



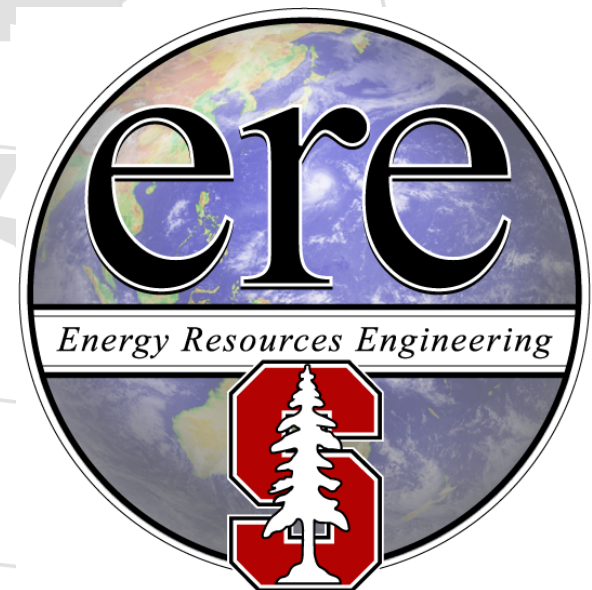
# Flow Behavior of Gas-Condensate Wells

## - the impact of composition

**Hai Xuan Vo, Chunmei Shi and  
Roland N. Horne**

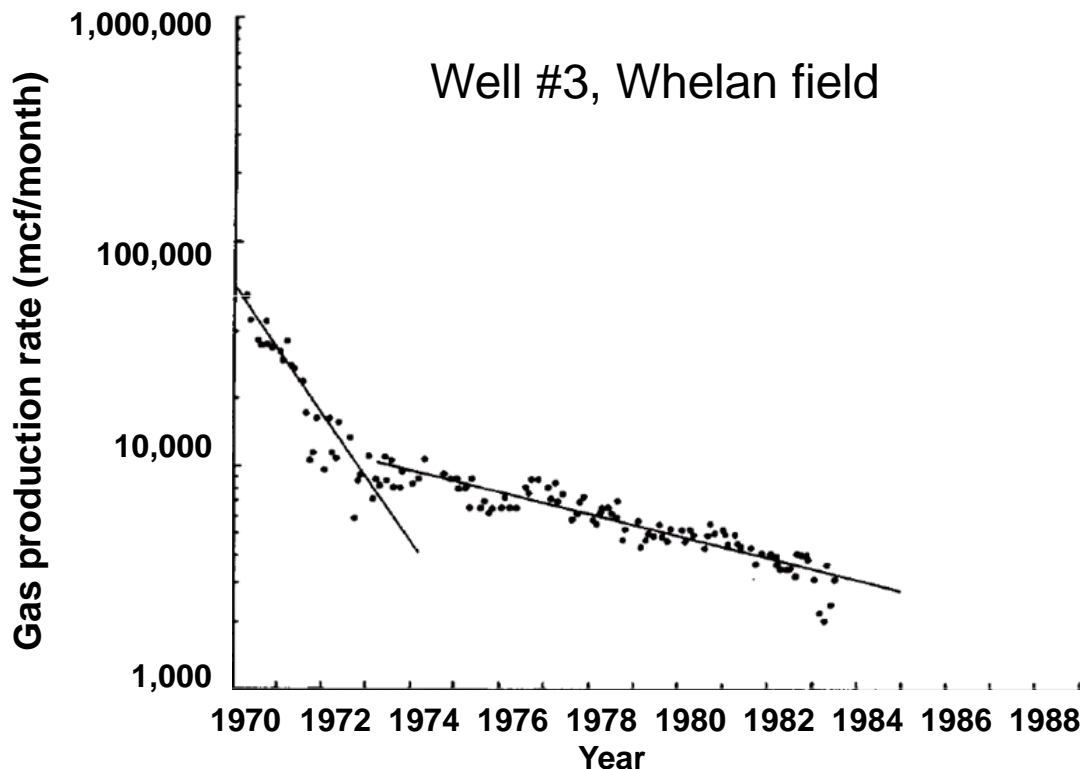
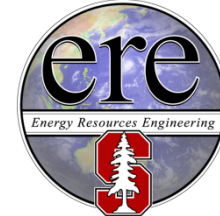
**Stanford University**

**April 15, 2010**





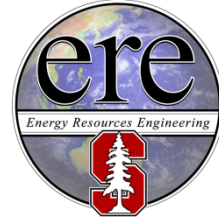
# Condensate blockage



- The productivity loss caused by the condensate buildup is striking, in some cases, the decline can be as high as a factor of 30, according to Whitson (2005).
- Barnum et al. (1995) reviewed data from 17 fields, and concluded that severe loss of gas recovery occurs primarily in **low productivity reservoirs** with a permeability-thickness below 1000 md-ft.

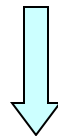


# The composition change



- Heavy component composition in the flowing phase decreases once the reservoir pressure drops below the dew point pressure.

Composition	Well K401 @ initial reservoir condition	Well K233	
		Year 1995	Year 1999
$C_1+N_2$	77.28	83.86	86.08
$C_2$	7.935	7.78	9.3
$C_3$	3.126	2.38	2.6
$C_4$	2.505	1.52	0.65
$C_5^+$	8.908	4.4	1.31

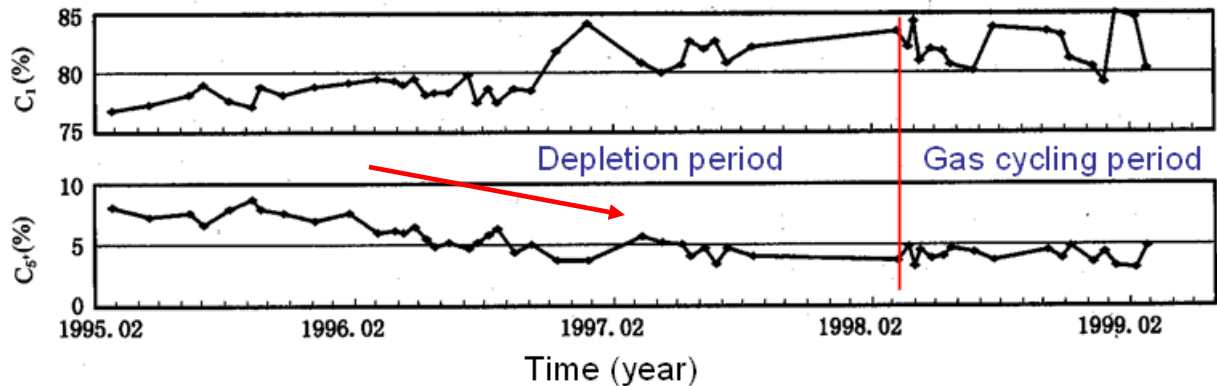


(A field case from KekeYa gas field, China)

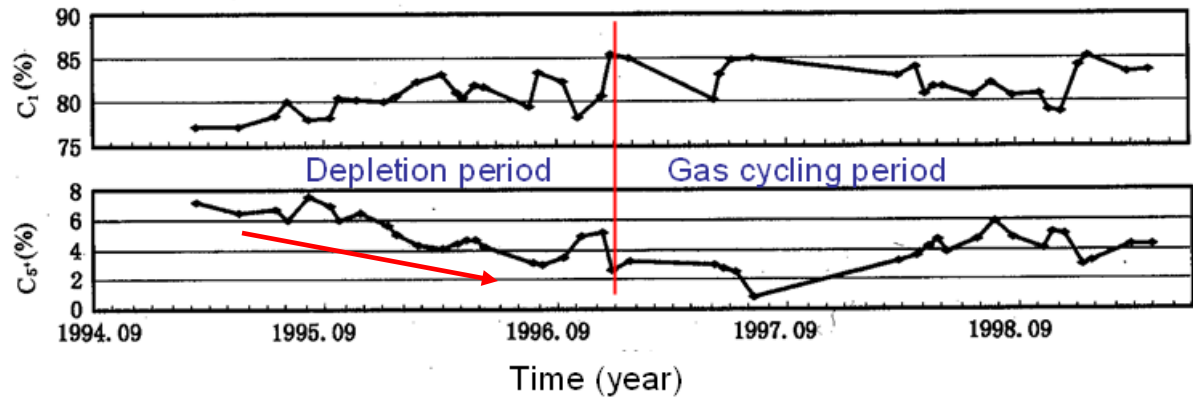
Source: Yuan Shiyi, Ye Jigen and Sun Zhidao “*Theory and practices in gas-condensate reservoir development*”.

# The composition change

- The composition of the heavier component in the flowing phase decreases once the reservoir pressure drops below the dew-point pressure.



a) Profile of component composition for well K233

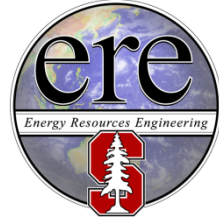


b) Profile of component composition for well K243

(A field case from KekeYa gas field, China)



# Why study composition?



- To understand the phase behavior change.
- To understand the dynamic condensate saturation build-up.  
Due to compositional variation and relative permeability constraints, the condensate saturation build-up is a dynamic process and varies as a function of time, place (distance to wellbore) and phase behavior.
- To develop optimum producing schemes.  
Changing the well producing schemes can affect the liquid dropout composition and can therefore change the degree of productivity loss.

## Objectives of this study:

- Verify the composition change by experiment.
- Develop optimum producing schemes for condensate recovery.



# Project Management Plan

- Task 1.0. Project Management Plan ✓
- Task 2.0. Technology Status Assessment ✓
- Task 3.0. Technology Transfer ✓
- Task 4.0. Scoping Study ✓
- Task 5.0. Condensate Banking Study – Numerical and Experimental (in progress)
- Task 6.0. Developing Optimal Production Strategy (third stage)



# 2009 Activities



# Project Management Plan

- Task 1.0. Project Management Plan ✓
- Task 2.0. Technology Status Assessment ✓
- Task 3.0. Technology Transfer ✓
- Task 4.0. Scoping Study ✓
- Task 5.0. Condensate Banking Study – Numerical and Experimental (in progress)
- Task 6.0. Developing Optimal Production Strategy (third stage)



## 2009 Achievements

- New gas chromatograph (GC)
- Core permeability measurement
- Core X-ray tomography (CT) scanning
- Experiments with old apparatus design
- Apparatus improvement
- Experiments with improved apparatus design
- Three-phase flow simulation



# New Equipment – Gas Chromatograph (1)



- Owning a GC has provided flexibility, better accuracy and saves time.
- Need to install and calibrate the GC.



# New Equipment – Gas Chromatograph (2)

Check after calibration	C1	C4
1	84.95%	15.01%
2	85.16%	15.01%
3	84.89%	15.01%
4	84.39%	15.32%
5	84.89%	15.24%
6	84.91%	15.15%
7	84.97%	15.11%
8	84.99%	15.01%
9	85.01%	15.02%
10	84.97%	15.00%
11	85.23%	14.98%
12	84.99%	14.97%
13	85.16%	14.98%
14	85.05%	14.98%
15	85.07%	15.00%
16	85.01%	14.99%
17	85.10%	15.00%
18	85.02%	14.99%
<b>Mean</b>	84.99%	15.04%
<b>Std deviation</b>	0.001762	0.000984

To: **Stanford University**

Issue Date: **June 19, 2009**

Attn: **Hai Xuan Vo**

Praxair Order Number: **NA**

Product Lot Number: **-1869167110**

Customer PO Number: **NA**

Product Part Number: **ME BU15ZC-FX**

Customer Reference Number: **NA**

## CERTIFICATE OF ANALYSIS (Certified Standard)

Cylinder Serial Number	Analytes	Specification	Analytical Results	Analytical Principle*/Instrument	Analytical Uncertainty
<b>RR 030388</b>	<b>Butane</b>	15.00 %	15.00 %	L / Gravimetric	±2% relative
	<b>Methane</b>	Bal	Bal	Assay By Difference	

Cylinder Style: **FX**

Valve Outlet Connection: **CGA 510**

Cylinder Pressure @70°F (21°C): **180 psig**

Filling Method: **Gravimetric**

Cylinder Volume: **50.7 cf**

Date of Fill: **June 16, 2009**

Expiration Date: **December 31, 2014**

Cylinders Shipped: **RR 030388**

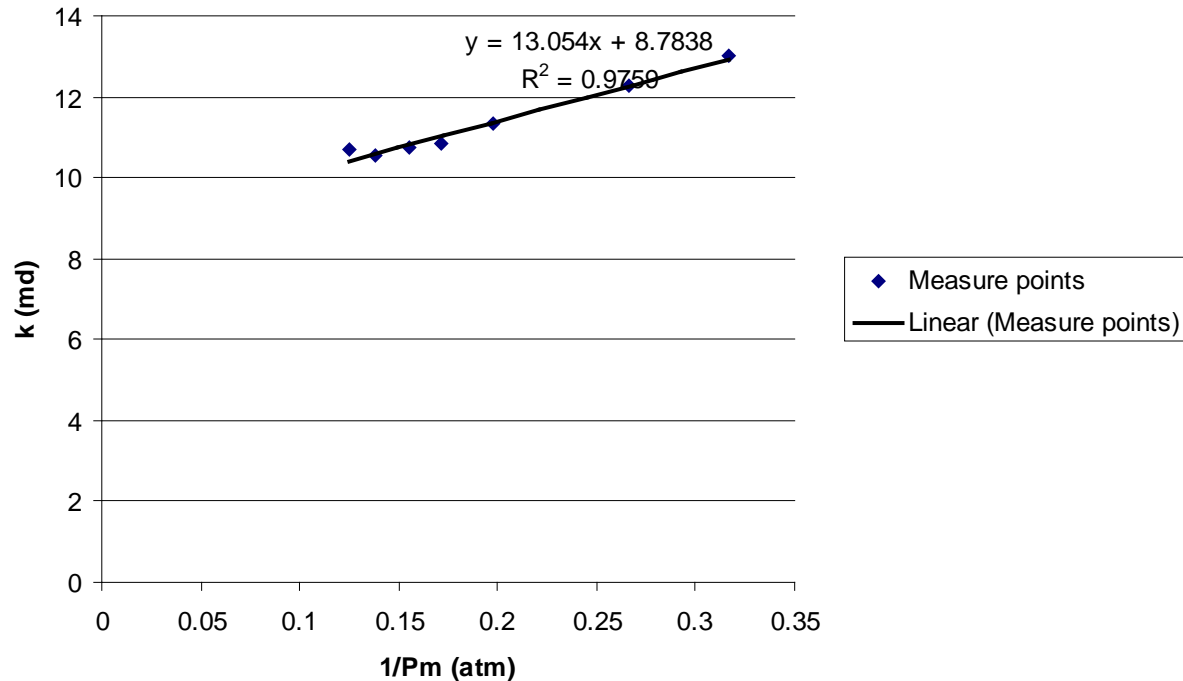
C of A Author: 

Approved Signer:   
(Quality Assurance Reviewer)

- GC is calibrated using a gas mixture standard of C1-nC4 with composition similar to the mixture that is used for experiments.



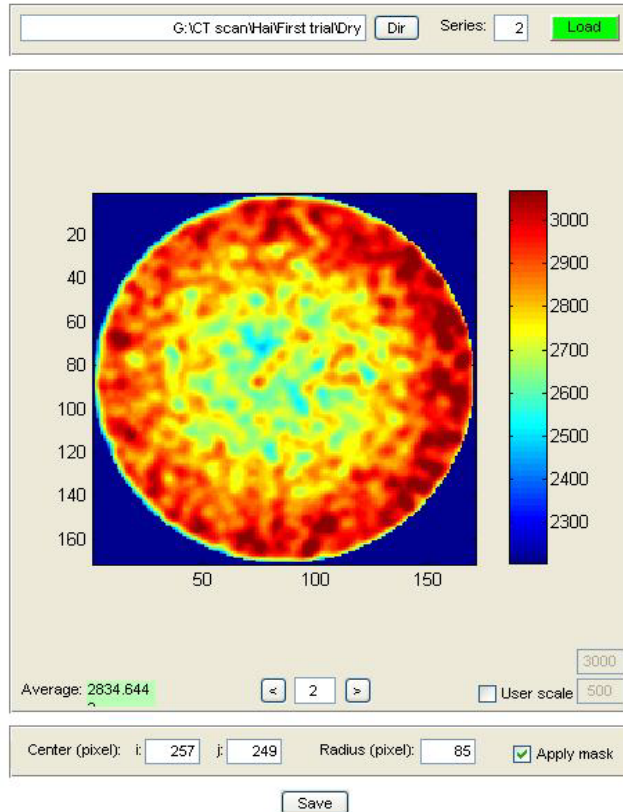
# Core Permeability



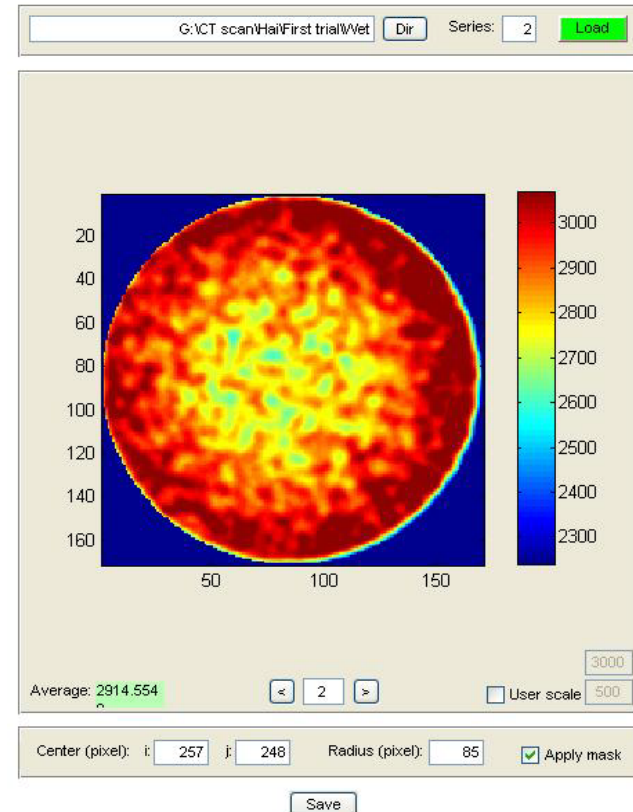
- Measurements are done using  $N_2$  gas
- $k \sim 8.7$  md



# Core CT Scanning



CT number image of core filled with C1 gas

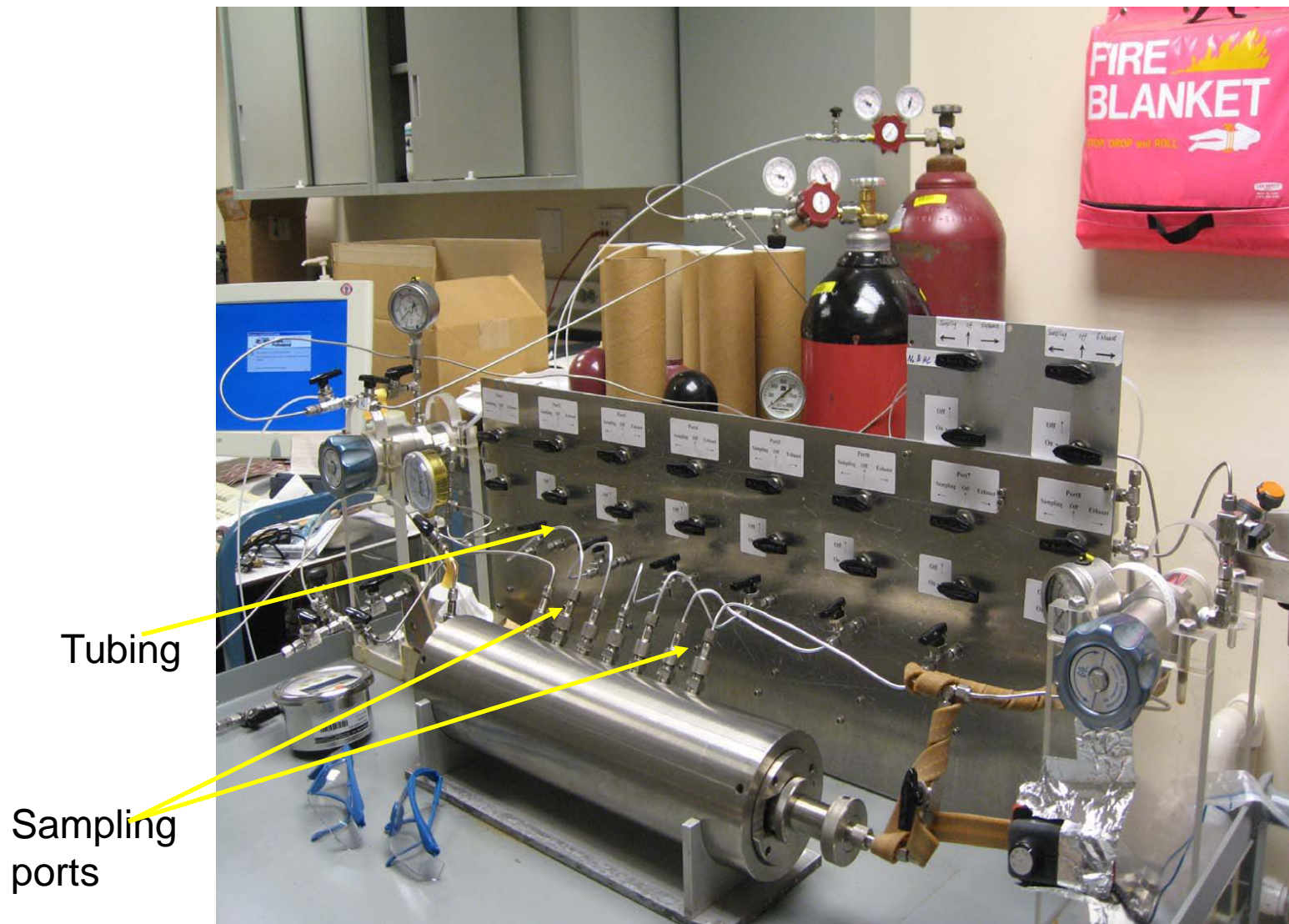


CT number image of core filled with n-C4 liquid

These will be used as “base lines” to calculate condensate saturation from CT scanning for core filled with the gas condensate.



# Previous Apparatus Design





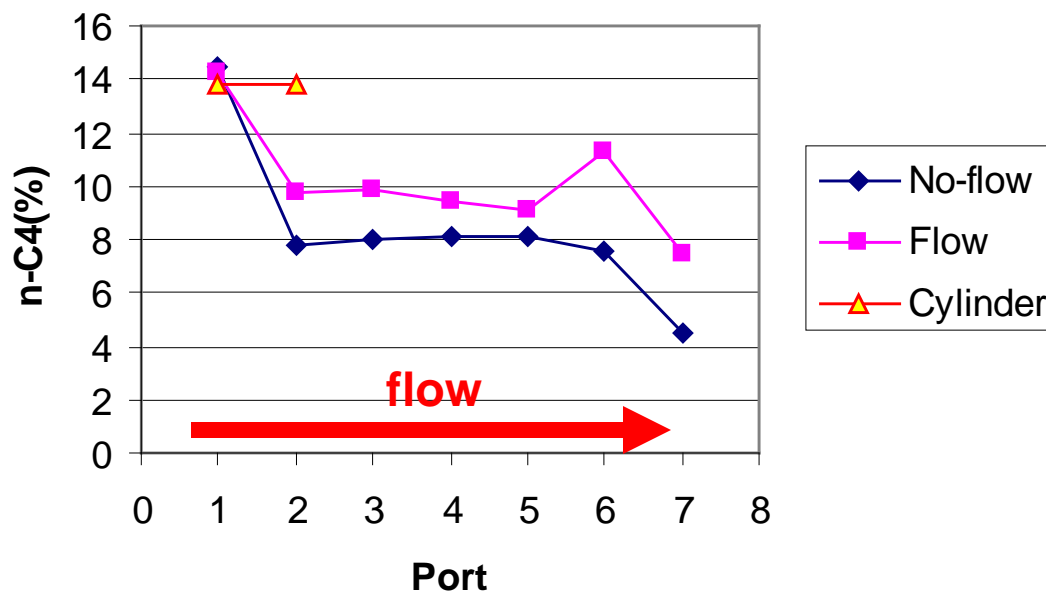
# Old Design: Noncapture Experiment (1)

## Steps:

- Core is vacuumed.
- Fill core with mixture of C1-nC4 to pressure about 100 psi above dew point pressure of C1-nC4.
- Take samples in no-flow condition.
- Flow the mixture at 1000 psi differential pressure through the core and take samples in flow condition.

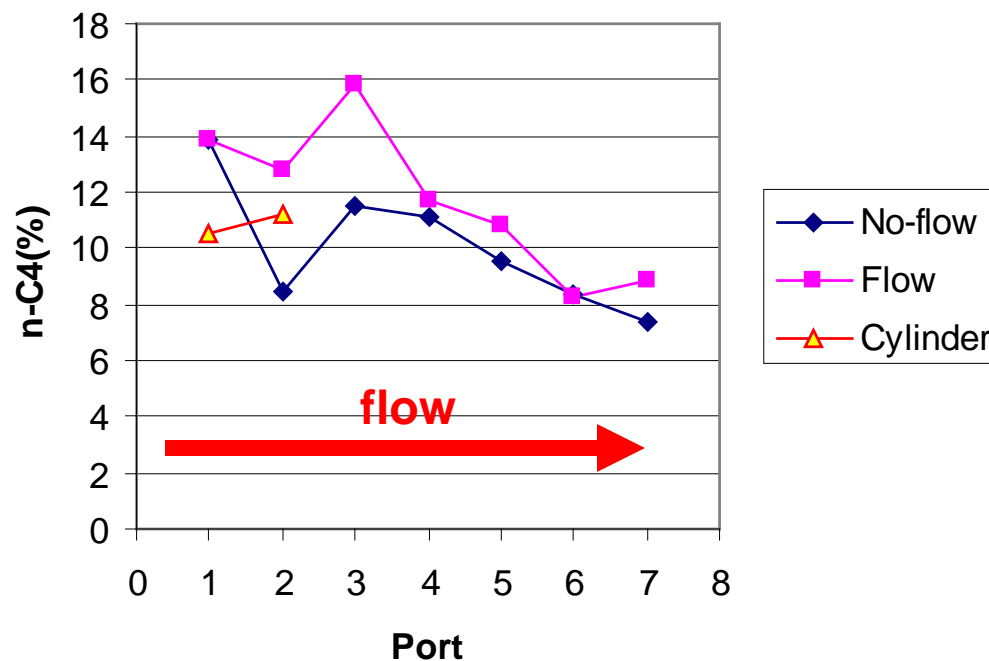
## Observation:

- In no-flow condition, n-C4 concentration is not constant.
- n-C4 concentration in flow condition is higher than the one in no-flow condition.





# Old Design: Noncapture Experiment (2)



- Did another noncapture experiment, with different result.
- Repeatability of experiments is important for scientific study.
- Is it because the gas in the tubing is not flushed away during the flow so the next samples are contaminated by the remaining gas?



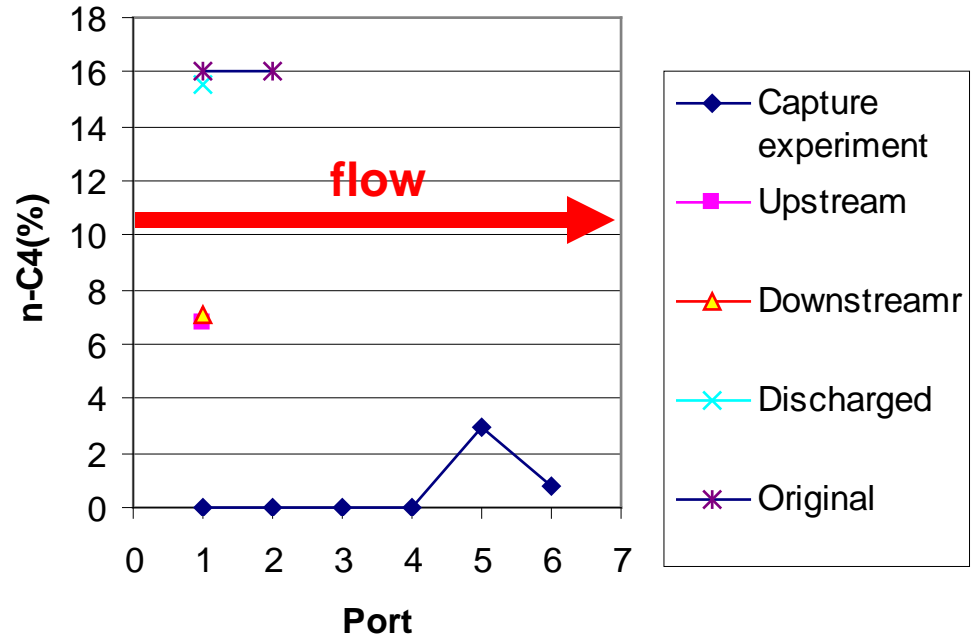
# Old Design: Capture Experiment

## Steps:

- Core is vacuumed and pre-saturated with C1 at 2000 psi (about 100 psi above dew point pressure of C1-nC4).
- Flush the C1-nC4 mixture through the core at 50 psi differential pressure for 10 minutes then 1000 psi differential pressure for 3 minutes.
- Close upstream and downstream valves.
- Take samples in capture-mode.

## Observation:

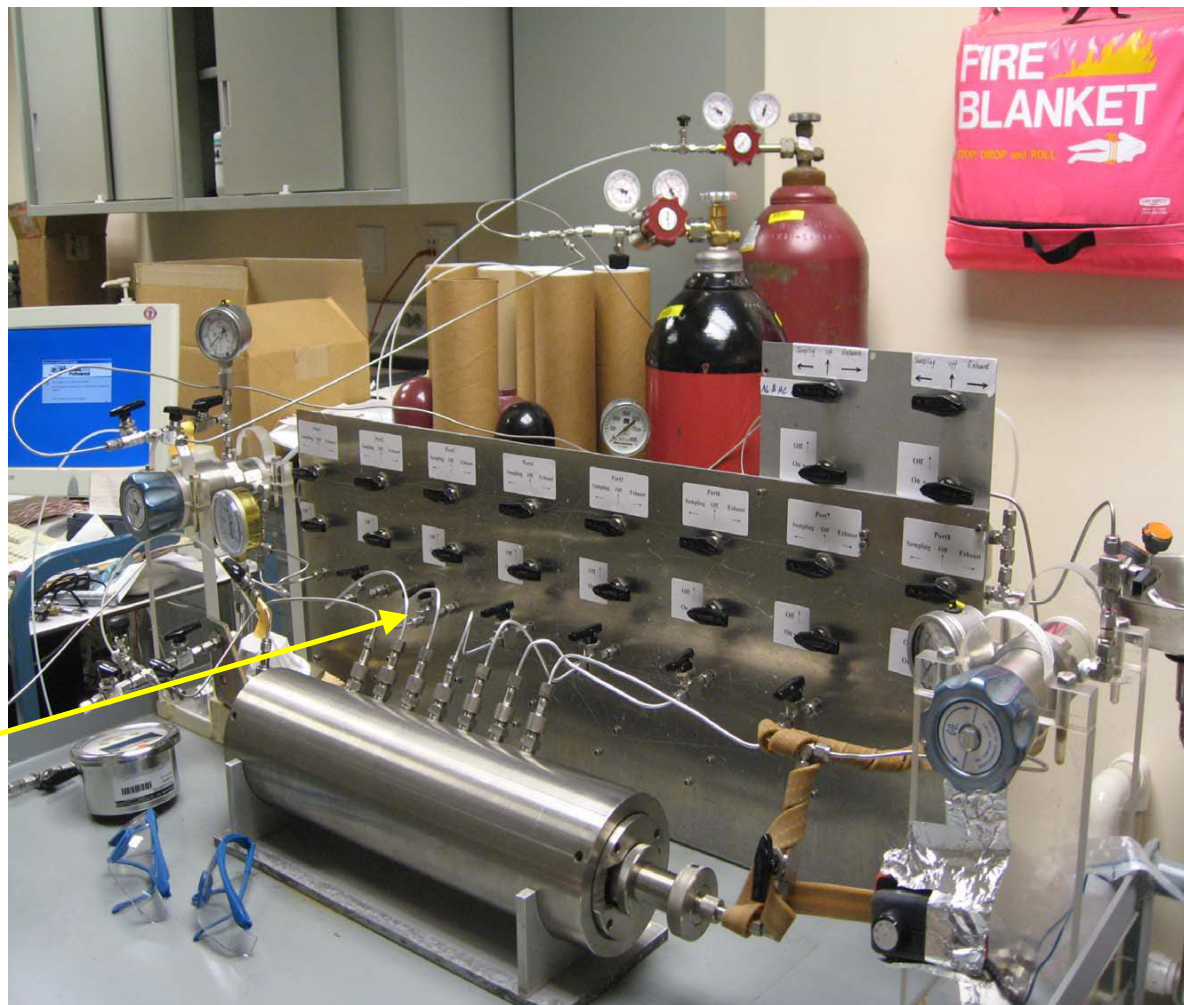
- Samples taken during flow contain mainly C1
- Is it because the C1 in the tubing is not flushed away during the flow?





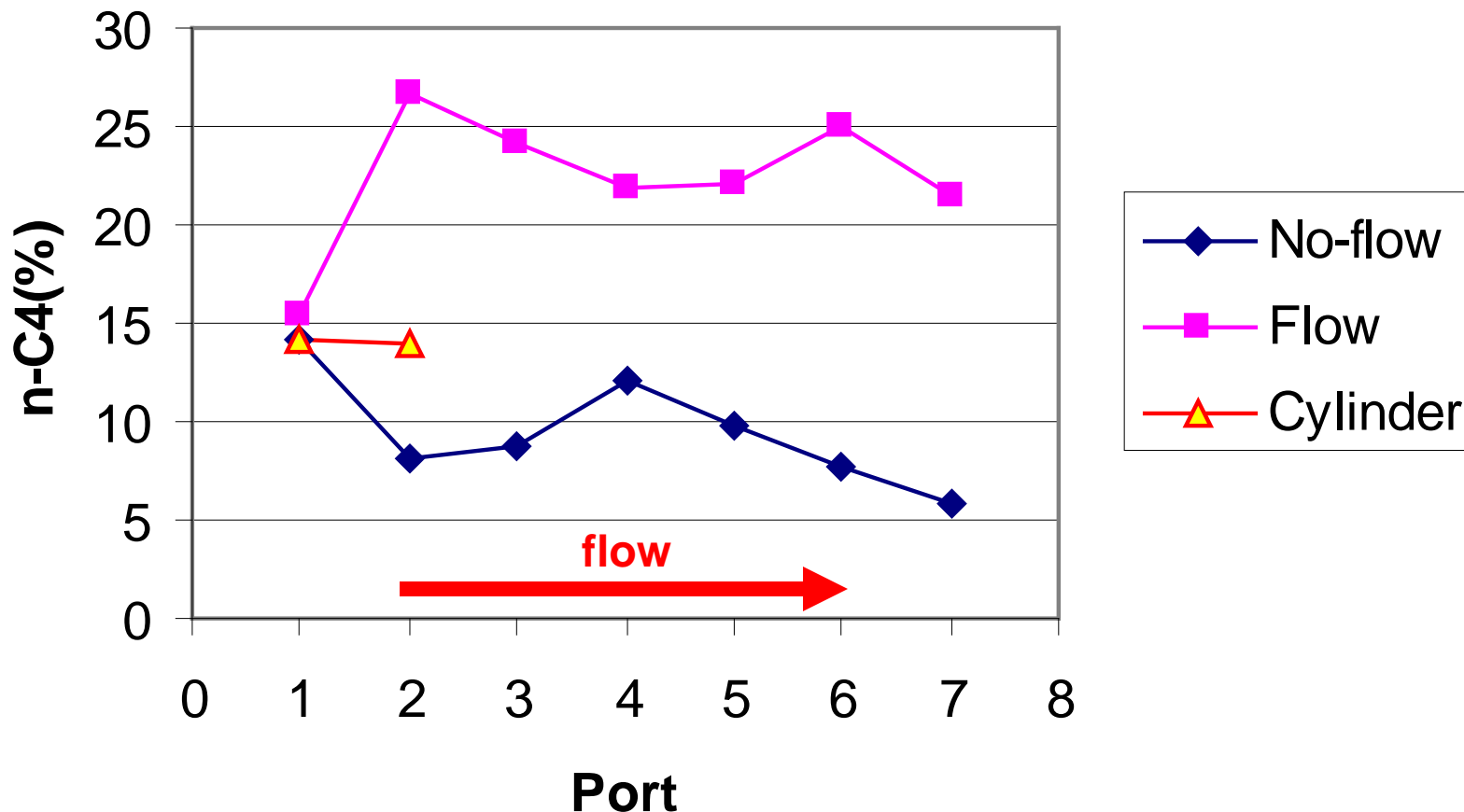
# Old Design

- During flow the tubing might be still filled with gas from previous condition.
- Purging tubing before taking flow sample may help?





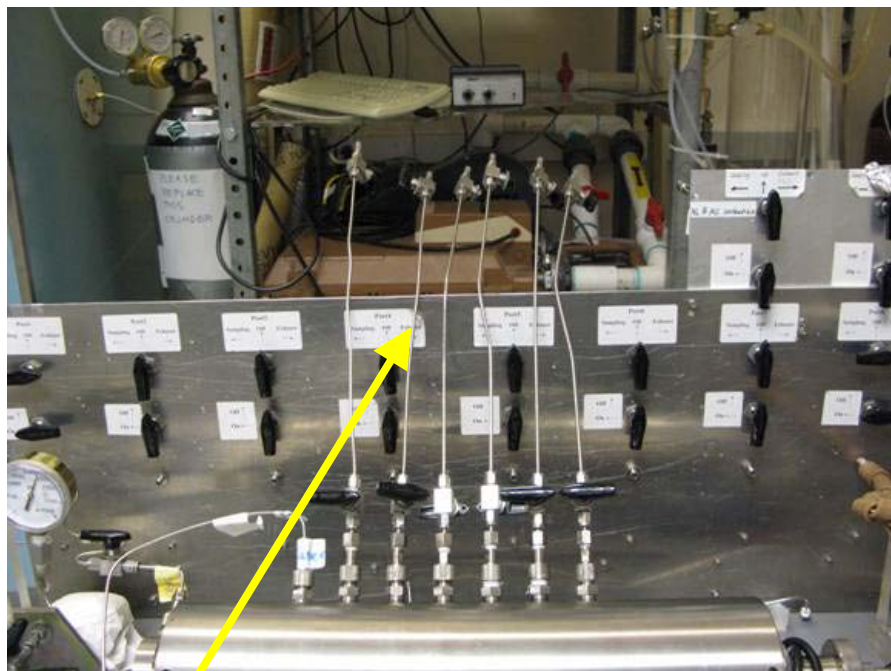
# Old Design: Noncapture with Purging



- Purging tubing before taking flow sample: liquid drops out hence n-C4 concentration is even higher than the concentration from cylinder.
- Purging is not a good solution.



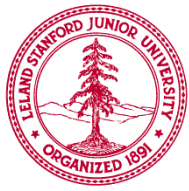
# Improved Apparatus Design



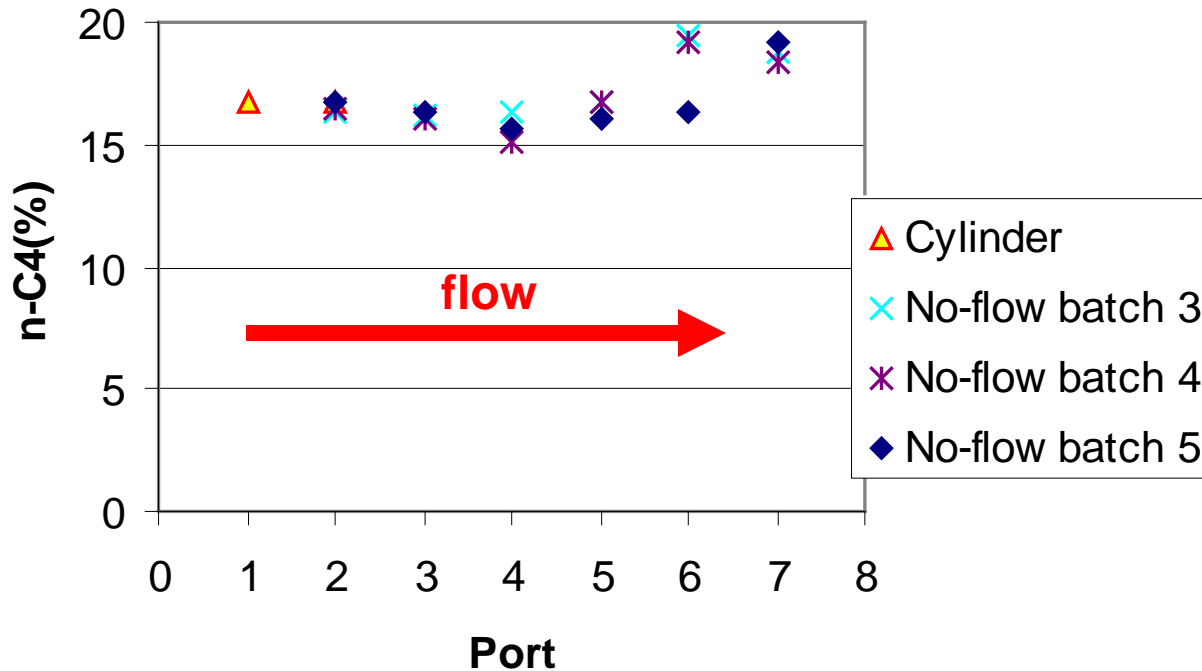
Able to vacuum tubing before taking samples.



Fit valves on core to minimize dead volume.



# Improved Design: Noncapture Experiment – Noflow Condition



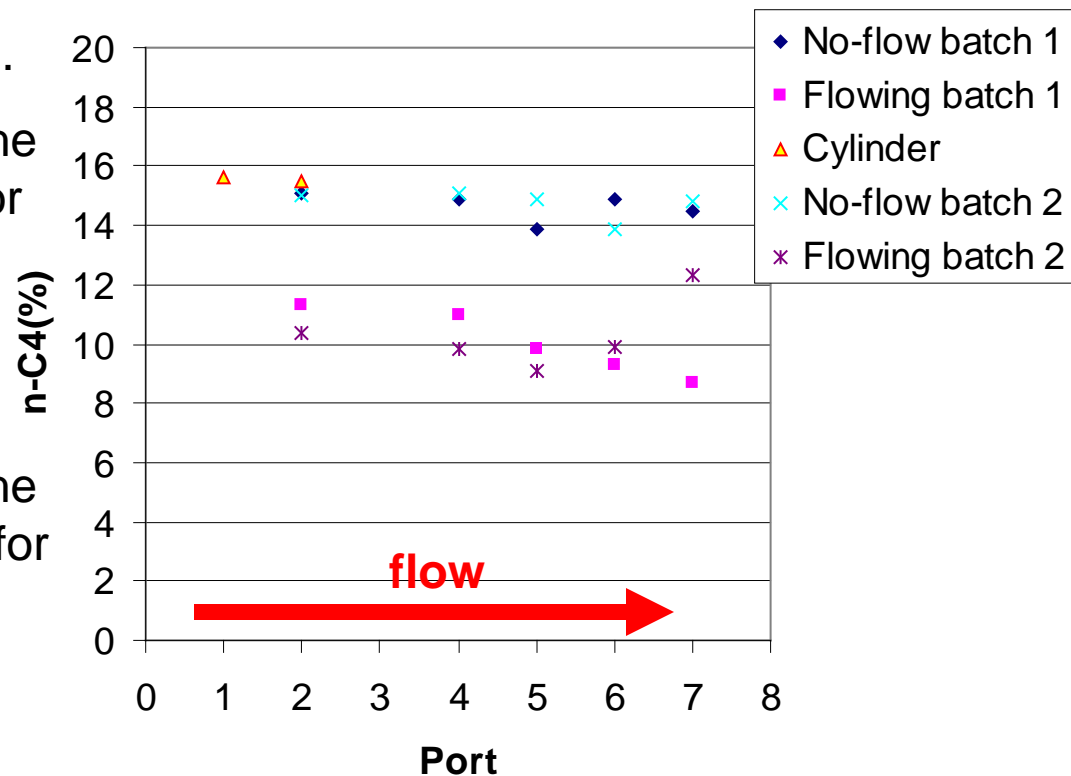
- Good repeatability in static conditions except ports 7/8.
- Possible that condensate liquid dropout along the core being flushed to the end. Is it because the gas mixture flowed directly in the vacuumed core without any cushion?



# Improved Design: Capture Experiment (1)

## Steps:

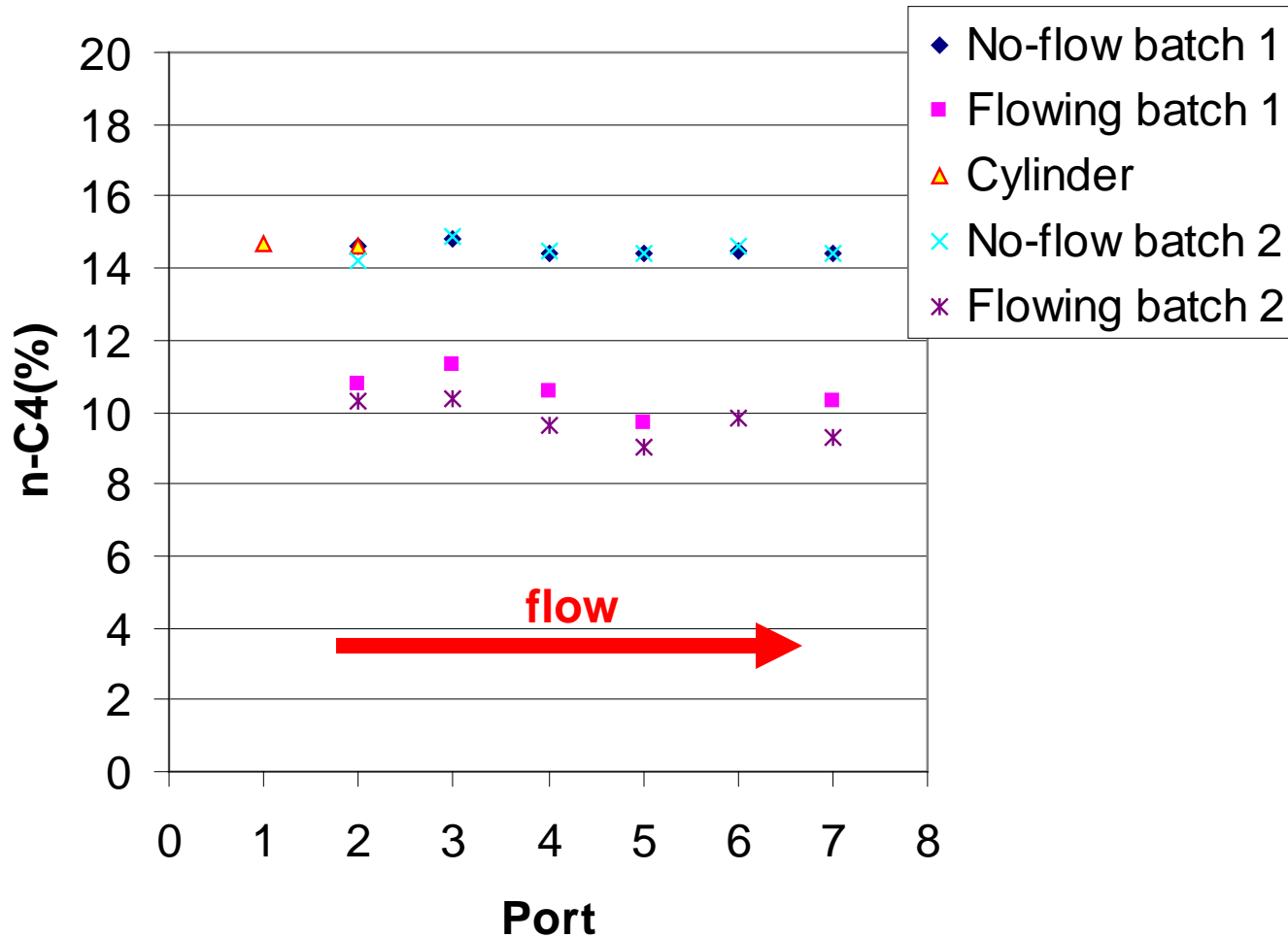
- Core is vacuumed and presaturated with C1 at 2200 psi (about 300 psi above dew point pressure of C1-nC4).
- Flush the C1-nC4 mixture through the core at 100 psi differential pressure for 10 minutes.
- **Close downstream valve and take samples in noflow condition.**
- Flush the C1-nC4 mixture through the core at 1000 psi differential pressure for 3 minutes.
- Close upstream and downstream valves and take samples in capture-mode.



- Good repeatability in static condition and flowing condition



# Improved Design: Capture Experiment (2)



- Did another experiment following the same procedure
- Good repeatability and confirm previous result.

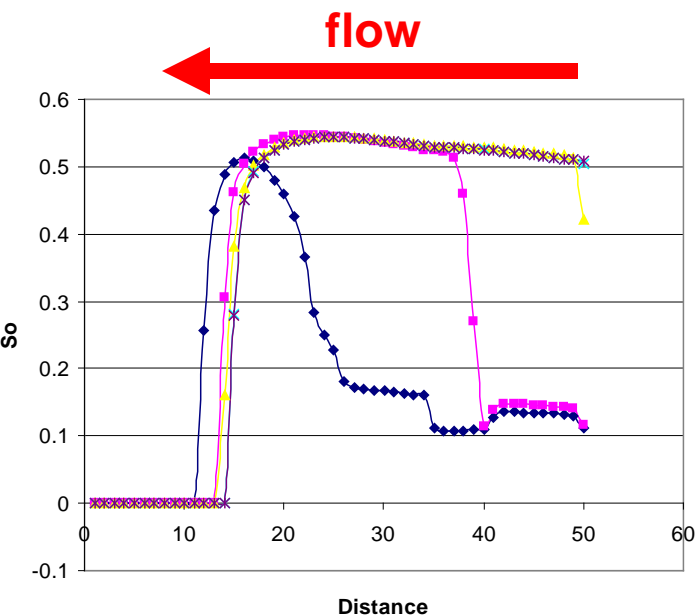


# Three-Phase Flow Simulation (1)

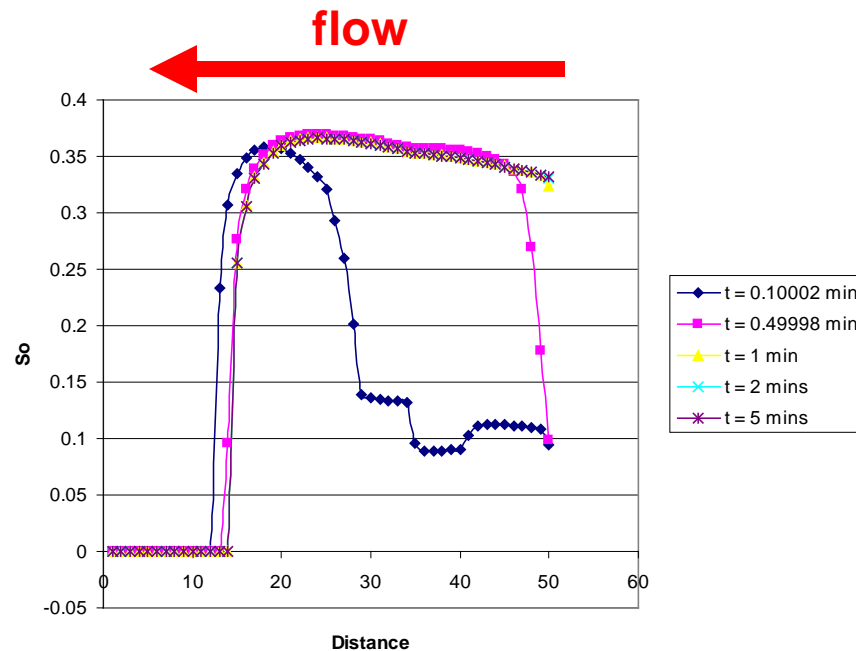
- Extension of previous work (two-phase gas-oil) but now **with presence of immobile water** (three-phase gas-oil-water).
- Mixture of *C1/n-C4* with initial molar composition = 0.85/.015.
- $S_{or} = 0.24$
- $S_{gr} = 0$
- $S_{wi} = 0.16$



# Three-Phase Flow Simulation (2)



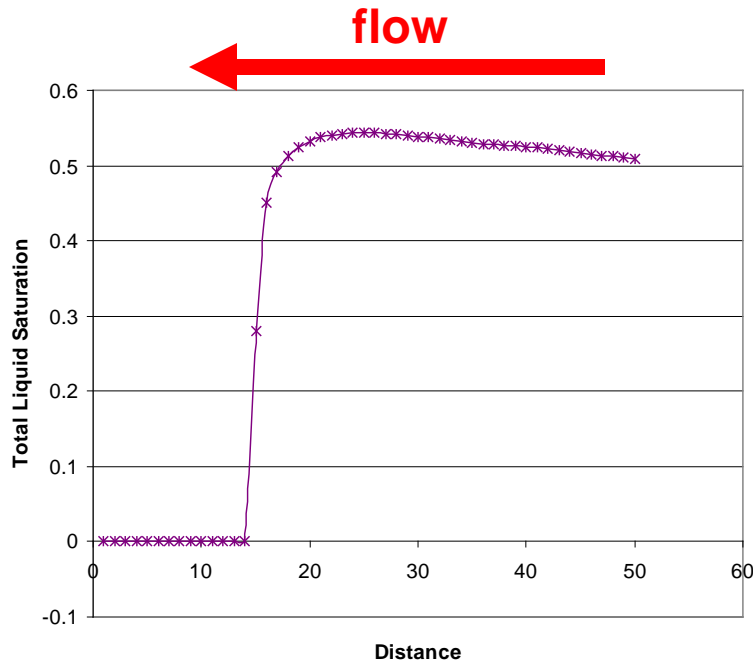
Two-phase (gas-oil): Oil saturation.  
Maximum condensate accumulation reaches about 53% in one minute.



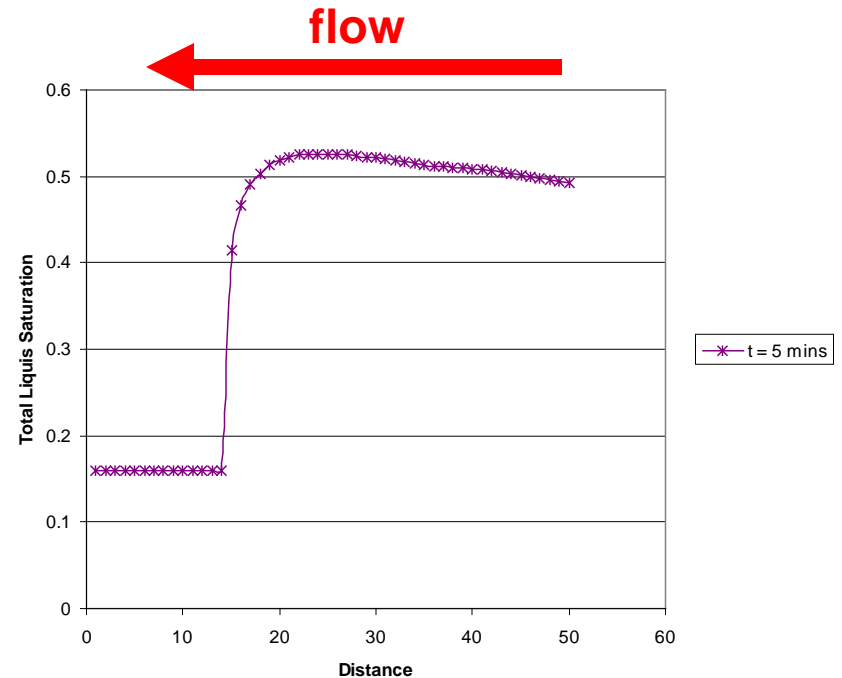
Three-phase (gas-oil-water): Oil saturation.  
Maximum condensate accumulation reaches about 37% in one minute.



# Three-Phase Flow Simulation (3)



Two-phase (gas-oil): total liquid (oil) saturation.



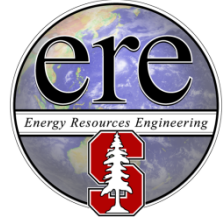
*Three-phase (gas-oil-water): total liquid (immobile water and oil) saturation.*

- The results of total liquid saturation versus distance for both cases are almost the same in the region where condensate drops out.
- Presence of immobile water has effect on the condensate dropout saturation.



# Plan Forward

- Do experiments with present of immobile water.
- Conduct optimization study.

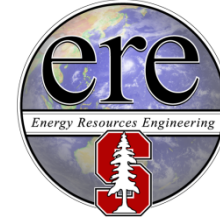


# Thank you!

Questions, suggestions and discussions



# Backup Slides



- Scoping study



# Compositional variation models



- One-dimensional linear flow

$$\frac{\partial z_i}{\partial t} = A_i \frac{\partial p}{\partial t} + B_i \left( \frac{\partial p}{\partial x} \right)^2 \quad i = 1, n_c$$

- Where:

$$A_i = \left( \frac{m_i}{m} - z_i \right) \frac{\partial \ln G}{\partial p}, \quad G = \sum_{i=1}^{n_c} G_i, \quad G_i = \sum_{j=1}^{n_p} x_{ij} \rho_j S_j$$

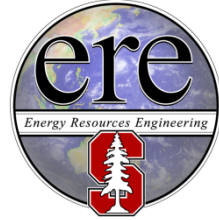
$$B_i = \frac{m_i}{\phi G} \frac{\partial}{\partial p} \ln \left( \frac{m_i}{m} \right), \quad m = \sum_{i=1}^{n_c} m_i, \quad m_i = \sum_{j=1}^{n_p} x_{ij} \rho_j \frac{kk_{rj}}{\mu_j}$$

- Three-dimensional radial flow

$$\frac{\partial z_i}{\partial t} = A_i \frac{\partial p}{\partial t} + B_i \left( \frac{\partial p}{\partial r} \right)^2 \quad i = 1, n_c$$



# Impact of $k_r$ models on $A_i$ and $B_i$



Three  $k_r$  models:

- Miscible  $k_{rcm}$  and  $k_{rgm}$
- Immiscible  $k_{rci}$  and  $k_{rgi}$
- Mixtures in between,  $k_r(IFT)$

$K_{r(IFT)}$  models are given by:

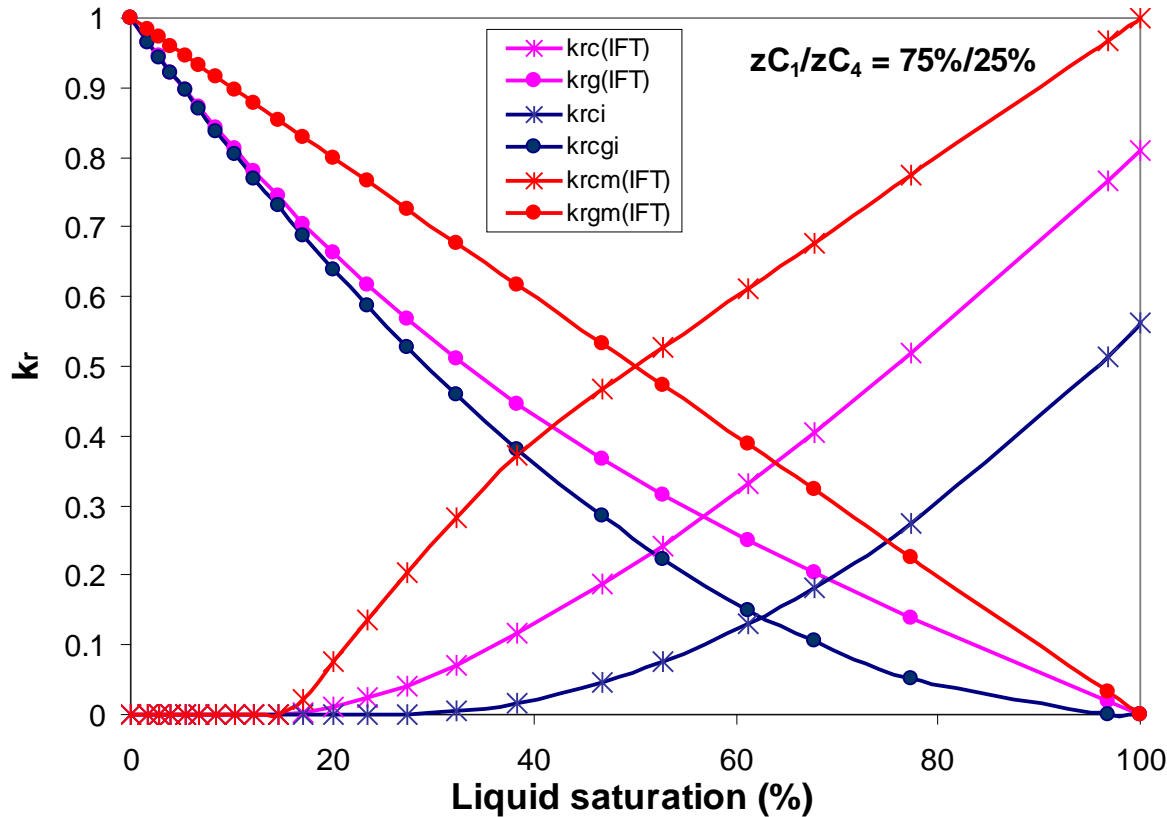
$$k_{rc} = f(\sigma)k_{rci} + (1 - f(\sigma))k_{rcm}$$

$$k_{rg} = f(\sigma)k_{rgi} + (1 - f(\sigma))k_{rgm}$$

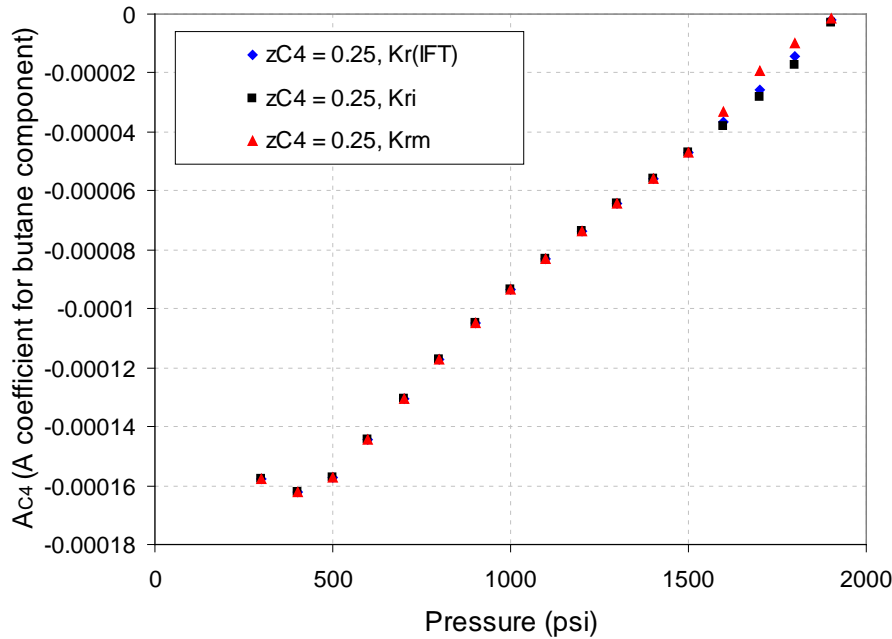
Where:

$$f(\sigma) = \left(\frac{\sigma}{\sigma^*}\right)^{\frac{1}{n}}$$

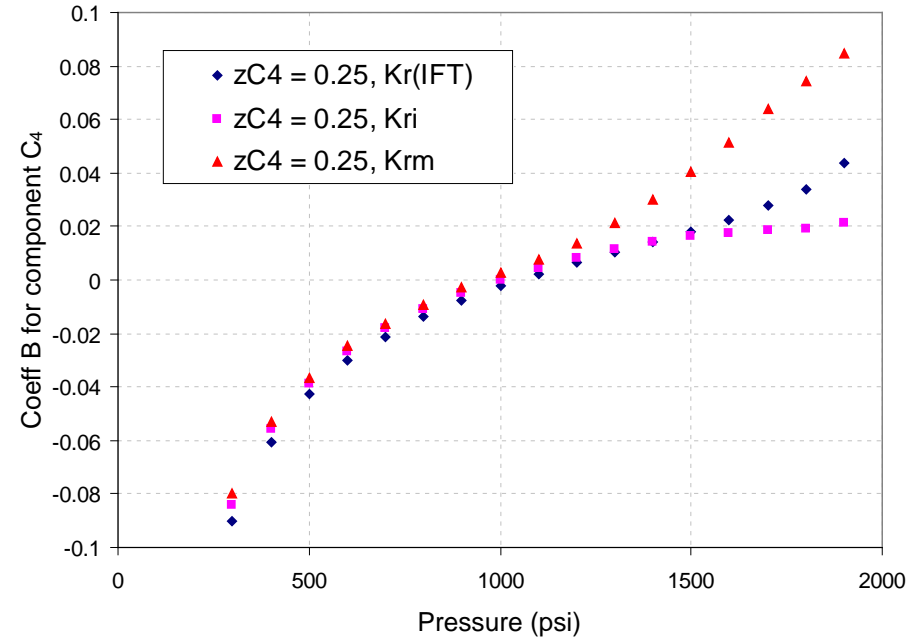
# Impact of $k_r$ models on $A_i$ and $B_i$



As the miscibility decreases in the fluid, liquid phase in the mixture needs to overcome greater critical condensate saturation to become mobile. The liquid mobility is also harmed as the phase interface becomes distinct.



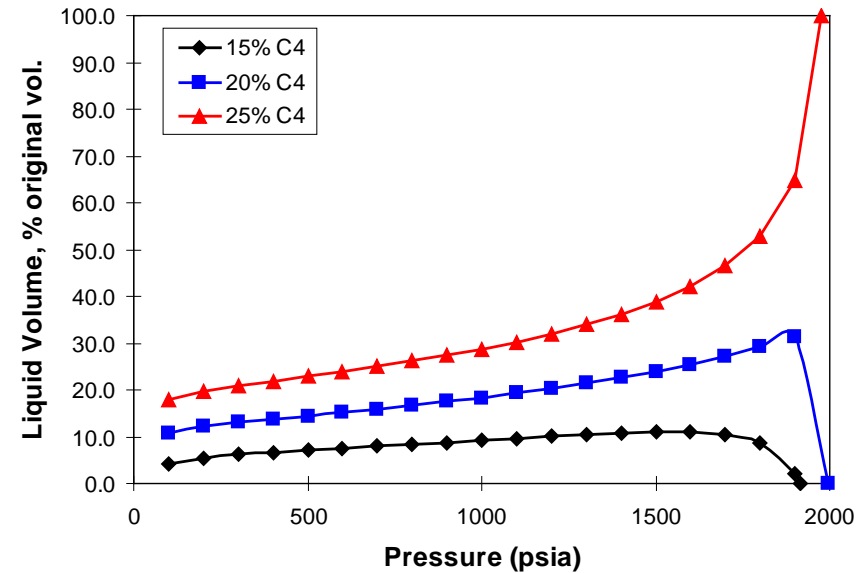
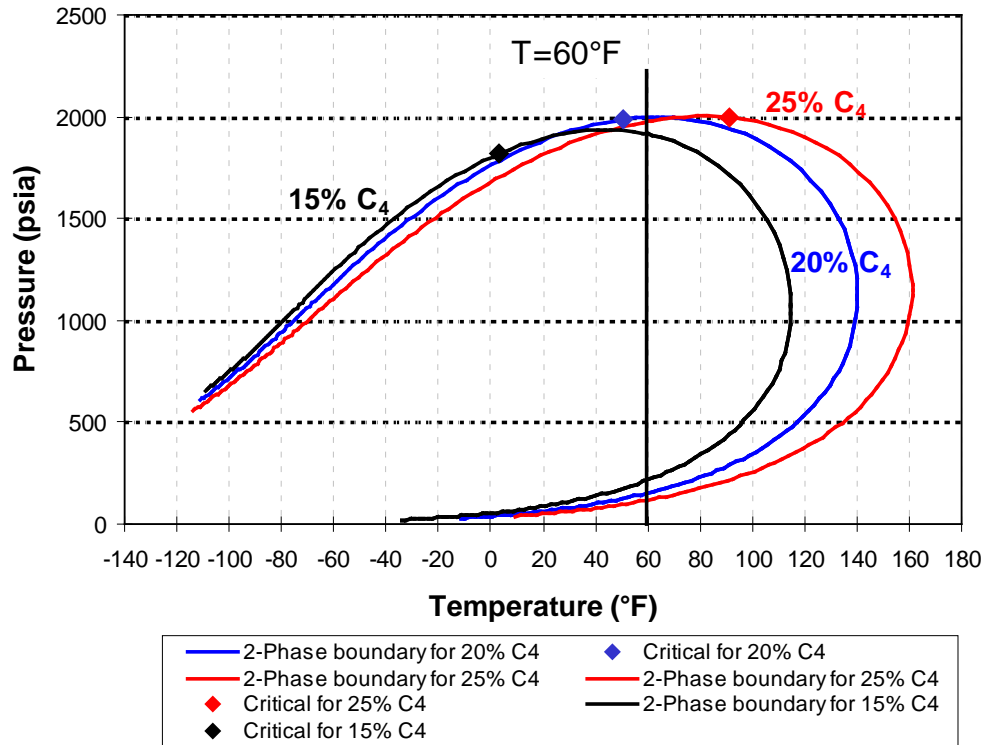
Impact of  $k_r$  models on  $A_{C4}$



Impact of  $k_r$  models on  $B_{C4}$

## Observations:

- Relative permeability has greater impact on term  $B_{C4}$  than on term  $A_{C4}$ .
- Miscible behavior tends to generate greater  $A_{C4}$  and  $B_{C4}$  values, while immiscible fluid has lower  $A_{C4}$  and  $B_{C4}$  values.

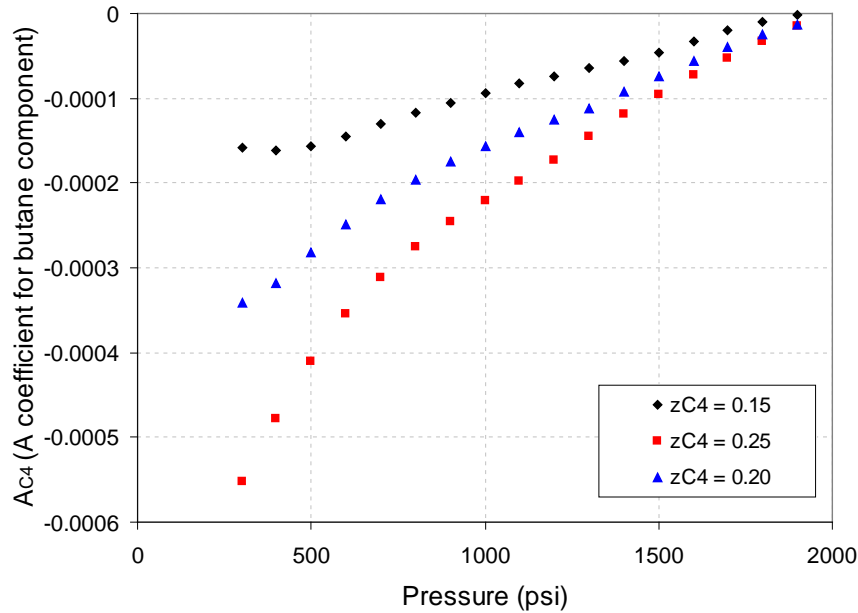
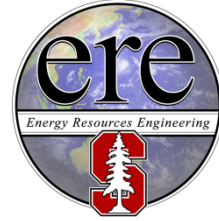


Liquid drop at  $T = 60^{\circ}\text{F}$

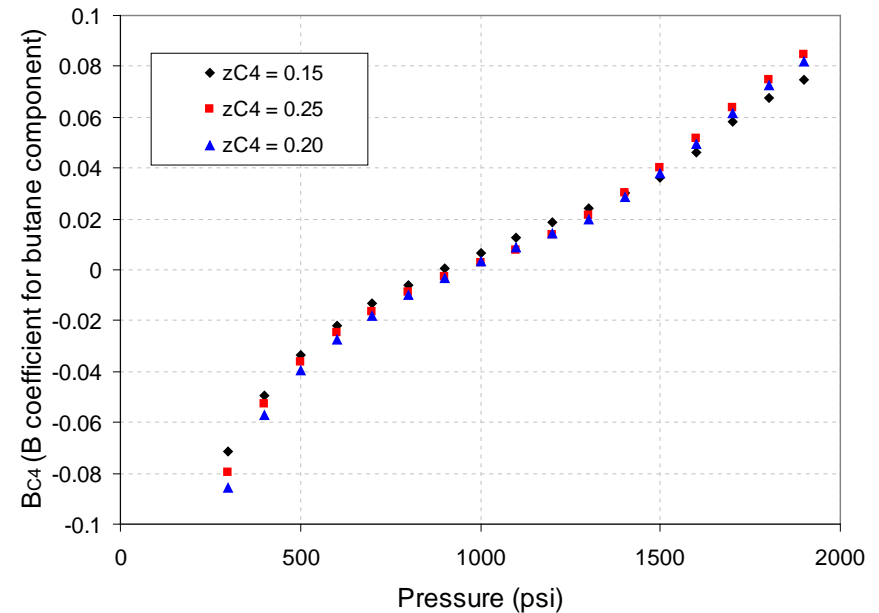
- The fluid with 15% butane is a lean gas-condensate system.
- The fluid with 20% butane is near critical gas-condensate.
- While the fluid with 25% butane is light oil.



# Impact of fluid type on $A_i$ and $B_i$



Impact of fluid type on  $A_{C4}$

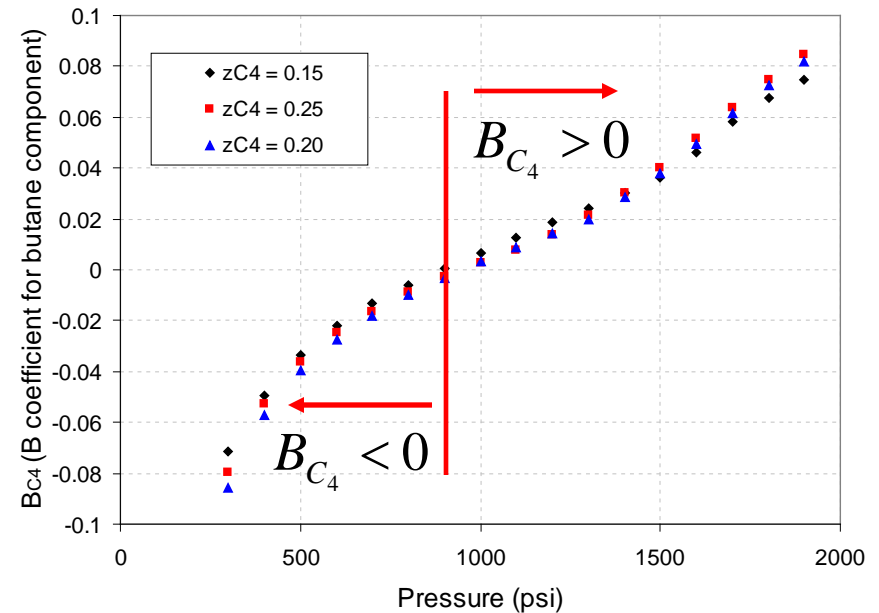
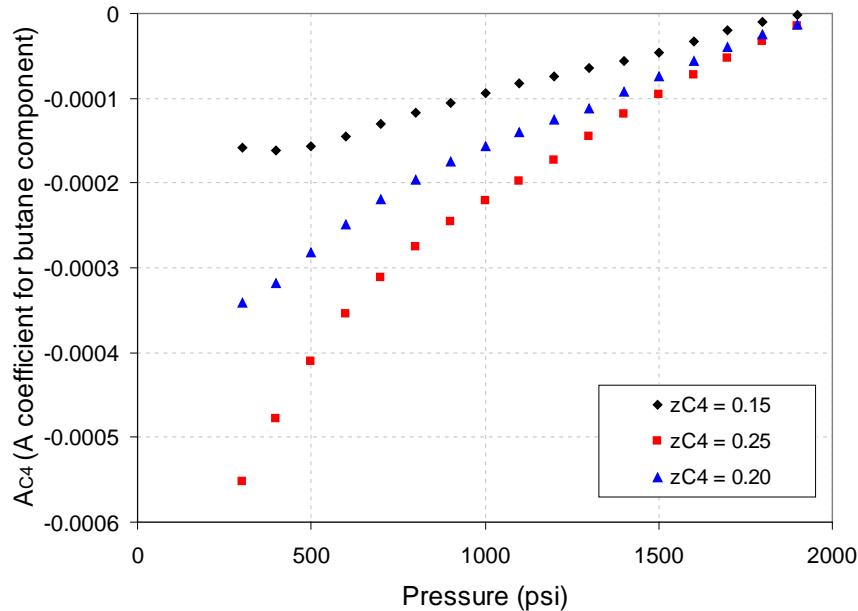


Impact of fluid type on  $B_{C4}$

## Observations:

- Fluid type has greater impact on term  $A_{C4}$  than on term  $B_{C4}$ .
- The difference on  $A_{C4}$  decreases as the fluid pressure increases. As the fluid pressure approaches dew-point pressure,  $A_{C4}$  approaches zero.

# Impact of pressure on $A_i$ and $B_i$



- Both  $A_{C_4}$  and  $B_{C_4}$  decrease as the pressure drops.
- $A_{C_4}$  value is negative and relatively small.
- $A_{C_4}$  approaches zero as pressure approaches dewpoint pressure.
- $B_{C_4}$  is 100 times greater than  $A_{C_4}$  in magnitude.
- $B_{C_4}$  is positive at higher pressure end, and negative on the lower pressure end.



# Theoretical analysis summary



$$\frac{\partial z_i}{\partial t} = A_i \frac{\partial p}{\partial t} + B_i \left(\frac{\partial p}{\partial r}\right)^2 \quad i = 1, n_c$$

**(analysis for  $z_i$  of the heavy components)**

1. When  $\frac{\partial p}{\partial t} = 0$ , or pressure approaches dewpoint pressure:

Near well region

$$\frac{\partial z_i}{\partial t} = B_i \left(\frac{\partial p}{\partial r}\right)^2 \begin{cases} \frac{\partial z_i}{\partial t} > 0, & \text{if } B_i > 0 \text{ } z_i \text{ increases as pressure decreases} \\ \frac{\partial z_i}{\partial t} \leq 0, & \text{if } B_i \leq 0 \text{ } z_i \text{ decreases as pressure decreases} \end{cases}$$

2. When  $\frac{\partial p}{\partial r} = 0$ , or  $B_i = 0$ :

Regions away from the well

$$\frac{\partial z_i}{\partial t} = A_i \frac{\partial p}{\partial t} \begin{cases} \frac{\partial z_i}{\partial t} > 0, & \text{if } \frac{\partial p}{\partial t} < 0 \text{ } z_i \text{ increases during depletion} \\ \frac{\partial z_i}{\partial t} \leq 0, & \text{if } \frac{\partial p}{\partial t} \geq 0 \text{ } z_i \text{ decreases with pressure support} \end{cases}$$