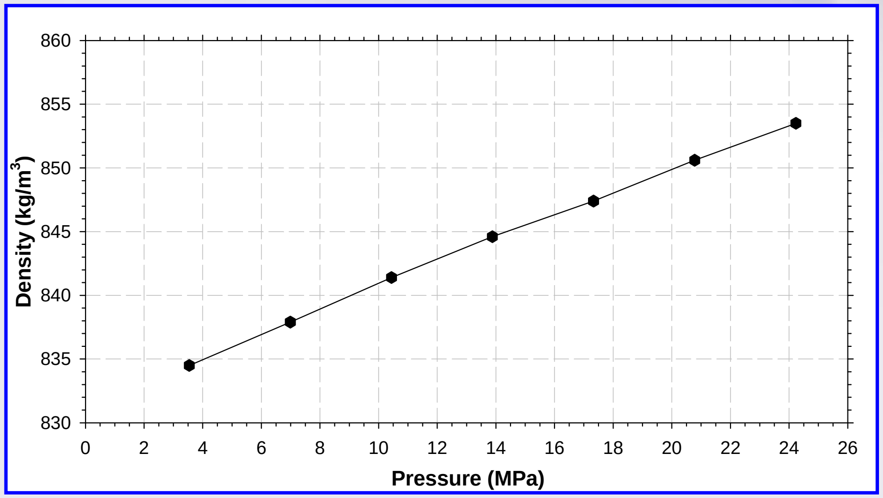

Volume-pressure relation




Y-function-pressure relation

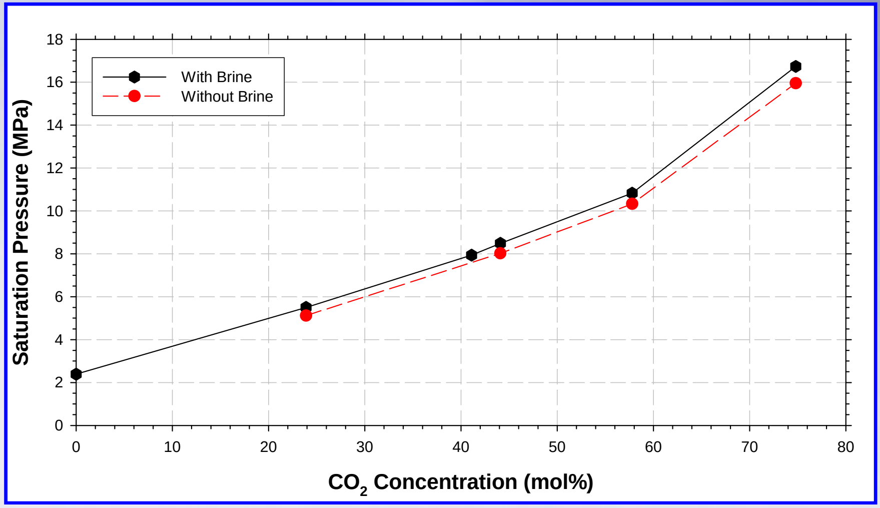



Pressure-viscosity relation

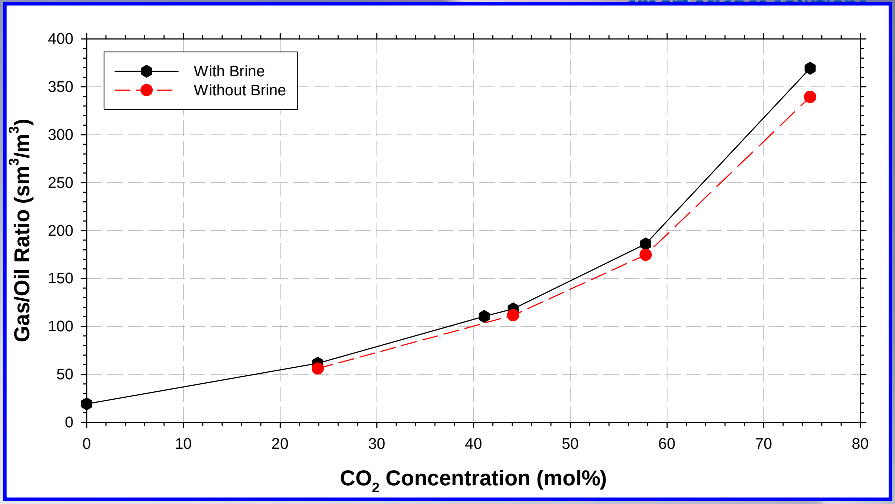



Pressure-density relation

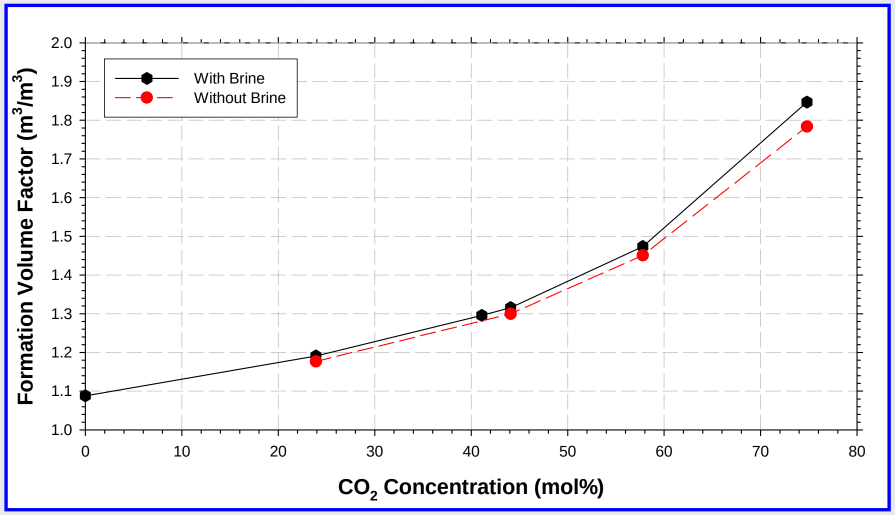
# PVT Properties of Reservoir Fluid – $CO_2$ System



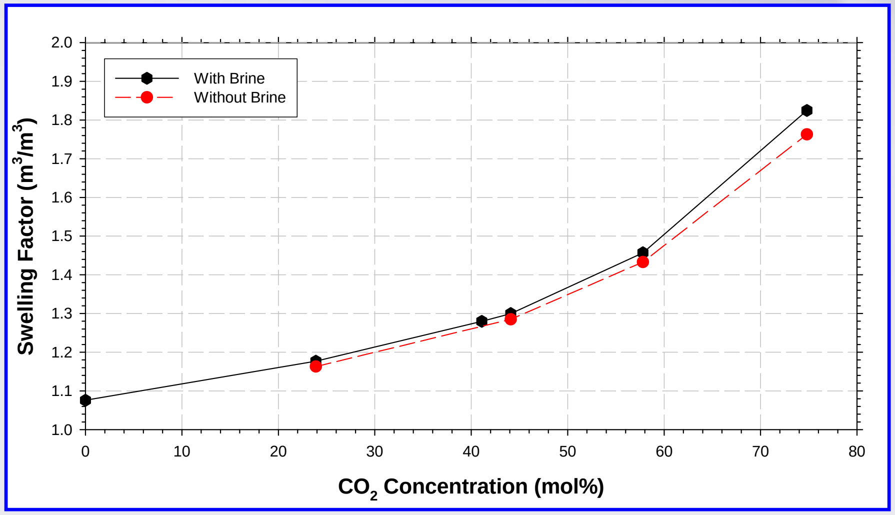

Saturation pressure




Gas/oil ratio




Formation volume factor

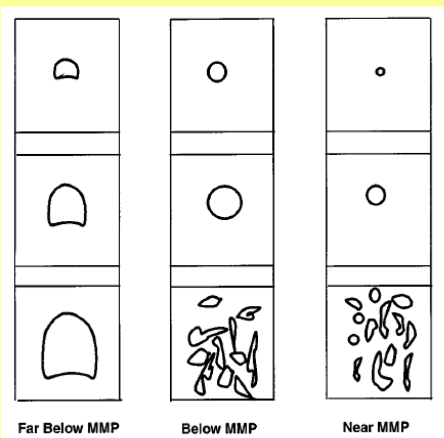



Swelling factor

# Minimum Miscibility Pressure

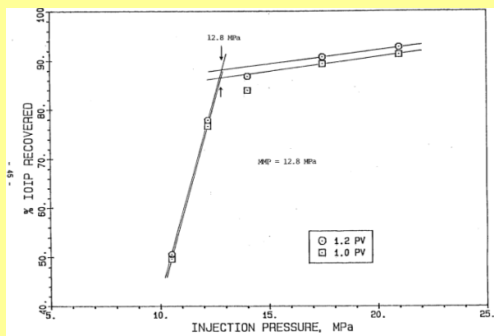


## Rising-Bubble Apparatus




Schematic of rising bubble shape at different pressures

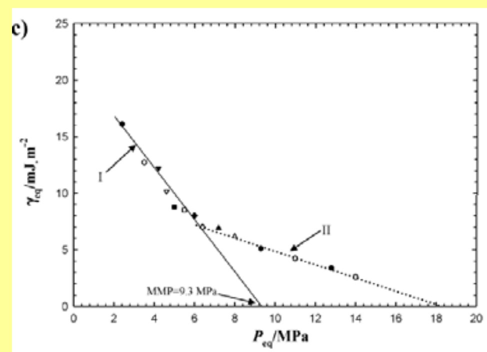
## Slim Tube Tests




Huang and Dyer, 1986, J. Can. Pet. Technol.

Oil recovery versus operating pressure at various pore volumes of $CO_2$ injected for Weyburn oil

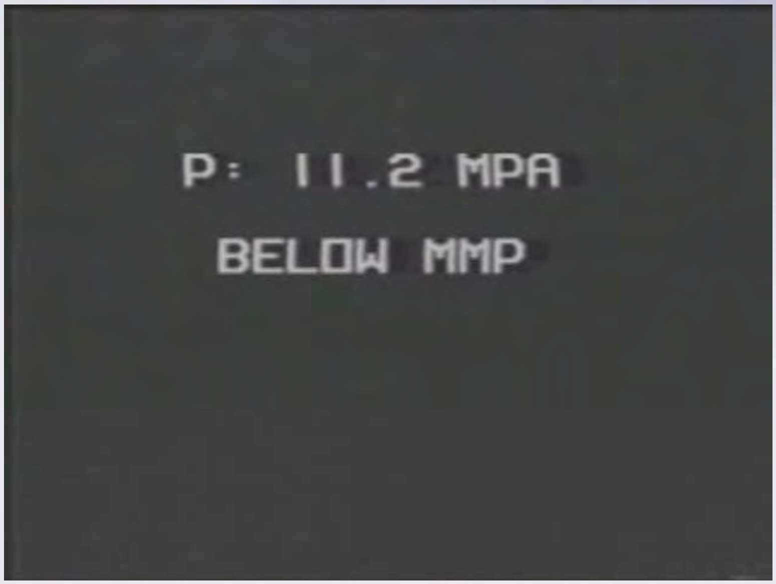
## Vanishing IFT Technique




Wang et al., 2010, J. Chem. Eng. Data

Equilibrium interfacial tensions of a light crude oil-$CO_2$ system at different equilibrium pressures

# Minimum Miscibility Pressure




$CO_2$ rising bubbles at different pressures (video)

## Measured and predicted $CO_2$ MMPs

| | Measured MMP (MPa) | | Predicted MMP (MPa) | |
|---|---|---|---|---|
| | Slim tube | RBA | Alston | Sebastian |
| Pure $CO_2$ | 12.8 | 11.7 | 13.3 | - |
| 3.1 mol% $N_2$+ 2.8 mol% $CH_4$ in $CO_2$ | - | 14.5 | 16.6 | 16.0 |
| 9.9 mol% $CH_4$ in $CO_2$ | 17.5 | 16.0 | 16.2 | 16.9 |
| 5.1 mol% $N_2$ + 5.1 mol% $CH_4$ in $CO_2$ | 21.2 | 20.5 | 20.5 | 17.1 |

# Multi-Contact Test

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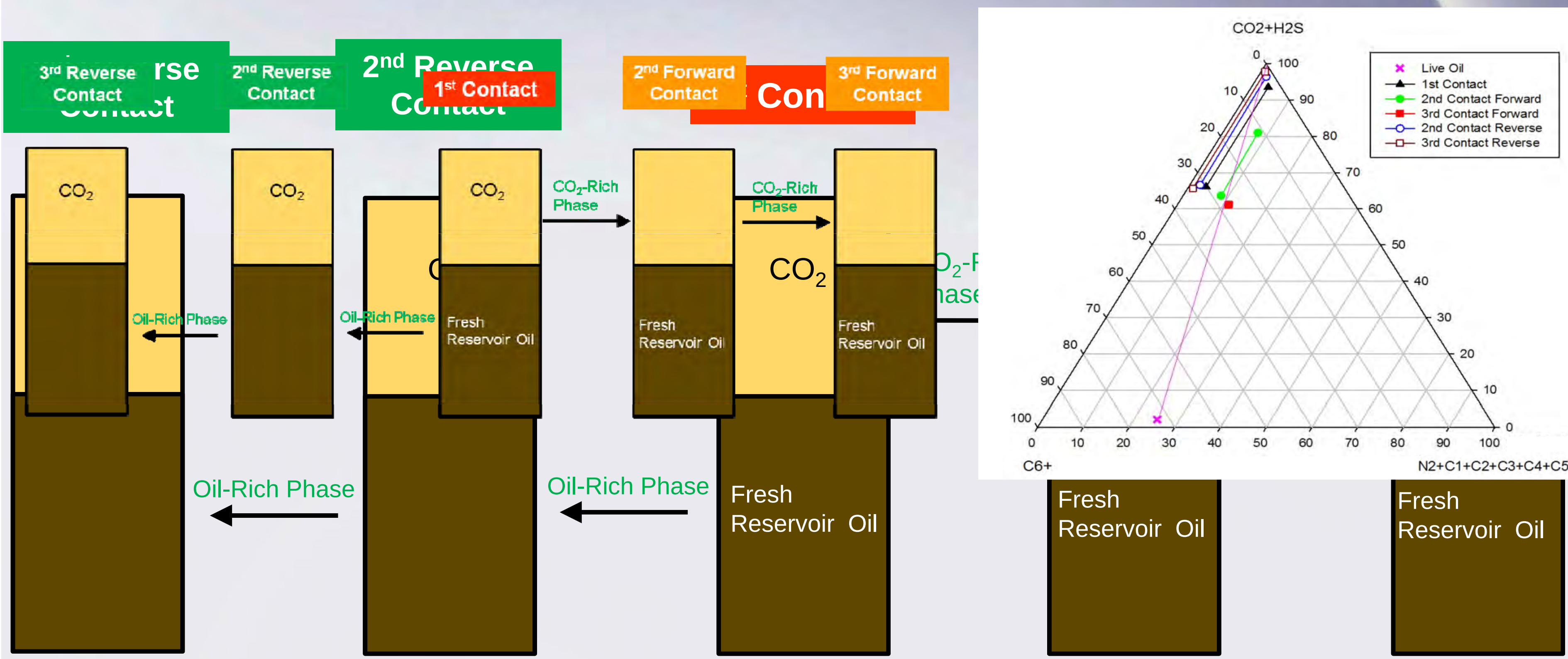
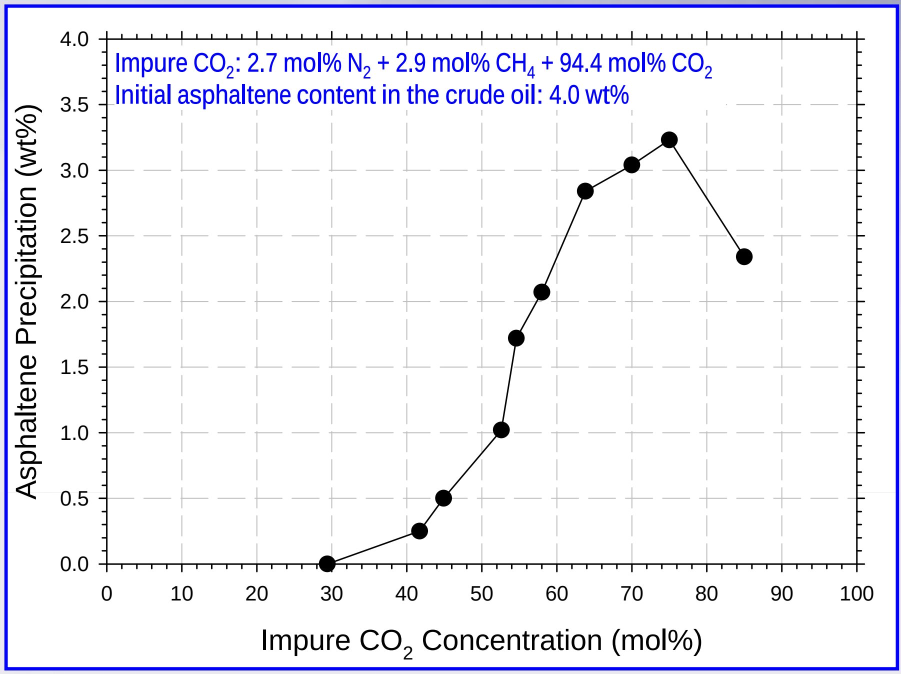
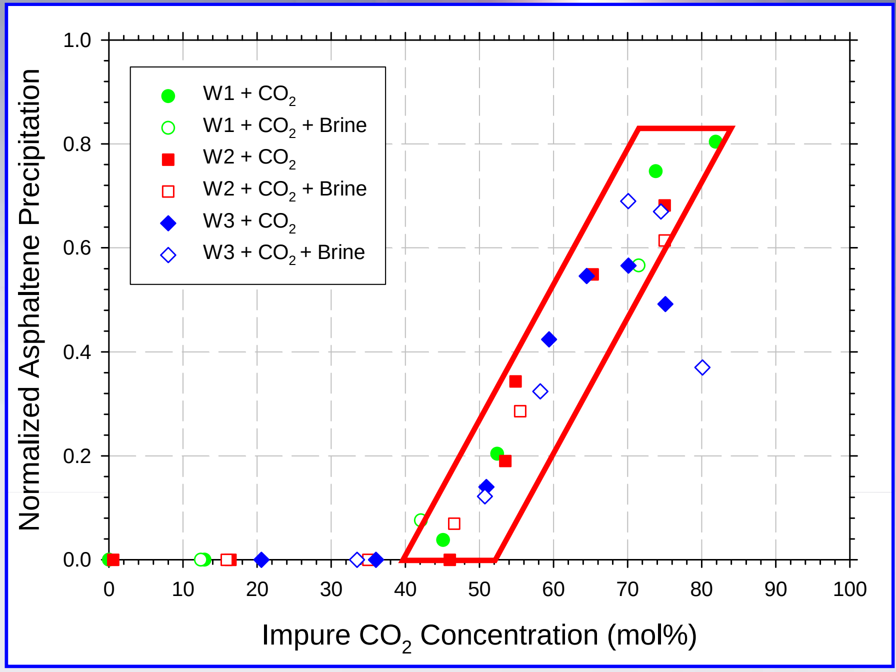
## Generate the complete range of compositions and interfacial tensions that are encountered in the reservoir under $CO_2$ miscible injection



# Asphaltene Deposition during $CO_2$ Flooding

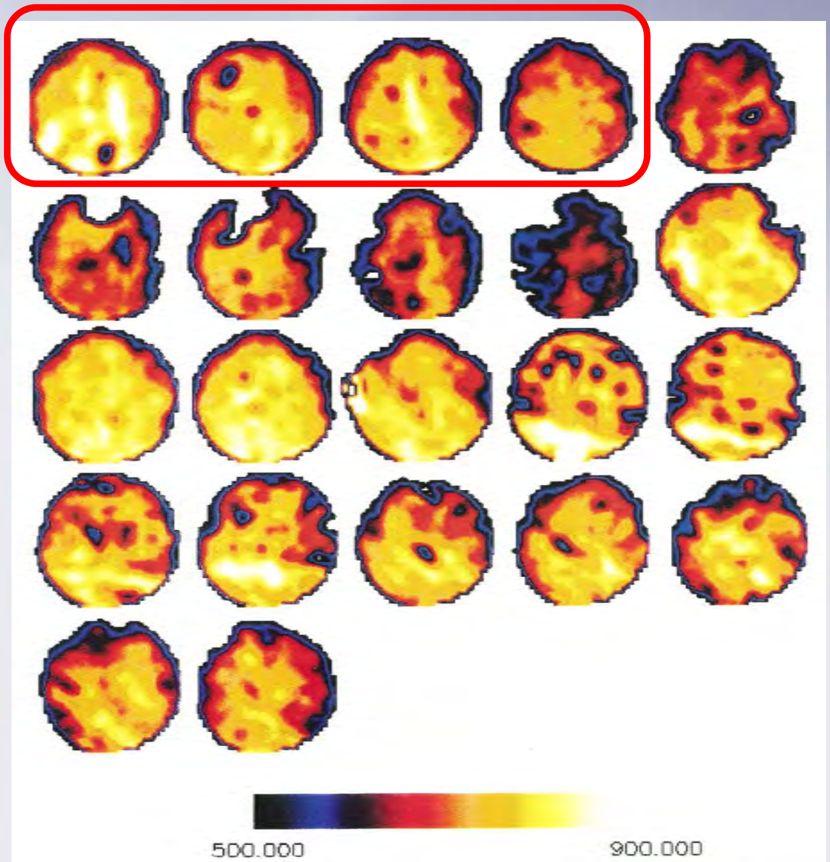


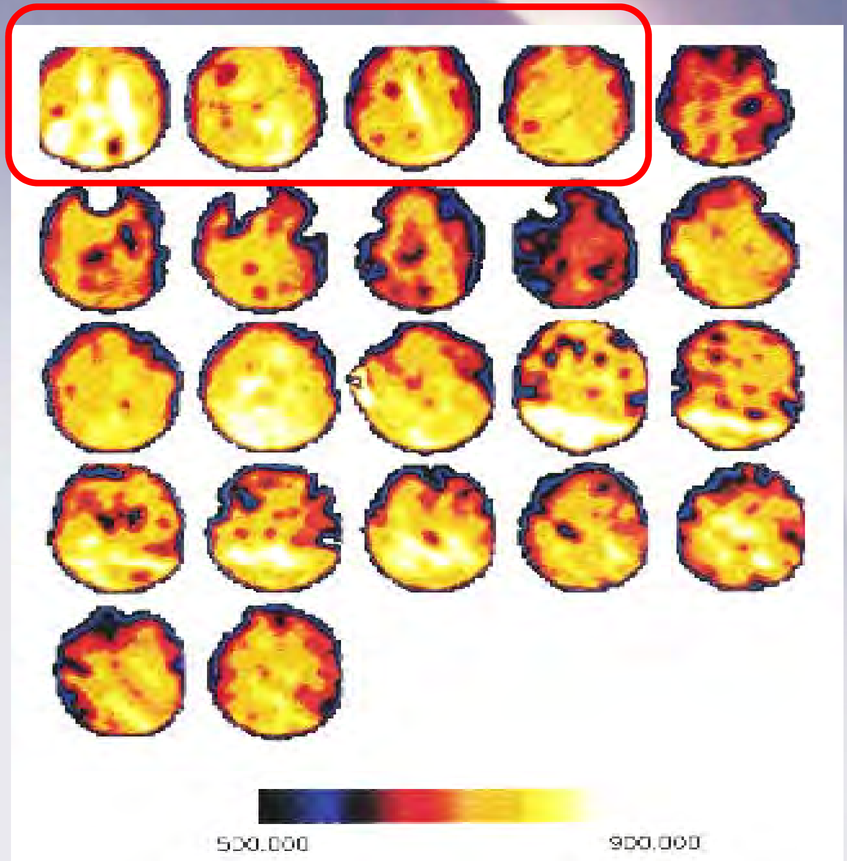

Asphaltene precipitation in Weyburn reservoir fluid W2 with impure $CO_2$ at 16 MPa and 61°C




Normalized asphaltene precipitation in three Weyburn reservoir fluids with pure/impure $CO_2$ at 16 MPa and 61°C

# Asphaltene Deposition during $CO_2$ Flooding

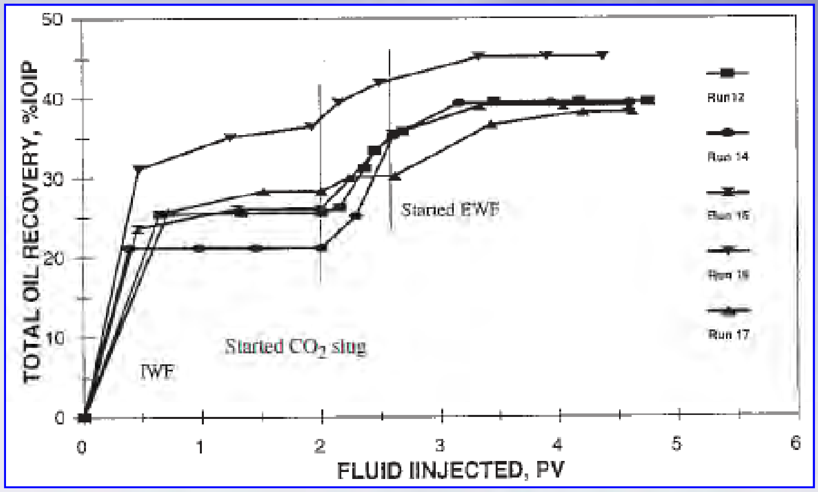


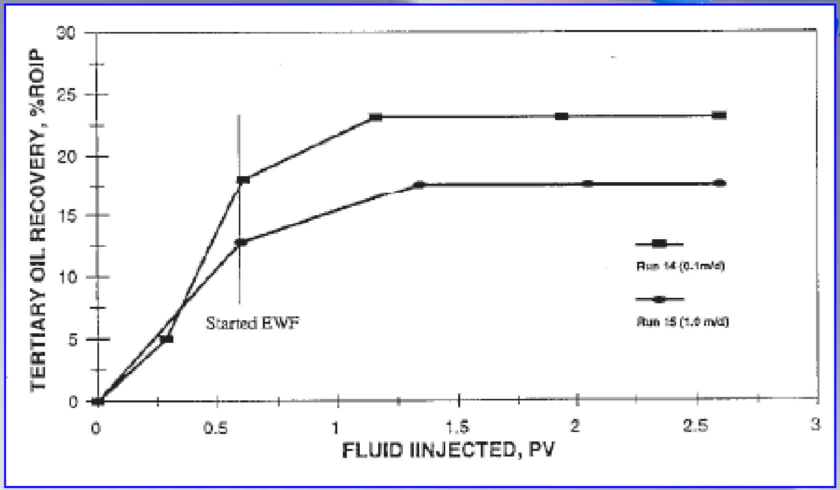

a b

X-ray CAT-scan images of (a) clean high-grain-size Vuggy core; and (b) $CO_2$-flooded core containing deposited asphaltenes at 1 cm along the length from top left to right.

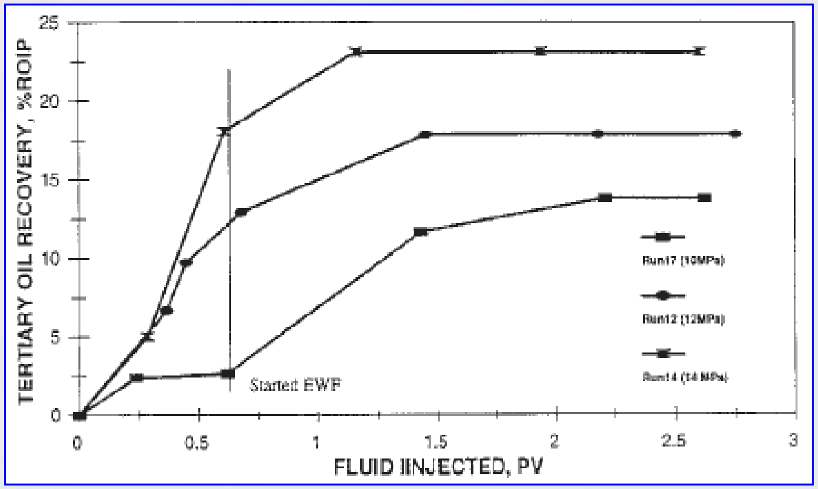
# Coreflood Studies



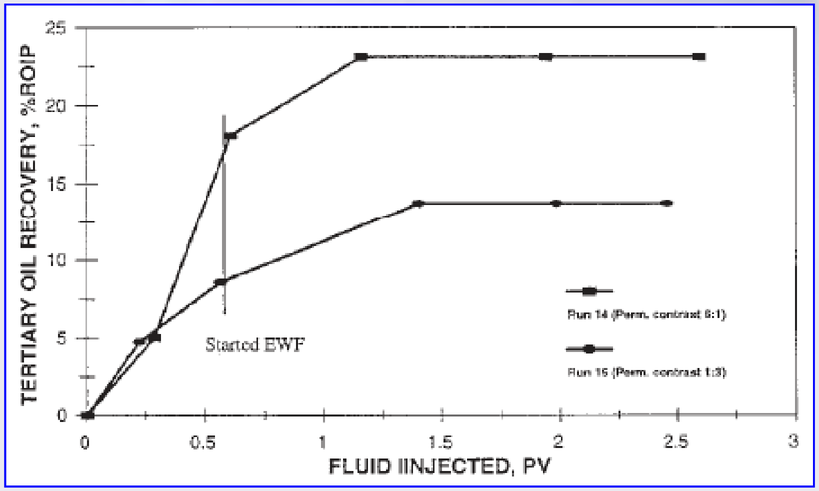

Total oil recovery as function of pore volume of fluid injected with dual-permeability cores




Effect of $CO_2$ injection rate on EOR with dual-permeability cores




Effect of operating pressure in the near-miscible region on enhanced oil recovery with dual-permeability cores




Effect of permeability contrast on enhanced oil recovery with dual-permeability cores

# $CO_2$ Flooding for Tight Oil Reservoirs
## — Bakken Formation

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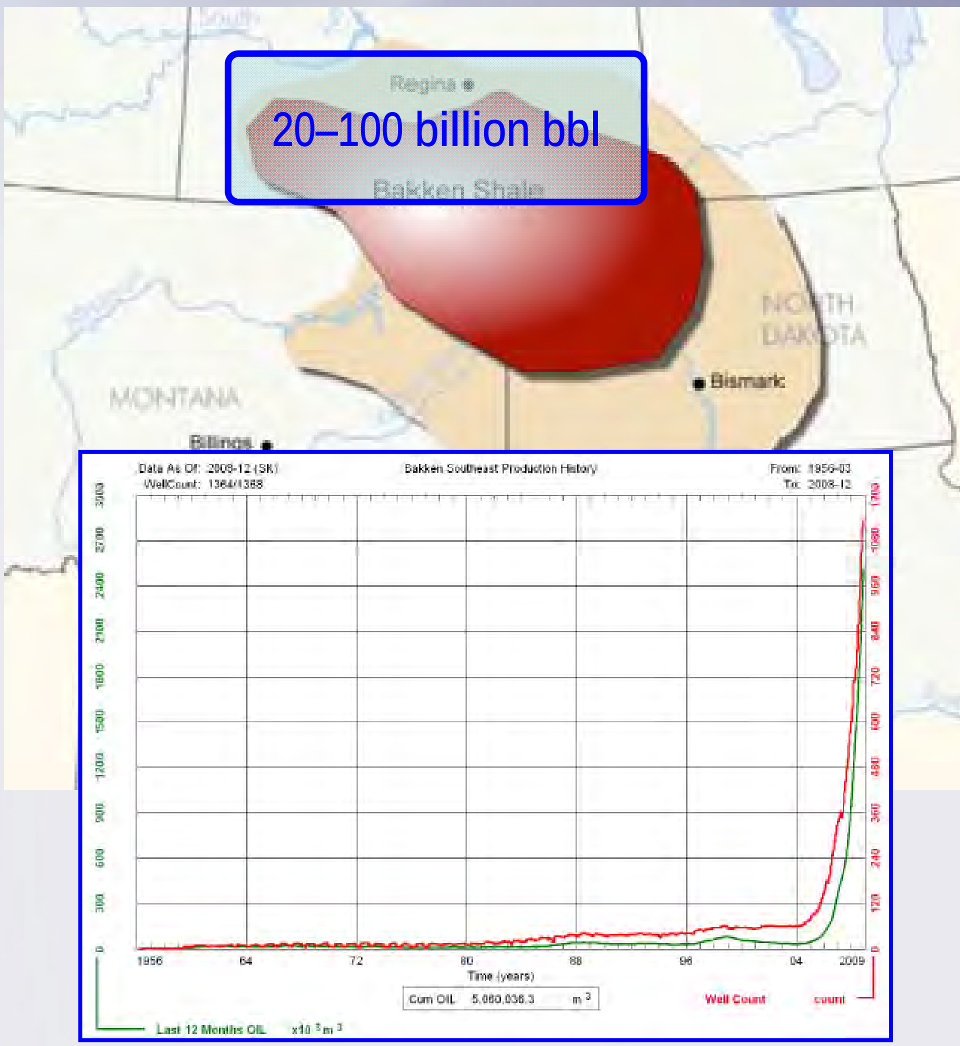
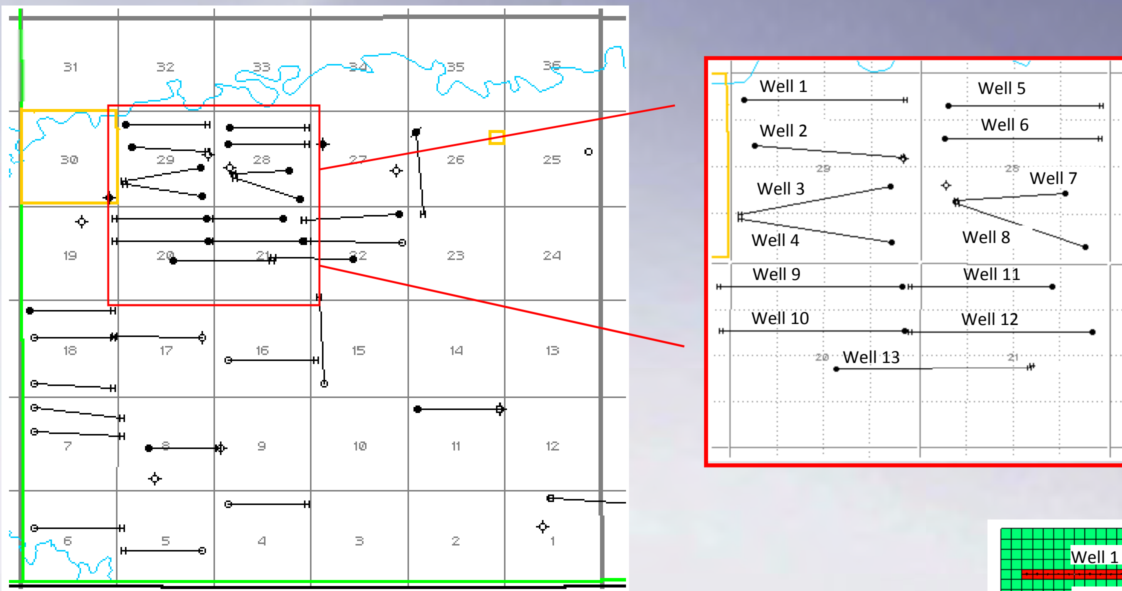



*Courtesy of Saskatchewan Ministry of Energy and Resources*

- Tight oil shale with extremely low permeability.
- 25% of Bakken formation is estimated in Saskatchewan with 25–100 billion bbls OOIP.
- Saskatchewan Bakken production is growing rapidly.
- Horizontal well drilling and multi-stage fracturing are the major technologies.
- $CO_2$ flooding is expected to increase recovery rate to as much as 25-30%.

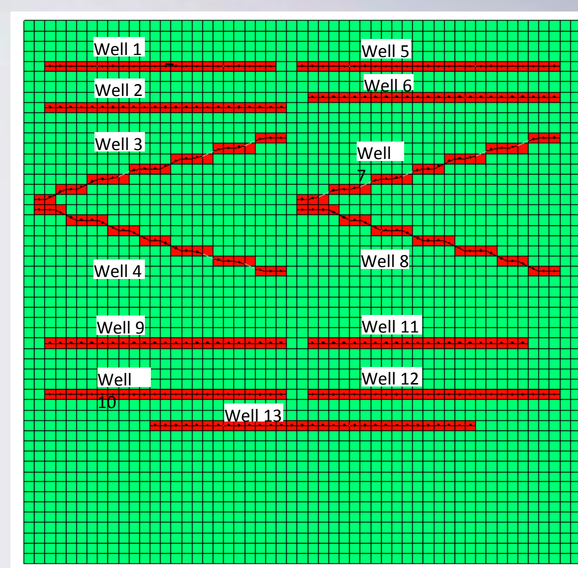
# $CO_2$ Flooding Potential for Bakken

## Reservoir Model




Map of a selected area in the Bakken pool

| Reservoir Properties | |
|---|---|
| Reservoir depth, m | 2050 |
| Upper shale perm, mD | 2.5 |
| Lower dolomite perm., mD | 0.04 |
| Porosity | 0.075 |
| Reservoir temperature, °C | 90 |
| Reservoir initial pressure, MPa | 28.0 |



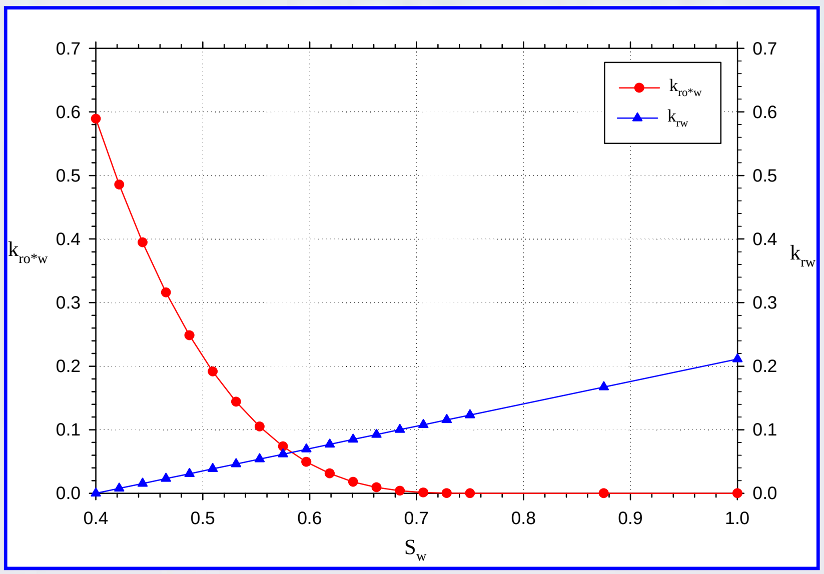

2-D view of reservoir model with 13 horizontal wells

# $CO_2$ Flooding Potential for Bakken

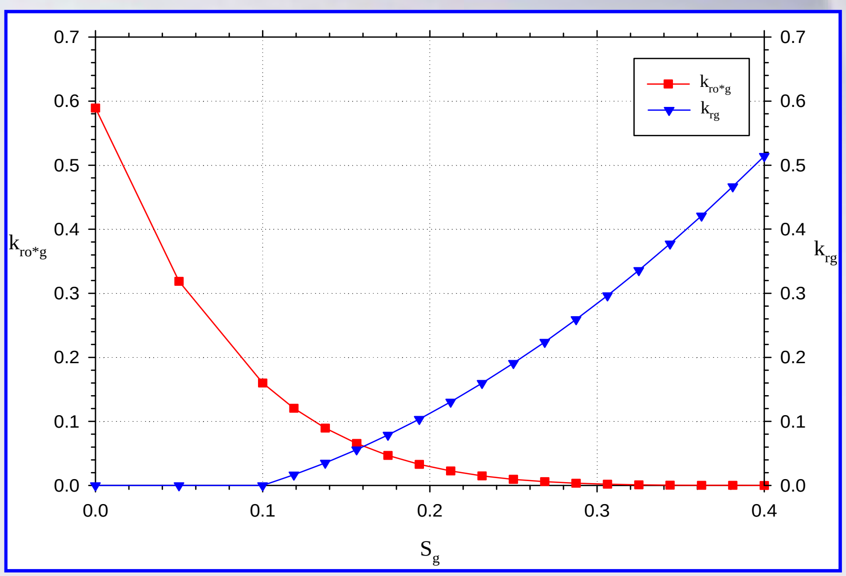
## Fluid Model

- The reservoir oil is divided into five different pseudo-components: $C_1$–$N_2$, $CO_2$, $C_2$–$C_5$, $C_6$–$C_{10}$, and $C_{11+}$.
- The MMP between reservoir oil and $CO_2$ is determined to be 23.6 MPa.

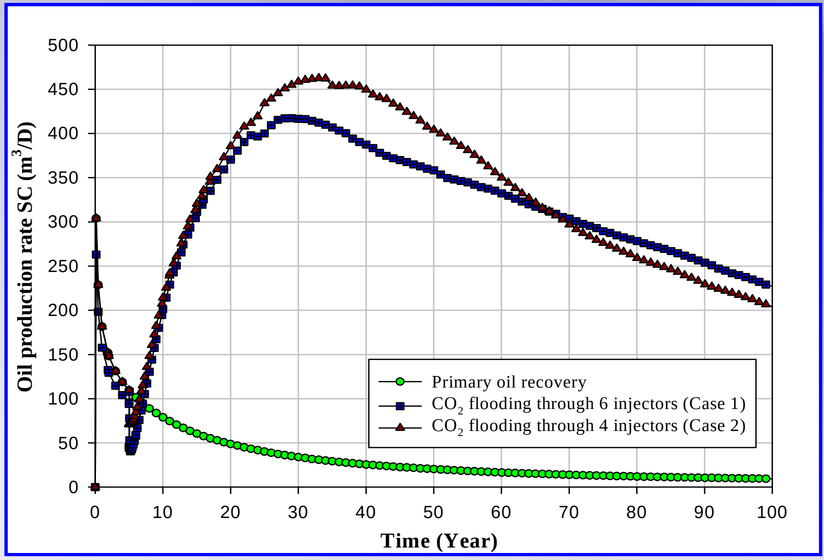
| Fluid Properties | |
|---|---|
| Oil Gravity | 42°API |
| Reservoir oil viscosity | 0.36 mPa·s |
| Initial GOR | 90 $m^3/m^3$ |
| OOIP | 33.91 MMbbl |



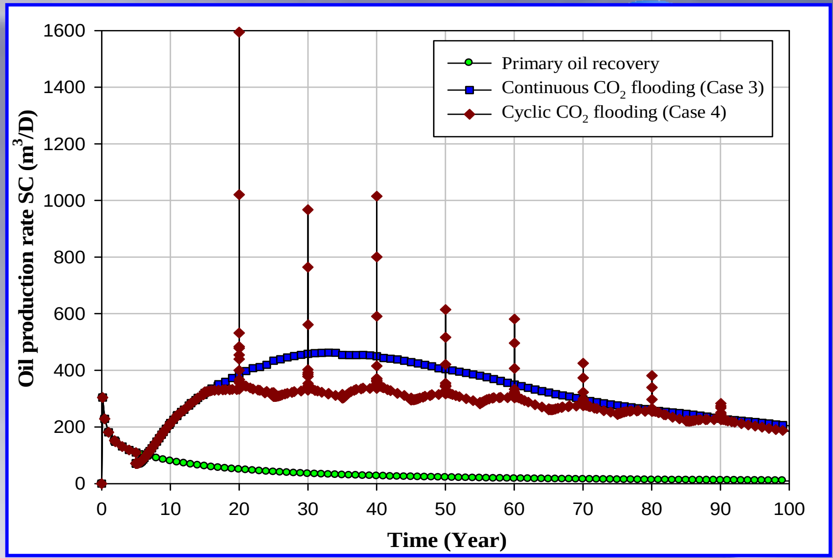

(a) Oil–water relative permeability curves



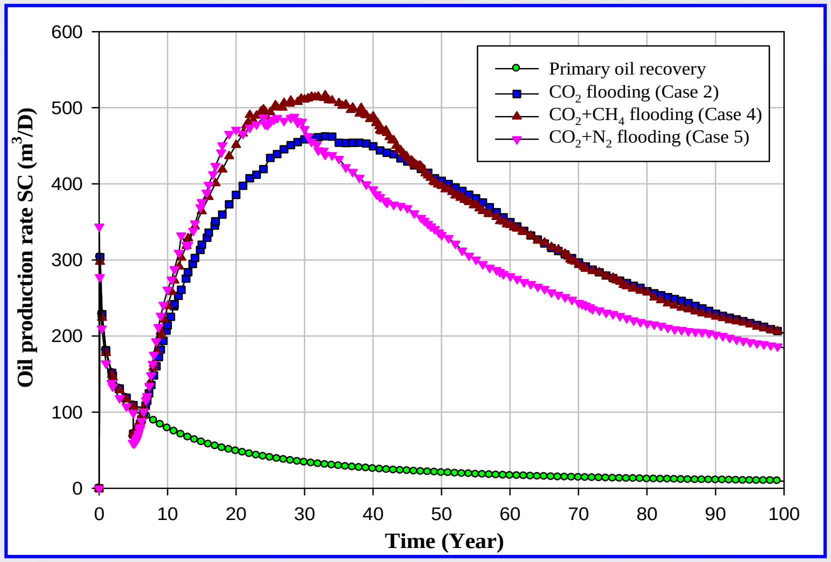

(b) Oil–gas relative permeability curves



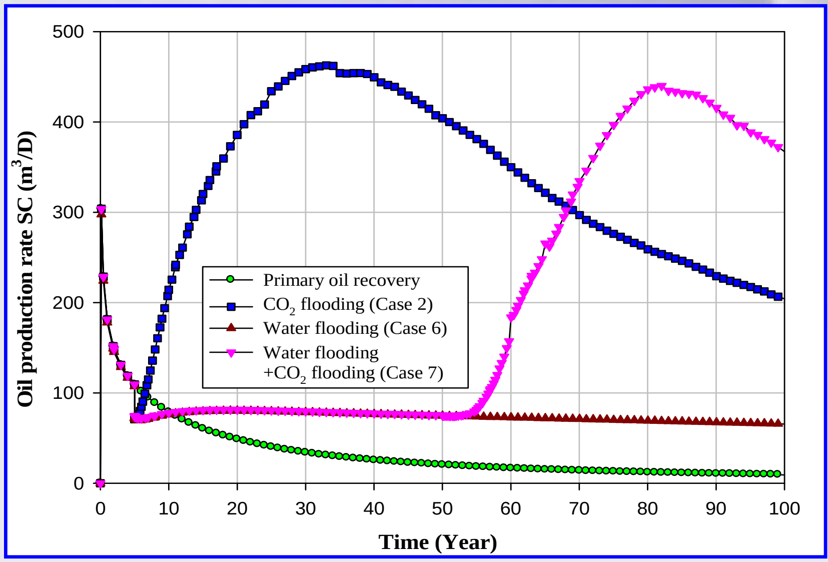

## 1. Different Injection Well Patterns




## 2. Different Injection Schemes




## 3. Different Injected Solvents




## 4. Different Production Schemes

# Reservoir Engineering Design for $CO_2$ Flooding

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- Collect valid input data

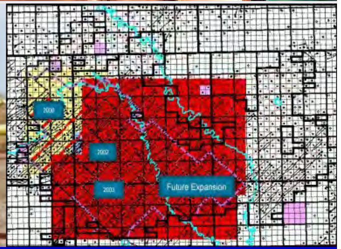
PVT properties of reservoir fluid-$CO_2$ at reservoir conditions and relative permeabilities of oil-water-gas phases.

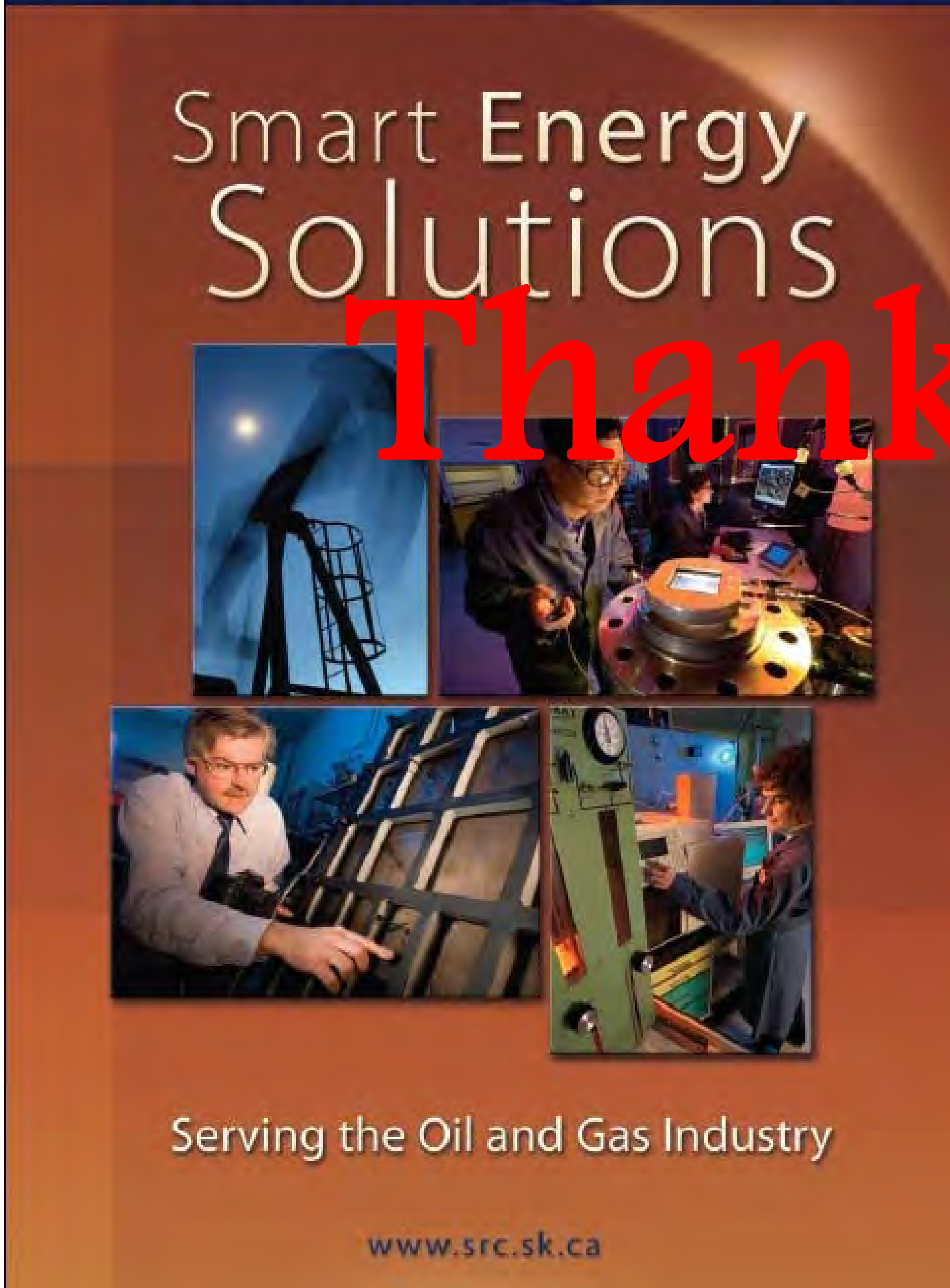
- History matching

Primary and secondary recovery performance used to develop and refine the reservoir description model.

- $CO_2$ performance prediction

Optimum flood design by evaluating various $CO_2$ injection schemes.






# Thank You!

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