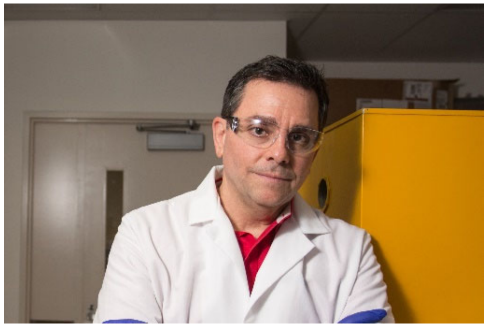

Dr. Konstantinos Kostarelos
Petroleum Engineering Department

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Application of Miscible Ethane Foam for Gas EOR Conformance in Low Permeability Heterogeneous Harsh Environments

Mohamad Salman, Konstantinos Kostarelos,
Pushpesh Sharma, Jae Ho Lee;

University of Houston

UNIVERSITY of HOUSTON

Overview

- Motivation
  - Brief review of previous work
- MMP characterization
- Surfactant formulation development
- Corefloods
- Conclusions

alternative injectants to CO2

Anand Selveindran,

former MS student - now PhD at UH

- Mature waterflooded brownfields
- Marginal economics
- CO_2 Access issues
- Surplus of HC gas

Research Value-add

- While CO_2/rich gas injection are proven technologies, L48 assets focused on CO_2
- Viability of HC gas as a CO_2 substitute experimentally investigated [Much recently published work focused on simulation]
- Actual sandstone cores used [compared to synthetic sandpacks]

Selveindran 2017

Slimtube results

Gas	MMP, psia
CO_2	2350
ethane	1900
natural gas (85% C1, 5% C2, 5% C2, 5% C4)	>3000

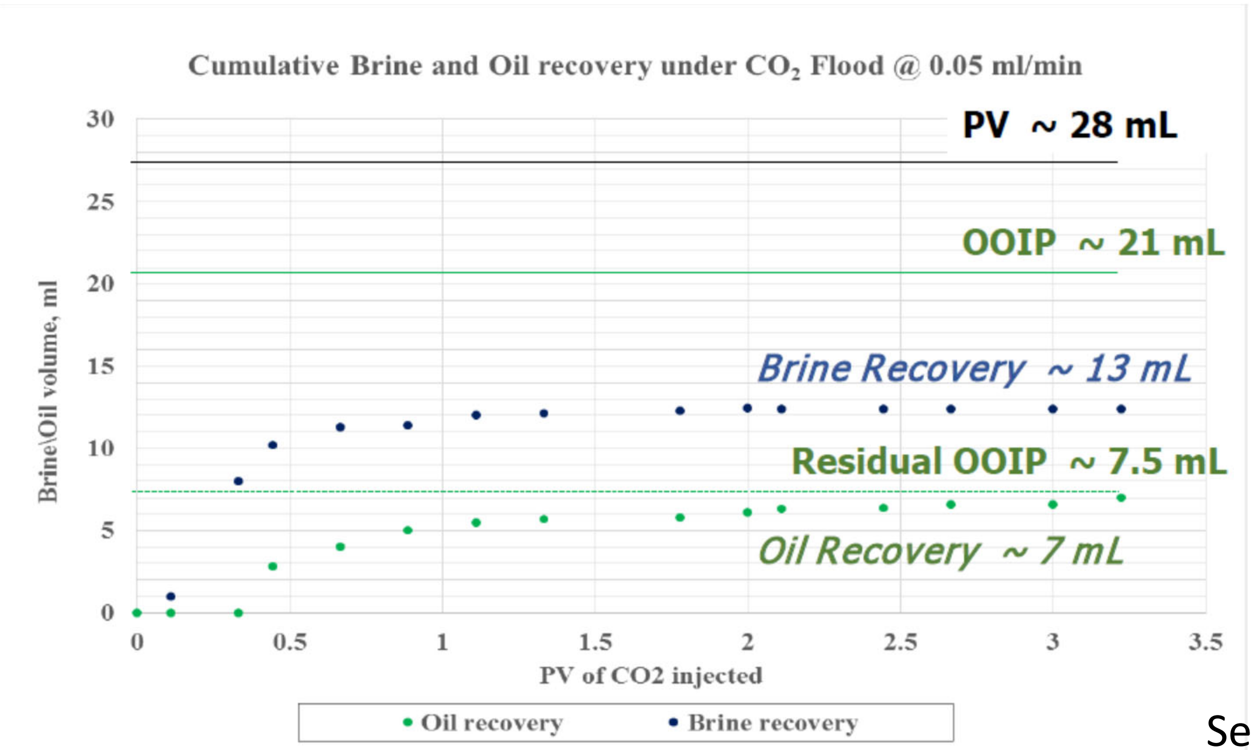
Selveindran 2017

alternative injectants to CO_2

- Several hydrocarbon gas blends investigated as an EOR injectants via numerical simulation
- Experimental work allowed for tuning PVT characterization and flow properties
- Core-scale and field-scale simulation demonstrate HC-gas mixture selected (35% ethane blend) matching CO_2 performance
- Ethane fraction contingent on field economics – sensitivity studies show even a 15% blend adds recovery over lean gas injection

Selveindran 2017

alternative injectants to CO_2



Selveindran 2017

alternative injectants to CO_2

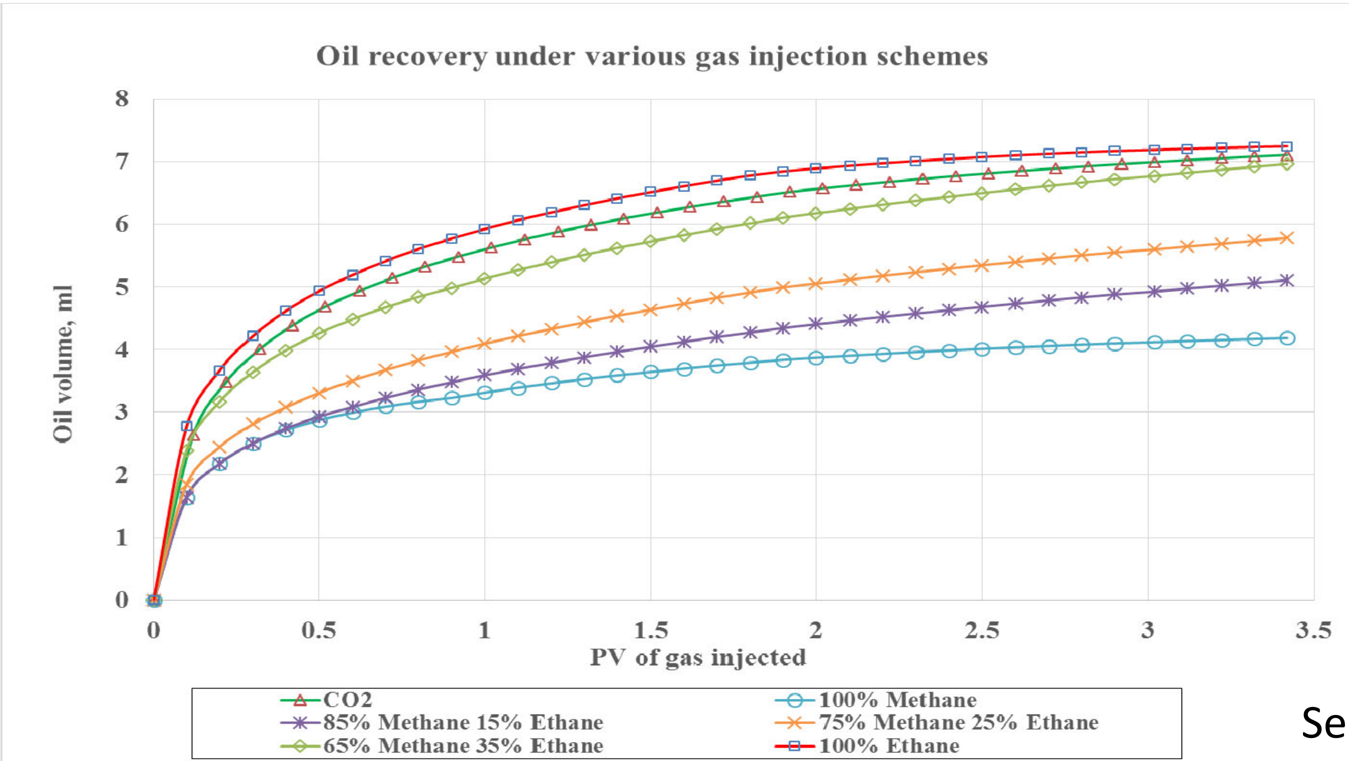
- Injector-producer pair setup in tight 5-acre spacing
- Production well perforated through 1st 4 layers
- Injection well perforated at bottom layer
- Injection rate set at 10 MMscf/D
- Model run for 6 years
- CO_2 injection compared with 65% methane / 35% ethane (HC) gas injection

Selveindran 2017

alternative injectants to CO2

injectant	recovery @ 1 PV, %	recovery @ 3 PV, %
CO_2	80	95
100% ethane	82	97
100% methane	40	55
85% methane, 15% ethane	53	74
75% methane, 25% ethane	60	87
65% methane, 35% ethane	76	96

alternative injectants to CO_2



Selveindran 2017

Application of Miscible Ethane Foam for Gas EOR Conformance in Low Permeability Heterogeneous Harsh Environments

Mohamad Salman, Konstantinos Kostarelos,
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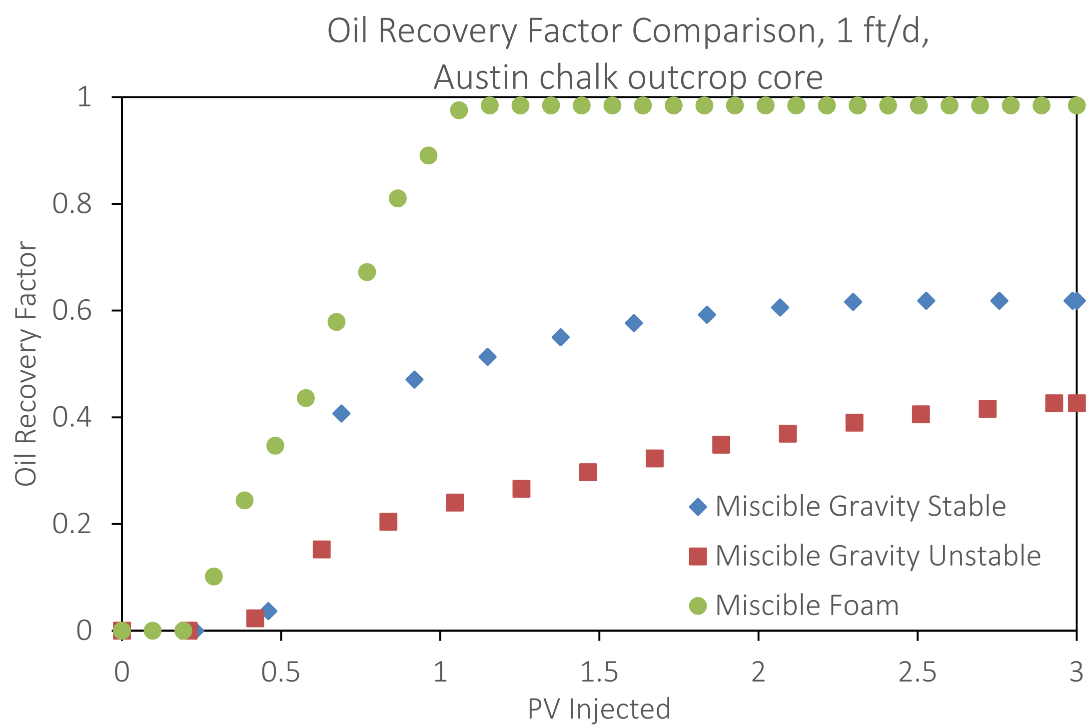
Preview

Key takeaway:

Miscible foam processes can substantially improve recovery in harsh environments

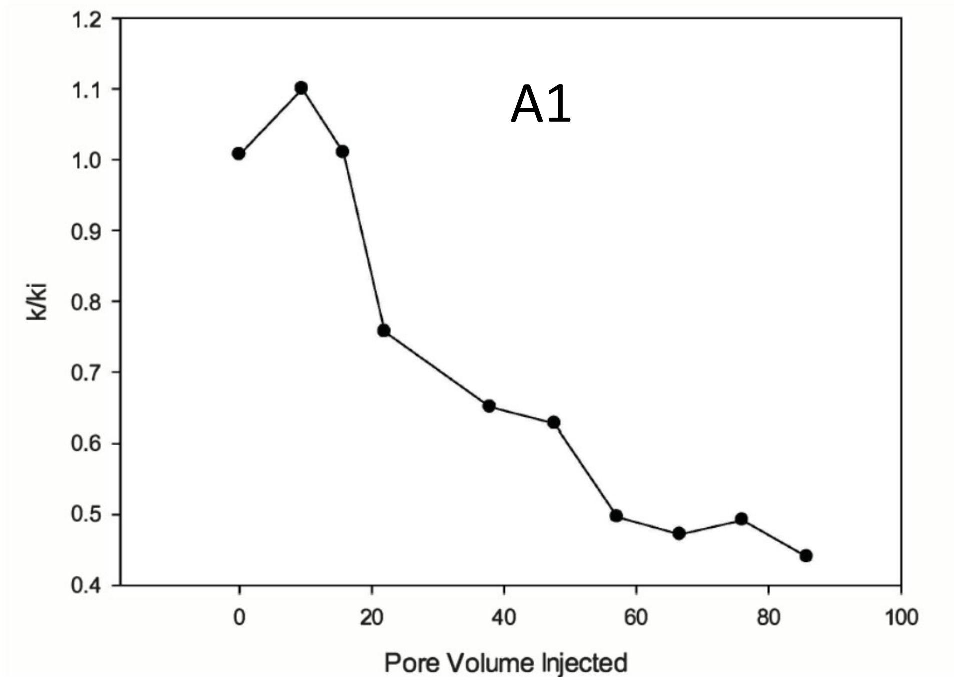


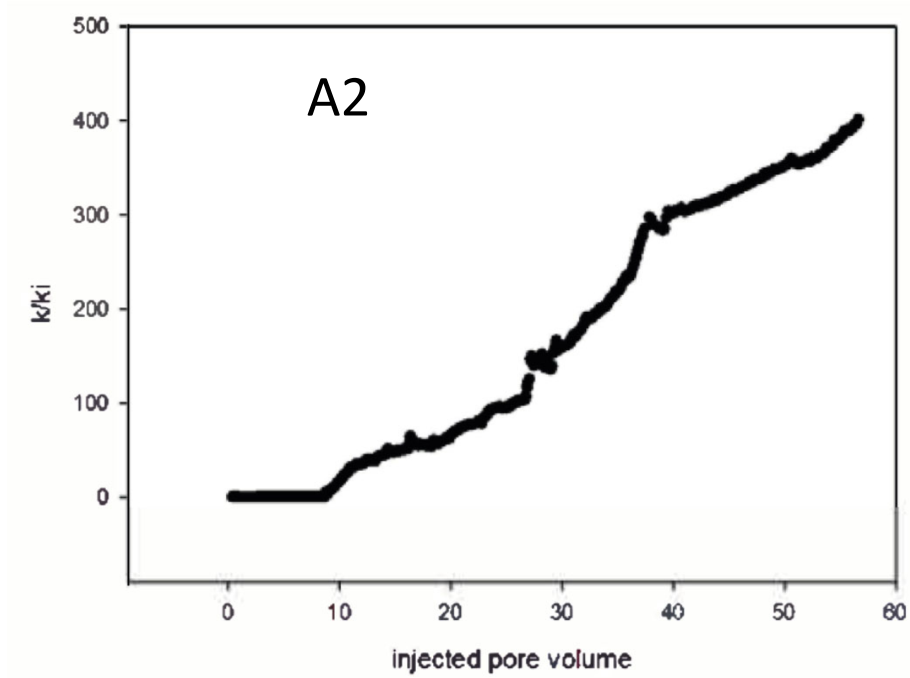
Salman 2018

Motivation

- Low primary recovery in low-k/tight formations leave room for improvement
- CO_2 injection processes are efficient, but have drawbacks (operational, supply chain)
- Ethane: an alternative
  - Comparable costs vs. CO_2
  - Lower MMP potential vs. CO_2
  - No corrosive effects
  - Lower water solubility vs. CO_2

Results of co-injection CO2+brine



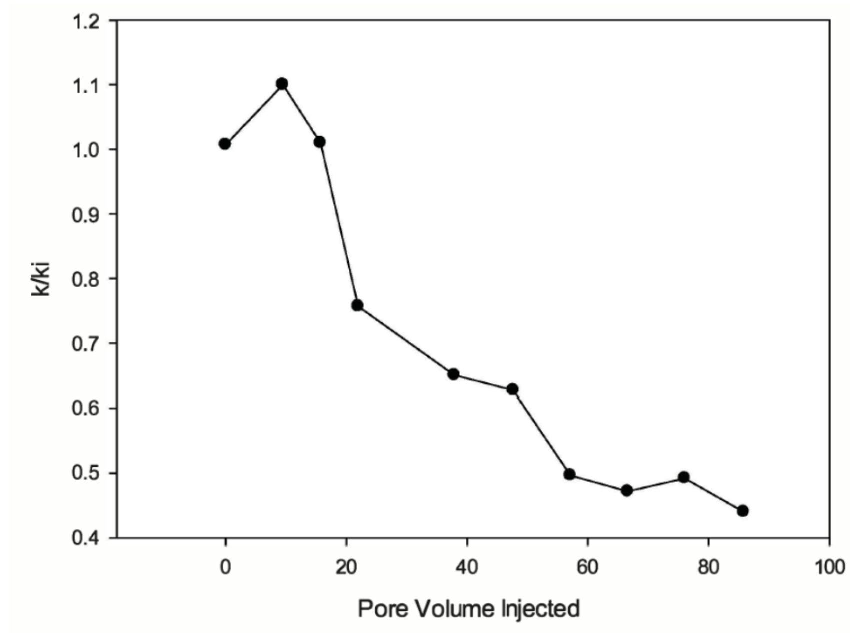


Danial Zareei, MS Student (currently at UH), Prof. Rostami

Petroleum Engineering Institute of University of Tehran

Results of co-injection CO2+brine

A1 (carbonate with lower acid solubility):
inlet and side view after 85 PV

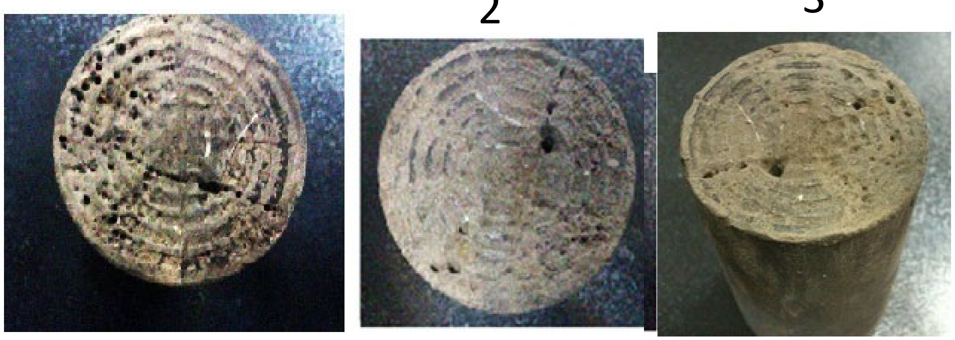


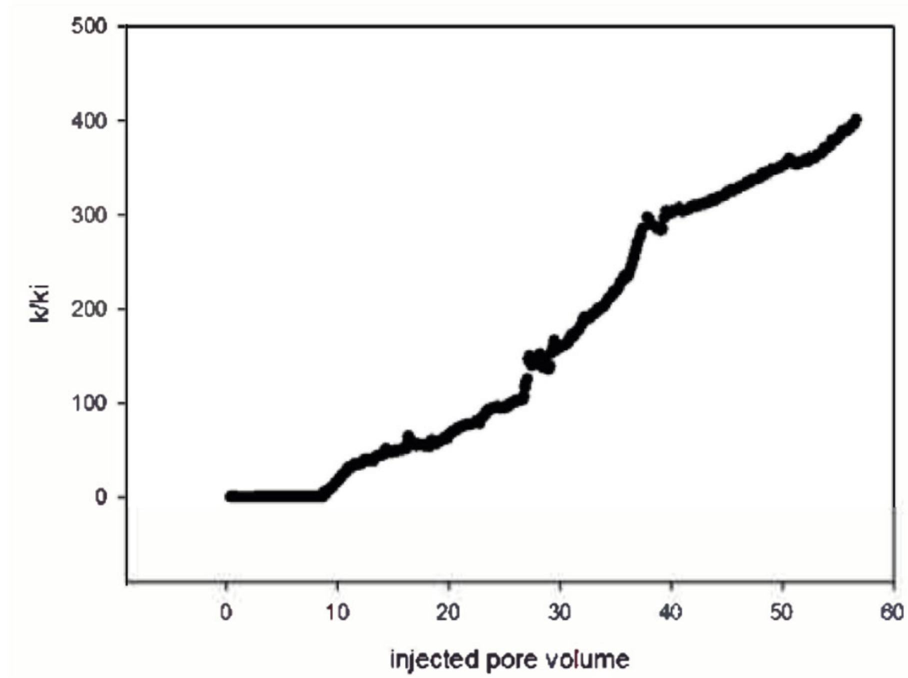
Danial Zareei, MS Student (currently at UH), Prof. Rostami
Petroleum Engineering Institute of University of Tehran

Results of co-injection CO2+brine

A2 (carbonate with higher acid solubility):
(1)inlet after 450 ml injected;
(2)inlet and (3) endview after 55 PV

1 2 3





Danial Zareei, MS Student (currently at UH), Prof. Rostami
Petroleum Engineering Institute of University of Tehran

Motivation

- Need robust gas conformance solutions
  - High temperatures: >140°F
  - High salinity: >100,000ppm total dissolved solids (TDS)
  - High divalent content: >2,000ppm TDS
  - Heterogeneity
- Develop solutions which support the use of produced water

Objectives

- Characterize ethane (C_2H_6) and carbon dioxide (CO_2) MMP with Wolfcamp dead crude oil
- Develop robust surfactant formulation capable of Type I microemulsion and stable foam at high temperature and salinity
- Compare the effects of gravity for miscible gas floods vs. unstable foam-assisted miscible gas flood in heterogeneous outcrop cores

Target environment

Wolfcamp Spraberry Trend

Reservoir temperature: 165°F

Reservoir pressure: 1,550 psia

High S_w (>0.5)

Heterogeneous carbonate (Austin Chalk outcrop)

Crude oil:

- 41.2API
- TAN: 0.32 mg KOH/g oil
- 5.2cP viscosity at 25 °C
- 2.2cP viscosity at °C
- High intermediate hydrocarbon content

Component	Value
Na^{+}, ppm	47,179.5
Mg^{2+}, ppm	3,603.6
Ca^{2+}, ppm	1,515.8
Cl^{-}, ppm	83,701.1
Salinity, wt.%	13.6

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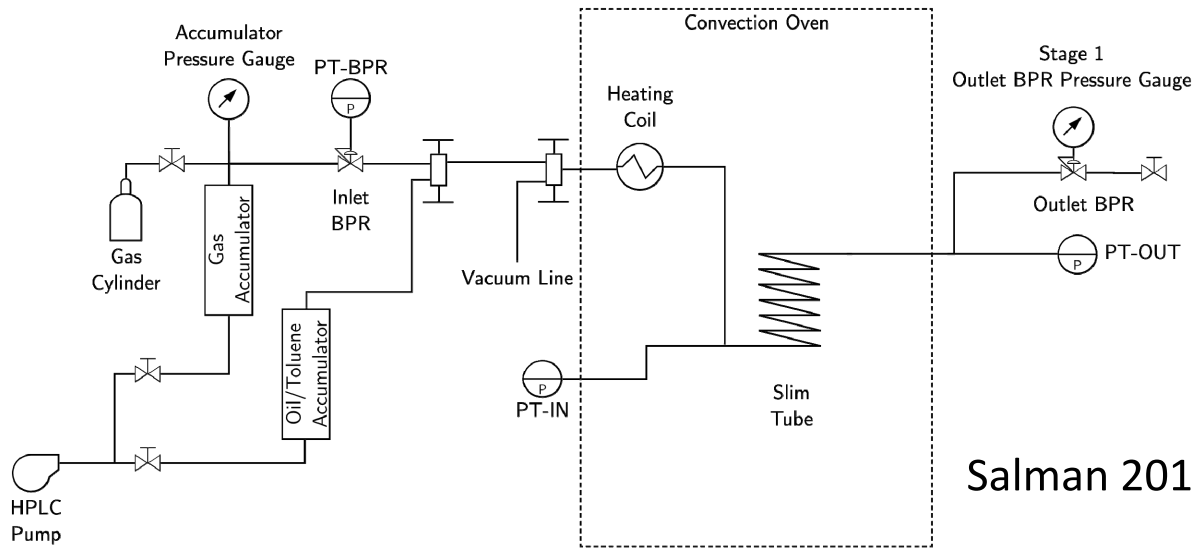
Miscible column (slimtube) tests

- 1D gas-oil displacement at 165°F
- MMP: 90% recovery breakpoint in oil recovery vs. pressure after 1.2PV injection
- C_2H_6 vs. CO_2



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Miscible column (slimtube) tests

1D gas-oil displacement at 165°F

MMP: 90% recovery breakpoint in oil recovery vs. pressure after 1.2PV injection

C_2H_6 vs. CO_2

Item	Literature	Lab Setup
Internal diameter, in.	0.12 – 0.63	0.31
Length, ft.	5 – 120	41.4
Packing material	Glass beads, sand	Glass beads
Material mesh size	50 – 270	100
Porosity, %	35 – 45	47.7
Permeability, Darcy	2.5 – 250	18.8
Displacement velocity, ft/d	30 – 650	101.7

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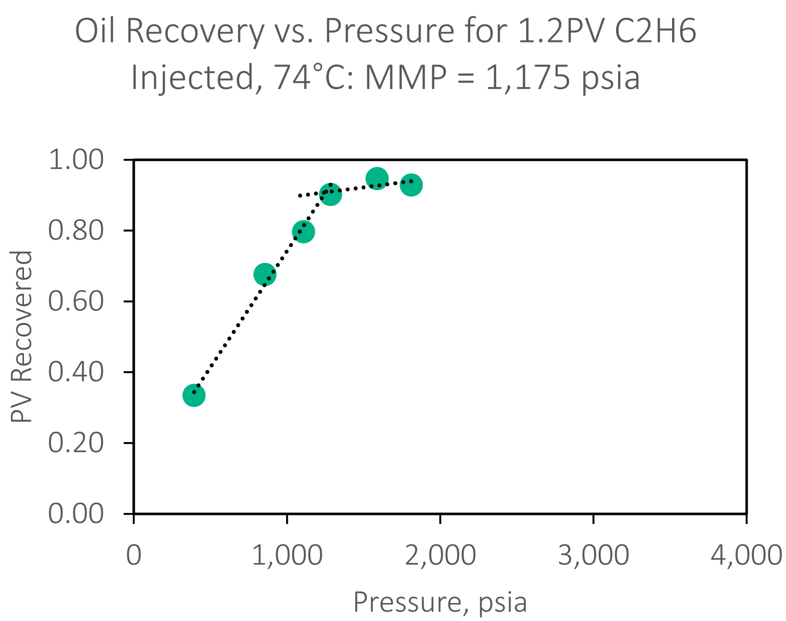
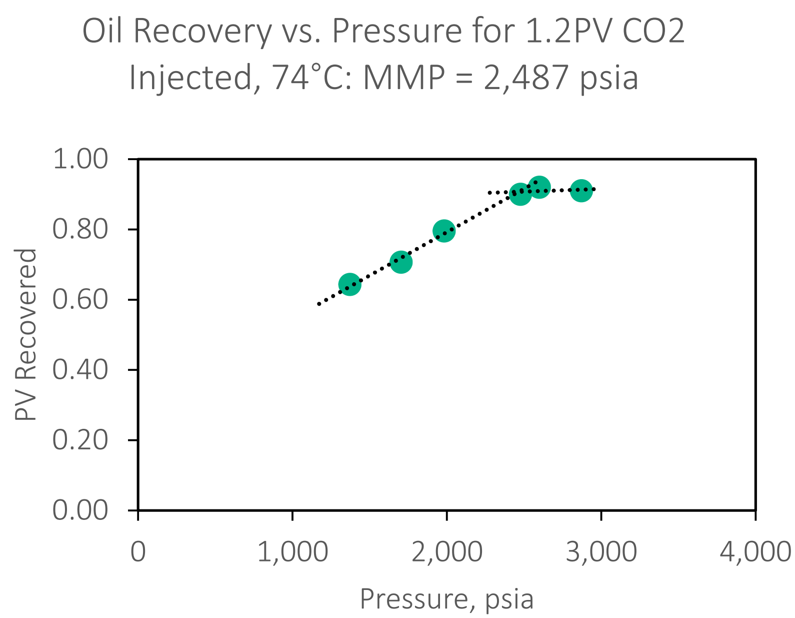
Slimtube test results





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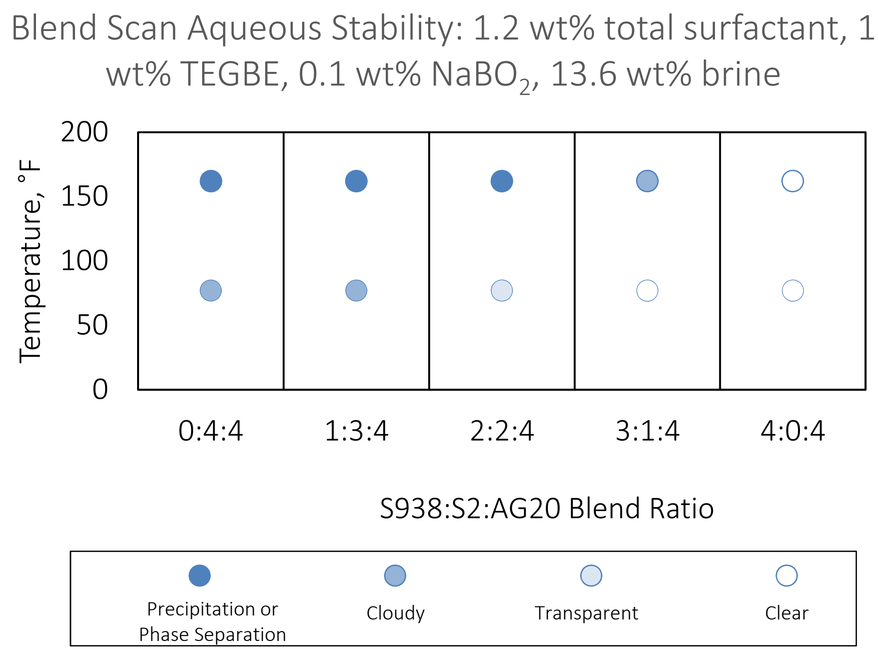
A robust surfactant formulation

- Type I at reservoir conditions
- Capable of generating stable foam
- Effective at produced water salinity

Surfactant formulation at reservoir salinity

Item	Value
Component A	Soloterra 938 (ethoxylated carboxylate, 7EO)
Component B	Petrostep S-2 (IOS, C15-20)
Component C	Linapol AG-20 (Decyl glucoside)
Co-solvent	Butoxytriglycol (TEGBE), 1 wt%
Alkali Buffer	$NaBO_2$, 0.1 wt%
Salinity	13.6 wt%



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Salinity scan at 165°F: 1:1WOR

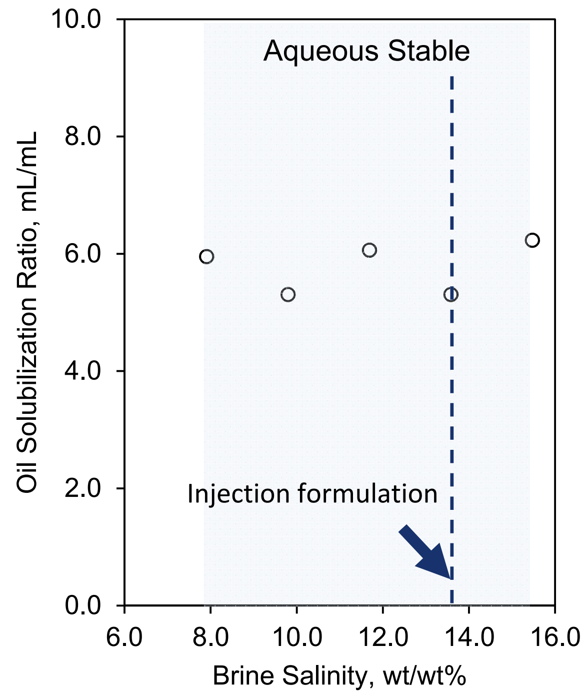
Formulation:

- 0.6 wt% S938
- 0.6 wt% AG20
- 1.0 wt% TEGBE
- 0.1 w% $NaBO_2$

Only Type I observed

SR_o at 13.6 wt% = 5.3

Huh equation:
σ = 0.01 dynes/cm



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Foam Stability Tests

- Interfacial/Surface Tension Tests
  - At room temperature
  - Characterized with Dataphysics OCA 15EC goniometer (pendant drop method)

Factor and Expression	Conditions for Stability
Entering Coefficient, $E = \sigma_{w/g} + \sigma_{w/o} - \sigma_{o/g}$	$E < 0$
Spreading Coefficient, $S = \sigma_{w/g} - \sigma_{w/o} - \sigma_{o/g}$	$S < 0$
Bridging Coefficient, $B = \sigma^2_{w/g} + \sigma^2_{w/o} - \sigma^2_{o/g}$	$B < 0$
Lamella Number, $L = 0.15 \frac{\sigma_{w/g}}{\sigma_{w/o}}$	$L < 1, most\ stable\ (A)$ $1 < L < 7, moderately\ stable\ (B)$ $L > 7, unstable\ (C)$

- Static Column Tests
  - In oven at 165°F
  - Air dispersed via frit at 3psig
  - Foam height decay with time

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Static Column at 165°F

Foam stability: interfacial/surface tension tests

Item	Value
$\sigma_{w/o}$	5.93 dynes/cm
$\sigma_{s/o}$	0.42 dynes/cm
$\sigma_{o/g}$	15.15 dynes/cm
$\sigma_{s/g}$	5.28 dynes/cm
Entering Coefficient	-201.47 $dynes^2/cm^2$, stable
Spreading Coefficient	-9.45 dynes/cm, stable
Bridging Coefficient	-10.29 dynes/cm, stable
Lamella Number	1.89, moderately stable (Class B)

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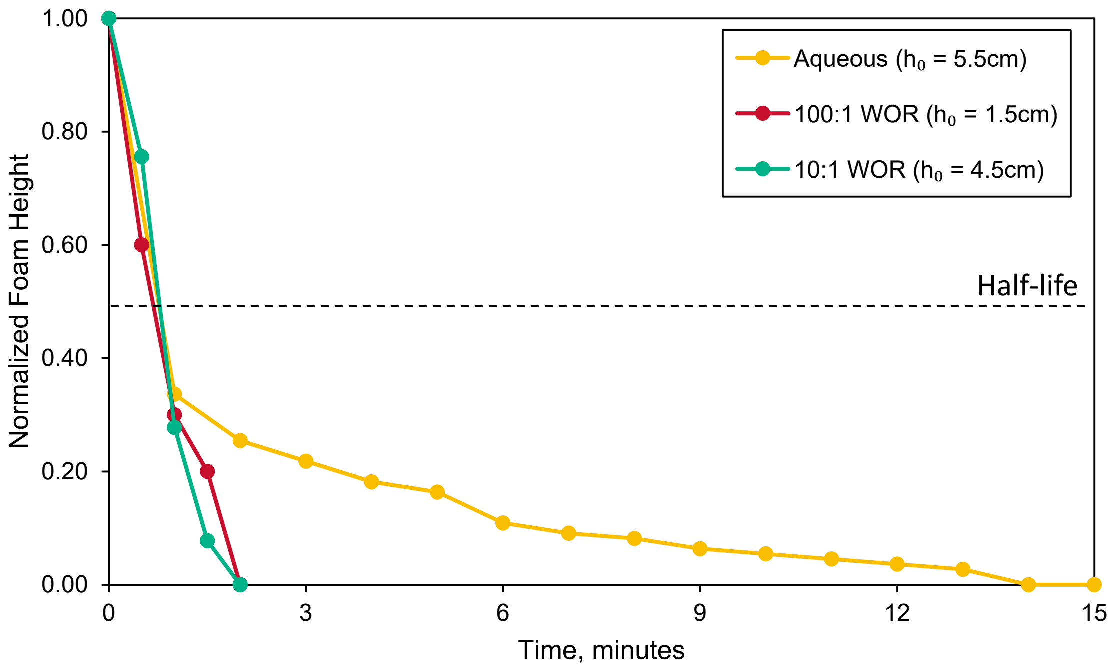
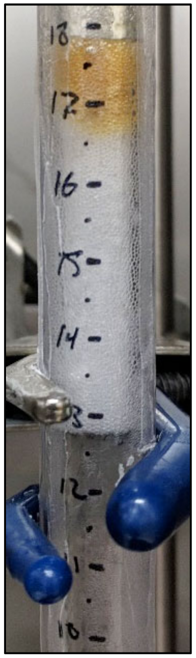
Foam stability: static column tests





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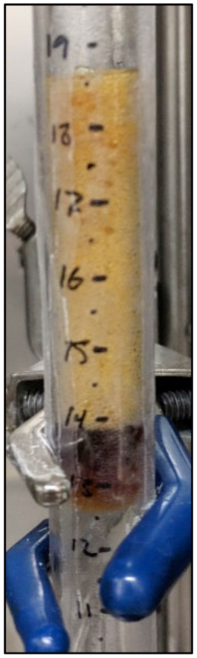

10:1 WOR

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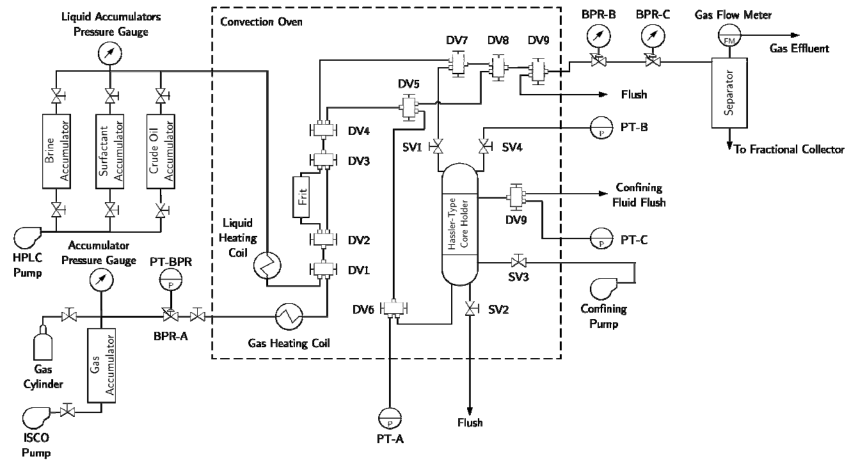
Multiphase displacement corefloods

At reservoir conditions

Gravity stable: injection utilizing favorable density orientation

Stable: downwards

Unstable: upwards



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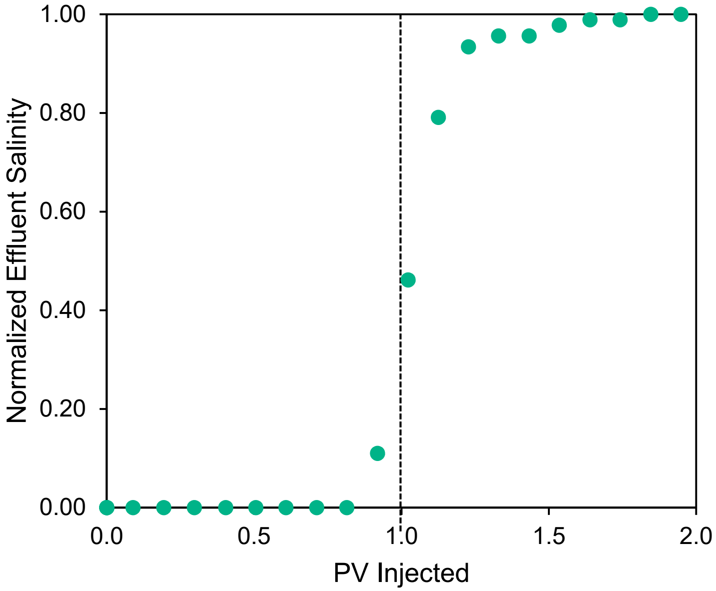
Foam quality scan in heterogeneous carbonate

Item	Value
Temperature, °F	165
Initial pressure, psia	1,550
Net confining pressure, psia	1,000
Frontal Velocity, ft/d	1.0
Core length, in.	5.91
Core diameter, in.	1.50
k_{brine}, md	8.70
Salinity tracer porosity, %	28.8
Salinity tracer PV, mL	48.9
Porous Media	Austin Chalk carbonate, heterogeneous

AC2-1 Salinity Tracer (22.7 wt% to 13.6 wt%): 28.8% porosity, 48.9 mL PV



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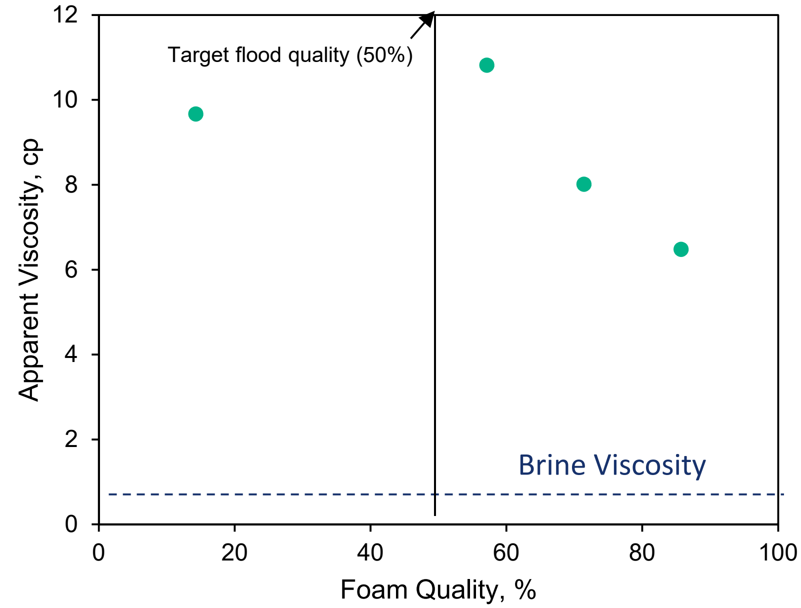
Foam Quality Scan in Heterogeneous Carbonate

parameter	value
Temperature, °F	165
Initial pressure, psia	1,550
Net confining pressure, psia	1,000
Frontal Velocity, ft/d	1.0
Core length, in.	5.91
Core diameter, in.	1.50
k_{brine}, md	8.70
Salinity tracer porosity, %	28.8
Salinity tracer PV, mL	48.9
Porous Media	Austin Chalk carbonate, heterogeneous

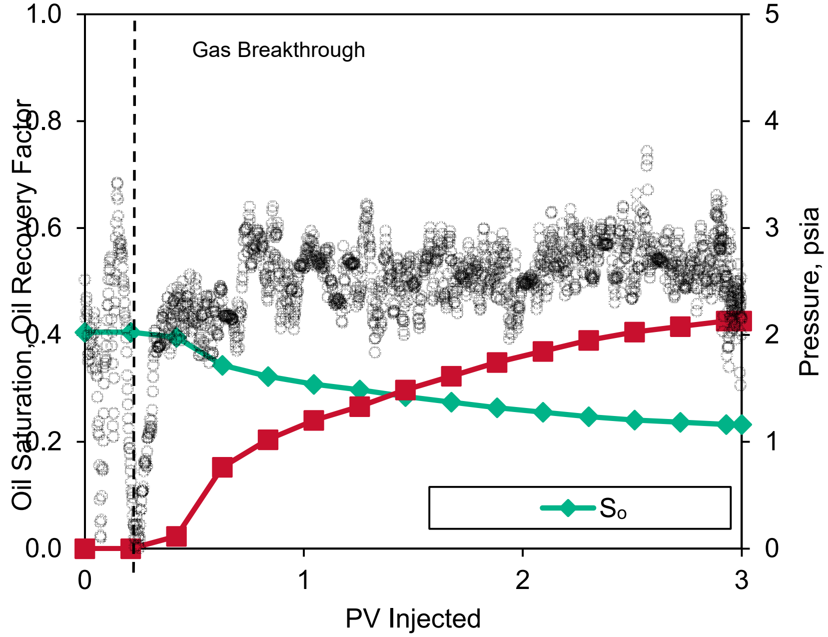
AC2-1 Foam Quality Scan (1 ft/d): Ethane, 1.2 wt% total surfactant, 1 wt% TEGBE, 0.1 wt% $NaBO_2$, 13.6 wt% brine



Gravity unstable miscible ethane flood: RF_o = 42.6%

parameter	value
Temperature, °F	165
Initial pressure, psia	1,530
Net confining pressure, psia	1,000
Frontal Velocity, ft/d	1.0
Core length, in.	6.02
Core diameter, in.	1.50
k_{brine}, md	15.2
Porosity, %	29.0
PV, mL	49.8
S_{wi}	0.60
RF_o, %	42.6
N_C/N_B	5.94
M°	3.08

Austin Chalk carbonate, heterogeneous



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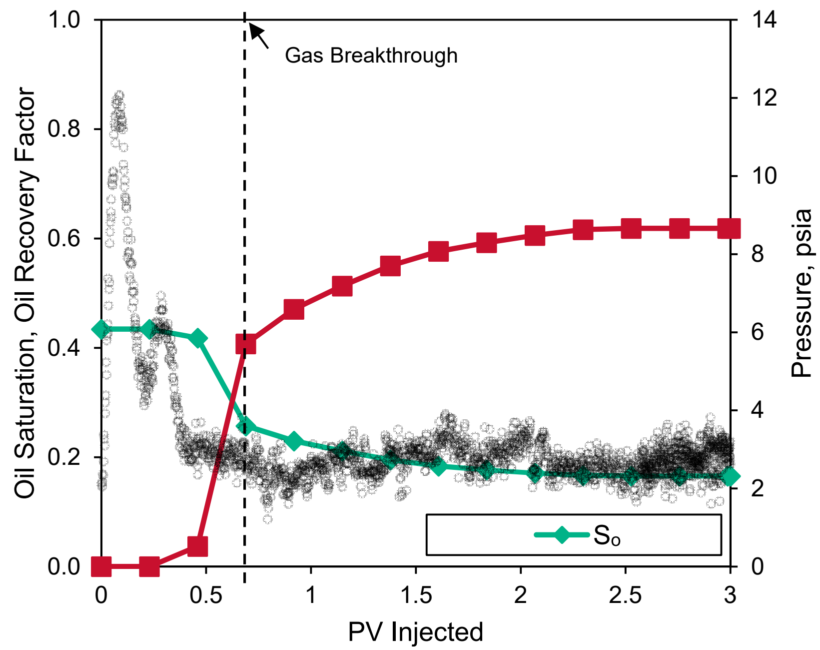
Gravity stable miscible ethane flood: RF_o = 61.9%

Parameter	value
Temperature, °F	165
Initial pressure, psia	1,600
Net confining pressure, psia	1,000
Frontal Velocity, ft/d	1.0
Core length, in.	5.91
Core diameter, in.	1.50
k_{brine}, md	10.3
Porosity, %	25.7
PV, mL	43.6
S_{wi}	0.57
RF_o, %	61.9
N_C/N_B	7.93
M°	2.38

Austin Chalk carbonate, heterogeneous



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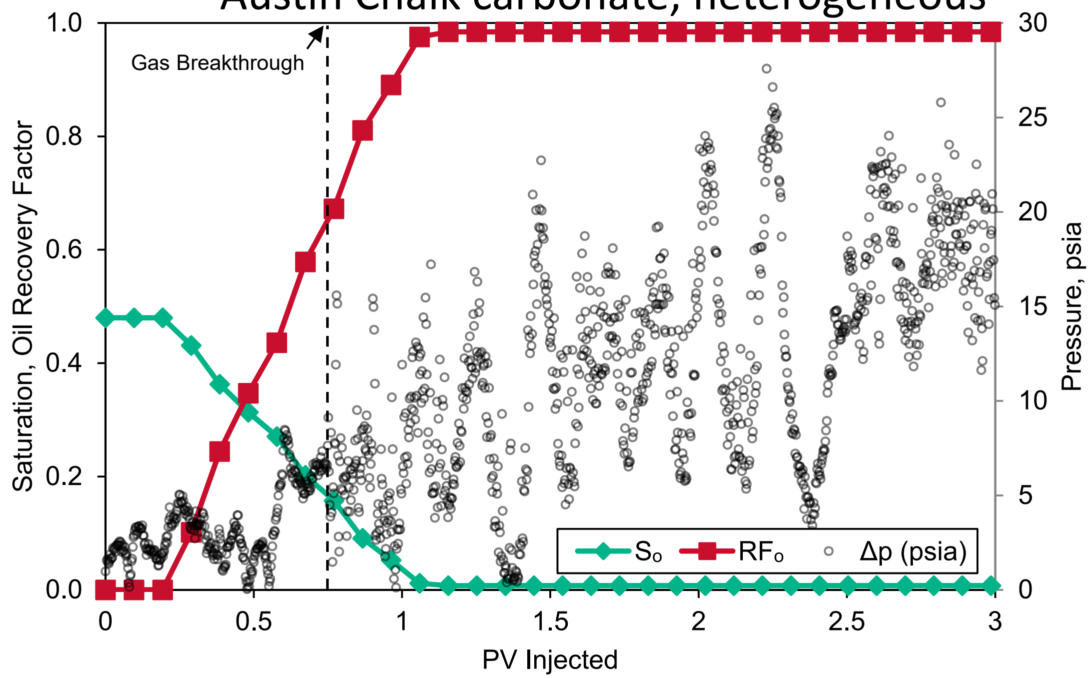
Gravity unstable miscible ethane foam: RF_o = 98.4%

parameter	value
Temperature, °F	165
Initial pressure, psia	1,550
Net confining pressure, psia	1,000
Frontal Velocity, ft/d	1.0
Core length, in.	5.91
Core diameter, in.	1.50
k_{brine}, md	10.3
Porosity, %	26.9
PV, mL	46.6
S_{wi}	0.52
RF_o, %	98.4
N_C/N_B	12.4
M°	0.44
Foam quality	50%

Austin Chalk carbonate, heterogeneous



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Conclusions

- Low potential MMP values for C_2H_6 compared to CO_2 suggest that the application window for a C_2H_6 miscible project is much wider than CO_2

- Gravity stable gas injection processes in the presence of heterogeneity help prevent early gas breakthrough and ensure larger HCPV recoveries

- Recoveries are still sizeable even when a gravity unstable process introduces early gas breakthrough

Conclusions

- 0.6% ethoxylated carboxylate, 0.6% alkyl polyglucoside, 1% TGBE, and 0.1% $NaBO_2$ formulation was capable of producing stable foams and Type I microemulsion up to 15.5 wt% salinity

- Possible to tune this formulation to achieve Type III microemulsion phase behavior for lower salinities or apply it in reservoirs with higher salinities

Conclusions

- **Miscible gas foam processes are extremely efficient, even in unfavorable conditions.** Since C2H6 did not achieve FCM in this work, IFT is still present, albeit minimized (i.e., Type I Low IFT miscible gas foams more than adequate to maximize recovery in laboratory conditions in a gravity unstable environment).

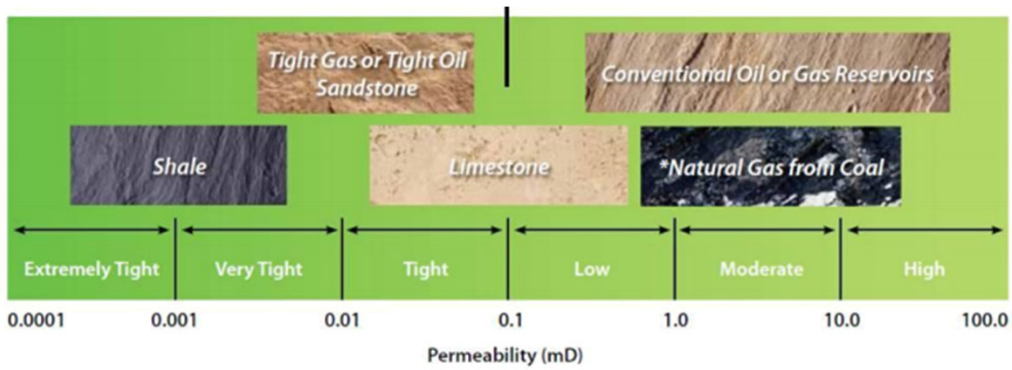
- Microscopic displacement improvement was addressed by the development of miscibility; however, miscible gas foam processes benefit more from an improvement in macroscopic displacement afforded by the presence of foams via an increased gas apparent viscosity.

Future Work

- Effluent compositional analysis for displacement tests to characterize drive mechanisms
- Immiscible ethane foam process characterization
- Ethane foam processes with other surfactants
  - Lauryl betaines, sulfonates, ethoxylated amines
- Role of ethane vs. CO_2, N_2, and CH_4 in foam stability in porous media
- Ethane foam in µd-nd, fractured porous media
- Pb depression in tight rock **=> see next slides…**

P_b depression in tight rock

1. Initial testing with sandstone (*e.g.*, Bentheimer)
2. Experimental Set-up will allow P_b determination
3. Continue testing with tight rock/siltstone (no clay; *e.g.*, Crab Orchard)
4. Final testing with clay-intensive siltstone or shale



Thank you