Field Pilot Test of Foam-assisted Hydrocarbon Gas Injection in Bakken Formations

DOE Award Number: DE-FE0031787

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University of Wyoming & Hess Corporation

U.S. Department of Energy

National Energy Technology Laboratory

2024 Resource Sustainability Project Review Meeting

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Program Overview

Overall Project Objectives

- The overall objective of this project is to increase recovery and sustain production from existing Bakken wells by implementing a new Enhanced Oil Recovery (EOR) technology. Additionally, we aim at resolving some of the key issues associated with gas containment in this field.
- The initial project duration was four years (Oct. 1, 2019 to Sep. 30, 2023).
- A two-year no-cost-time extension was added to Budget Period 2.

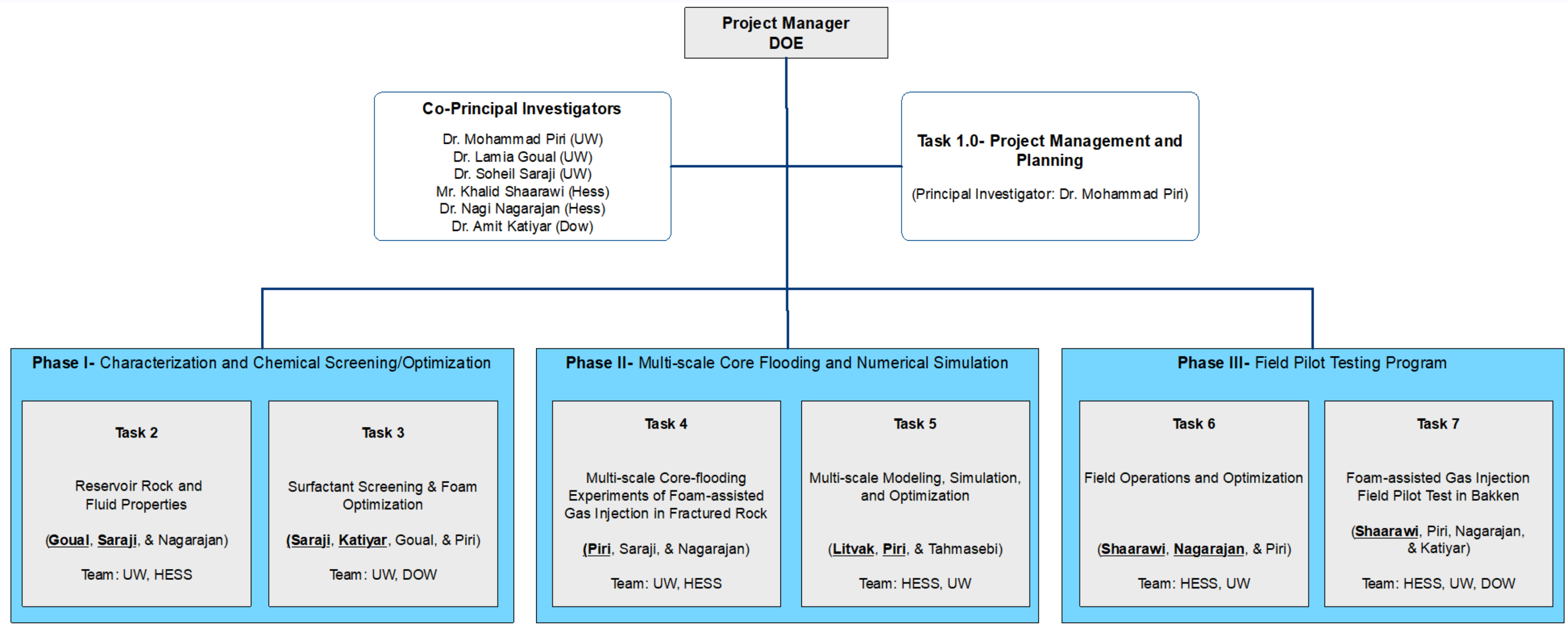
Project Participants

- University of Wyoming, Hess Corporation, and Dow Chemical Company

Funding (DOE and Cost Share): DOE: $8 million & Cost share: $2 million

	Budget Period 1		Budget Period 2		Budget Period 3		Budget Period 4		Total	
	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share
Applicant	$1,044,376	$235,887	$1,032,353	$182,968	$585,087	$182,968	$338,184	$150,456	$3,000,000	$752,280
Hess Corporation	$1,063,042	$0	$2,486,500	$182,000	$1,450,458	$169,000	-	$99,000	$5,000,000	$450,000
Dow Chem. Comp.	-	$299,808	-	$275,244	-	$111,614	-	$114,341	-	$801,007
FFRDC/NL, if proposed	-	-	-	-	-	-	-	-	-	-
Total ($)	$2,107,418	$535,695	$3,518,853	$640,213	$2,035,545	$463,582	$338,184	$363,797	$8,000,000	$2,003,287
Total Cost Share %		20.3%		15.4%		18.5%		51.8%		20.0%

Organization Chart



The organizational structure of the project integrates

- The expertise of the world's largest experimental research facility in the area of Flow through Porous Media (University of Wyoming),
- A major technology-focused operator (Hess Corporation), and
- A chemical manufacturer with significant CO_2 foam EOR and FAGI EOR experience (Dow Chemical Company).

Technology Background

- Enhanced oil recovery (EOR) processes are of paramount importance to address the problem of low primary recovery of hydrocarbons from unconventional reservoirs.
- The proliferation of hydraulic fracturing further compliments to the success of the EOR processes by providing a larger surface area to the injection fluid (EOR agent) in contact with the matrix.
- Miscible gas injection, through continuous flooding or cyclic huff-and-puff, has received a surge of interest in the last decade but remains rather inefficient in addressing gas containment and conformance control in highly heterogeneous formations.
- Results from various field tests suggest that issue related to gas conformance control may be resolved by generating stable foam using hydrocarbon gas and aqueous surfactant solution, within the fractures.

Technical Approach

- A detailed project management plan is developed to sketch a clear path to accomplish the project deliverables.
- Reservoir rock and fluid samples were acquired, and their chemical and physical properties are characterized.
- A rigorous surfactant screening was performed to identify 3-5 potential candidates for the field application.
- A state-of-the-art foam generation system was fabricated for evaluation of the selected chemicals and optimization of the foam parameters.
- Multiscale core-flooding and numerical simulations were performed to study the fracture-matrix interaction, effect of wettability and saturation on foam flow, optimization of foam-assisted gas injection parameters, and their impact on oil recovery.
- A field pilot testing program was developed to address critical issues such as land and regulations, field/well preparation, injection systems, and design specifications.

Technical Approach (Cont'd)

Project Milestones

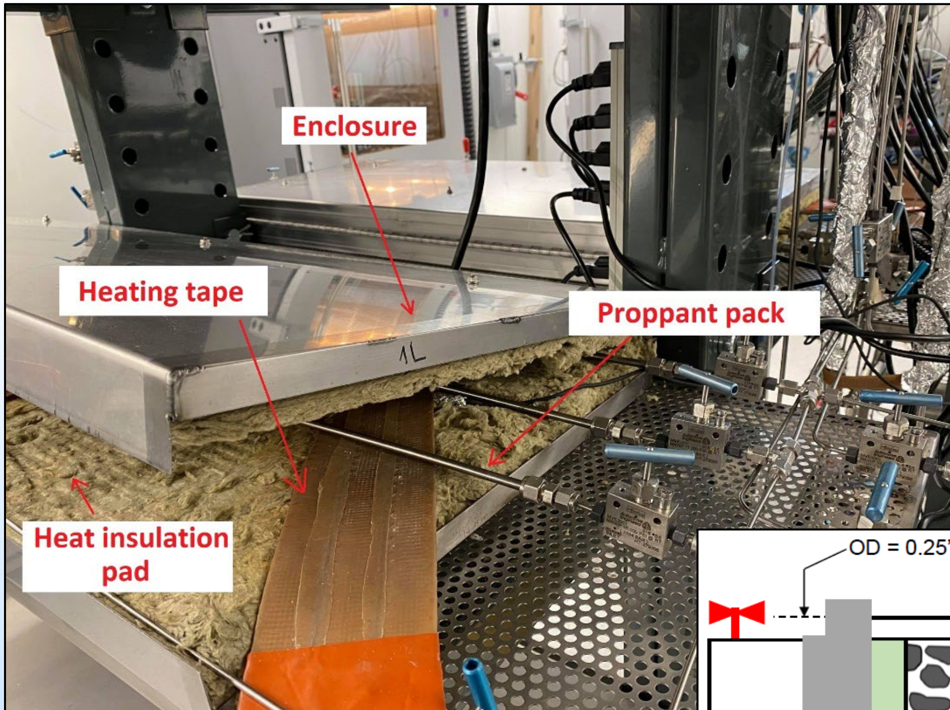
Task/ Subtask	Milestone Title & Description	Planned Completion Date	Verification Method
1.1	M1 - Update Project Management Plan	10/31/2019 (Completed)	Updated PMP is received by the DOE Project Manager
2.4	M2 - Determine Bakken reservoir rock wettability	06/30/2020 (Completed)	Measured contact angles on aged reservoir rock samples
3.1, 3.2, 3.3, 3.4, 4	M3 - Identify optimum chemical formulation for cycle 1 of pilot test	09/01/2020 (Completed)	Dow and UW report to Hess optimum chemical formulation
5.3, 5.4	M4 - Develop a pad-scale model for foam EOR	10/01/2020 (Completed)	Hess reports simulation results using the pad-scale model
7.1	M5 - Implement first cycle of the field pilot test	11/30/2023*	Hess reports the data generated by the field pilot test
3.1, 3.2, 3.3, 3.4, 4	M6 - Re-assess optimum chemical formulation and foam properties for cycle 2 of the field pilot test	10/01/2024*	Dow and UW report to Hess optimum chemical formulation.
5.4	M7 - Validate the pad-scale model for foam EOR against data from cycle 1 of the field pilot test	05/01/2024*	Hess presents comparison of model predictions against counterparts from cycle 1 of the field pilot test
7.1	M8 - Implement second cycle of the field pilot test	11/30/2024*	Hess reports the data generated through pilot test
5.4	M9 - Validate the pad-scale model for foam EOR against data from cycle 2 of the field pilot test	01/01/2025*	Hess presents comparison of model predictions against counterparts from cycle 2 of the field pilot test
7.2	M10 - Evaluate the field pilot test success	06/30/2025*	Hess reports field pilot test data and the results of success evaluation

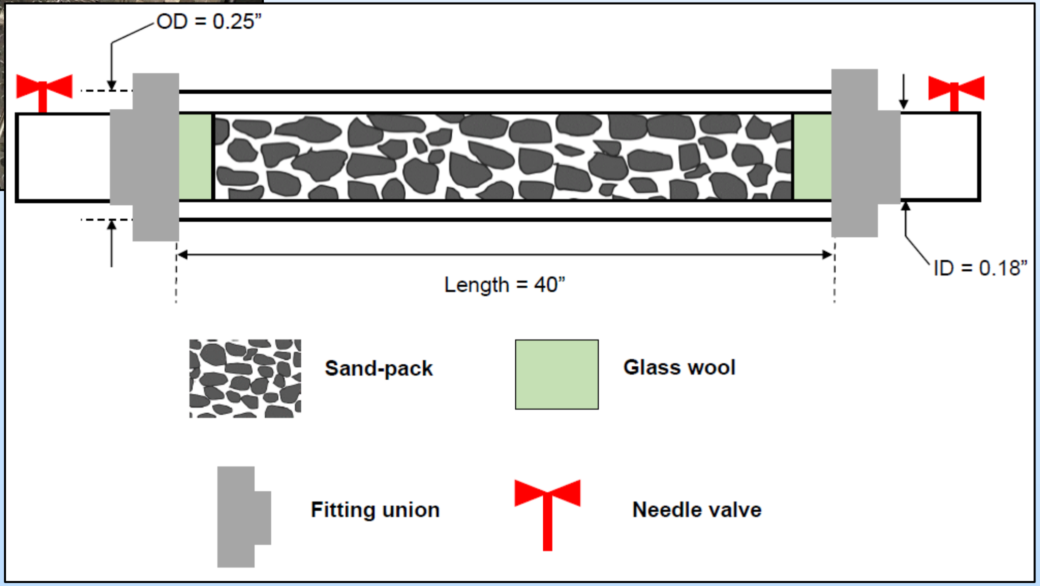
* Planned completion date has been shifted due to COVID-19 pandemic and consequent crash of oil prices.

Foam Evaluation Facility

- **State-of-the-art HPHT Laboratory** designed, fabricated, and commissioned at COIFPM to support Field Pilot Test in Bakken.
- Investigations of **the impacts of foam generation parameters** on foam properties in proppant packs.
- Probes on **dynamic and bulk foam performance analysis**.
- **Identification of superior foaming agents** for field applications.

Foam Evaluation Facility (Cont'd)

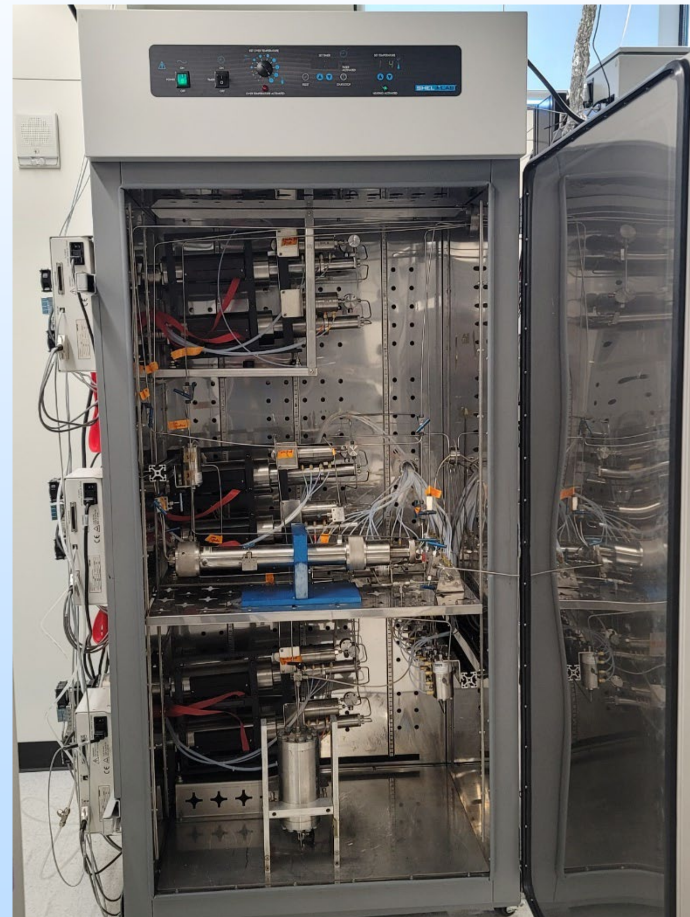




Schematic diagram of the proppant pack placed inside a Hastelloy tubing (Length = 40 inches; Inner diameter = 0.18 inches).

Foam Evaluation Facility (Cont'd)

- The laboratory is also equipped with state-of-the-art **<u>two core-flooding systems</u>** to conduct **<u>Gas Foam EOR</u>** experiments on oil-wet fractured and whole core samples at HPHT, allowing macro-scale probes of various injection scenarios.



Key Attributions of Foam Evaluation Facility

- Capable of conducting **eighteen (18)** experiments simultaneously **at elevated pressure and temperature conditions.**
- The laboratory consists of **10,000 psi** Hastelloy components, Quizix precision pumping systems, and visual cells for safe and efficient HPHT operations.
- **World's largest and most diverse library** of foam data from approximately **1,850 reservoir conditions foam experiments**.
- Allows **Fast-track characterization** of the performance of foaming agents/conformance additives.

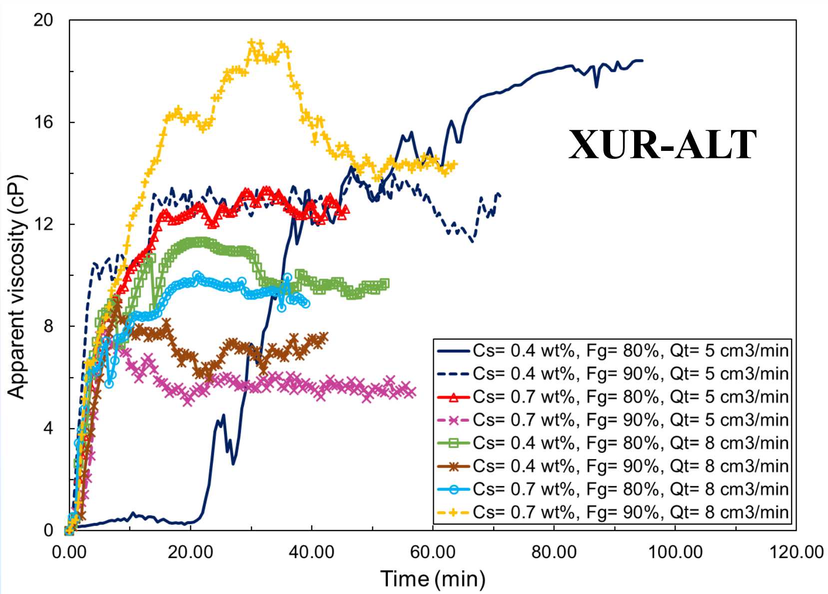
Foam Evaluation Tests

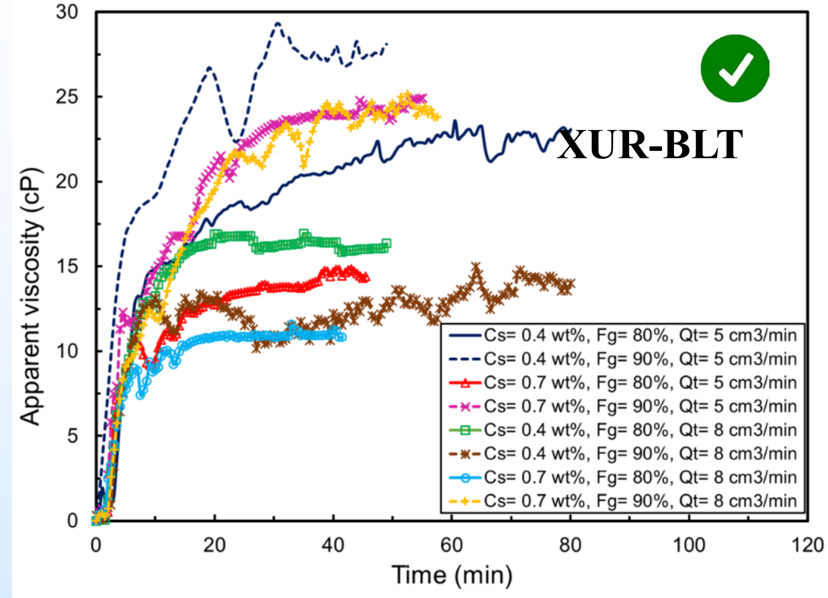
- Approximately **1,850** foam performance evaluation tests have been conducted on proppant packs with different wettability states using methane at reservoir conditions (3,500 psi and 115 °C).
- Sensitivity tests were conducted for various foam generation parameters such as foam quality, total injection rate, concentration, and salinity as well as the operating pressure.
- After an initial screening, surfactants XUR-BLT (denoted as B) and UWYO-A (denoted as D) were chosen for the extensive sensitivity tests. This allowed us to determine foam parameters for optimum foam performance.

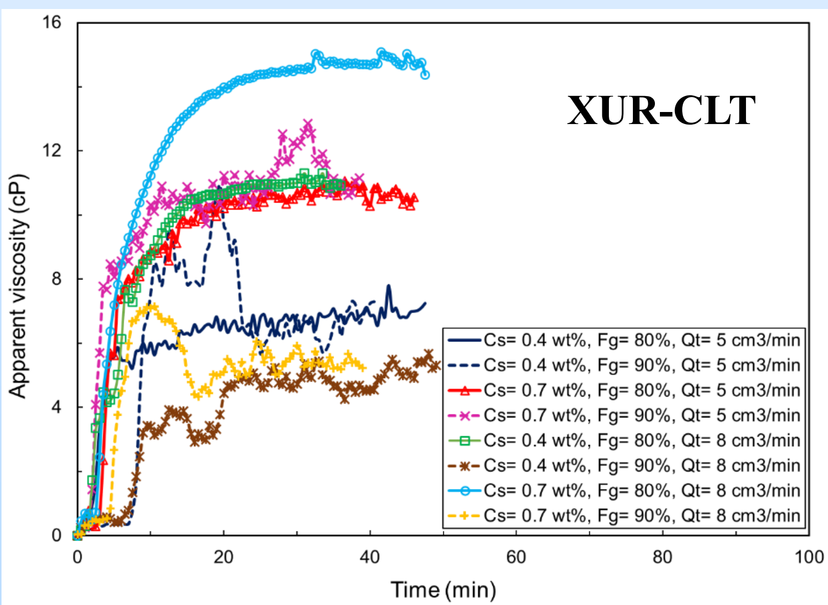
Photos of water-wet (left) and oil-wet proppants (right).

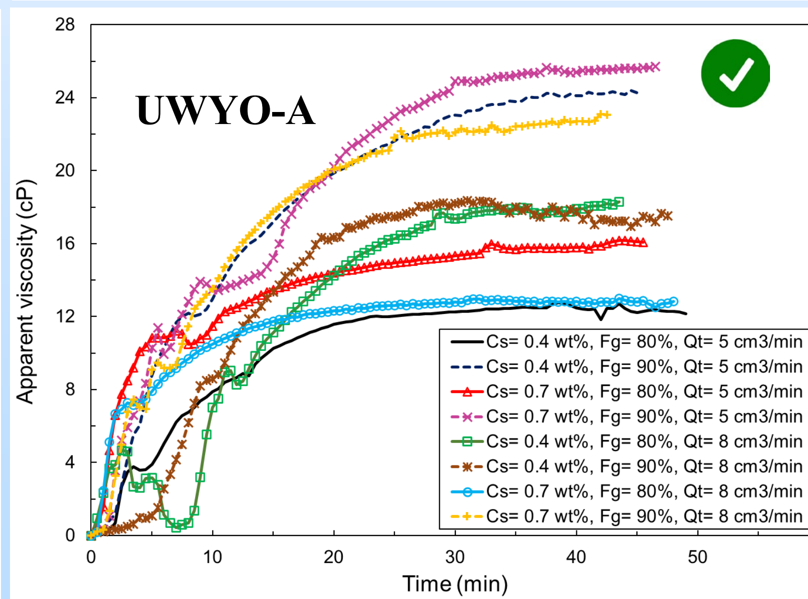
Foam Evaluation Tests (Cont'd)

Foam-induced pressure profiles for different surfactants on water-wet proppant packs





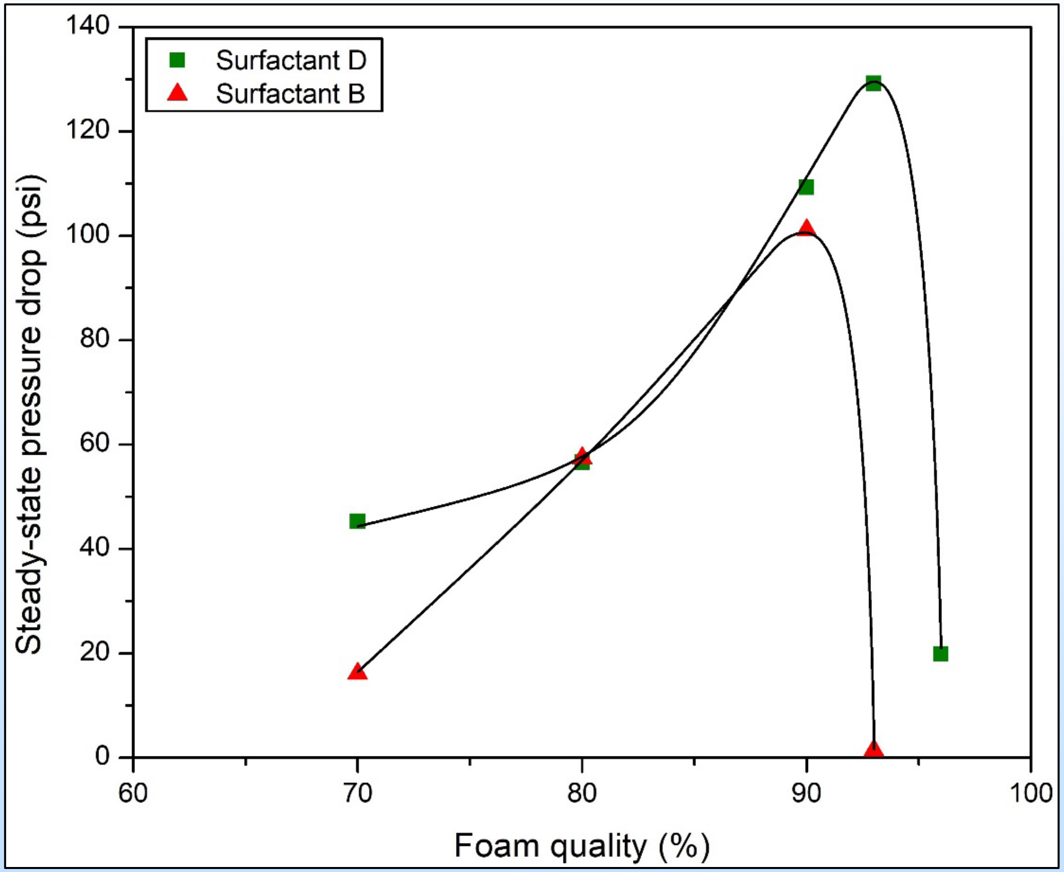




Foam Evaluation Tests (Cont'd)

<u>Foam Quality Sensitivity -- Oil-wet Proppant Packs</u>

Reservoir Conditions



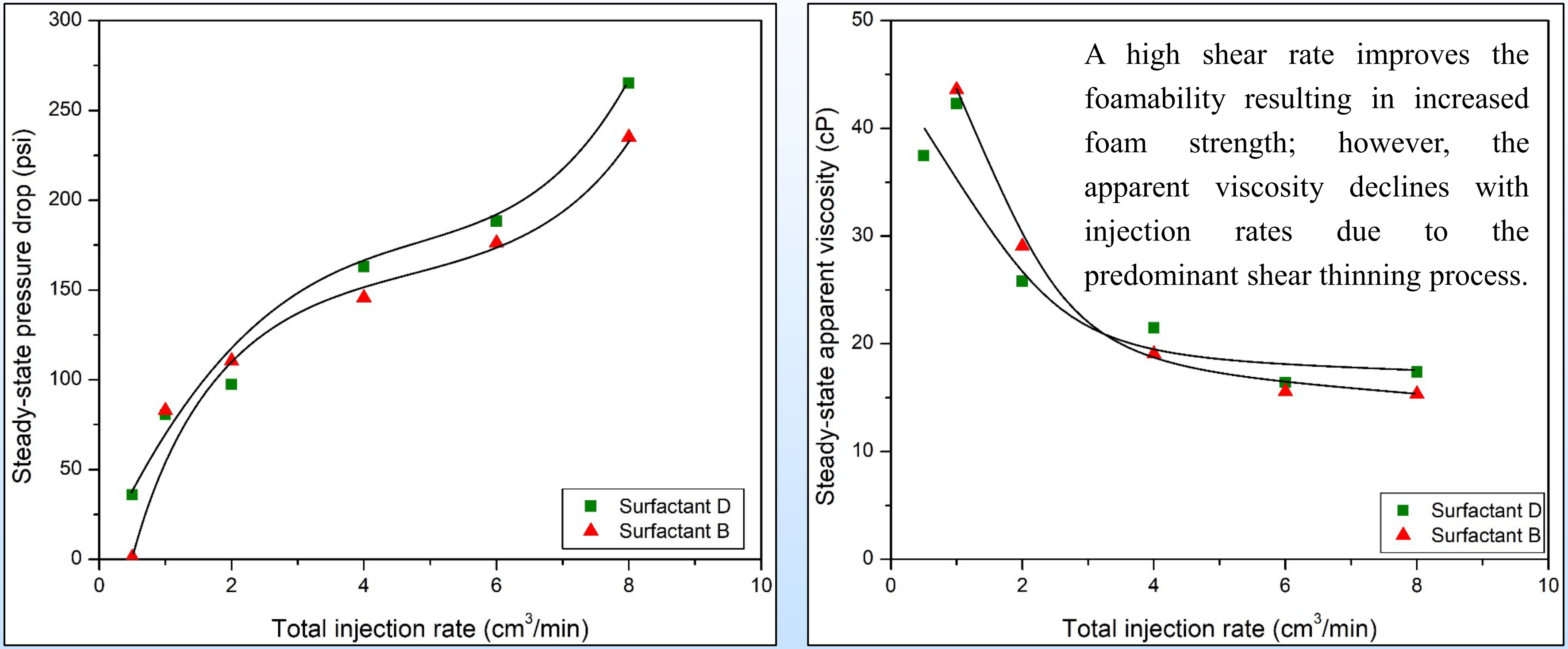
- Anionic surfactant B exhibits lower transition foam quality compared to its counterpart surfactant D.
- Also, surfactant B shows higher sensitivity to foam quality at lower values.

Variations of steady-state pressure drop with changes in foam quality for **<u>surfactants D and B</u>** at 1 cm^3/min total injection rate, 200,000 ppm salinity, 0.4 wt% surfactant concentration, and 10% initial oil saturation.

Foam Evaluation Tests (Cont'd)

<u>Total Injection Rate Sensitivity in Oil-wet Proppant Packs</u>

Reservoir Conditions



Steady-state pressure drop (left) and foam's apparent viscosity (right) variations with changes in the total injection rate for **<u>surfactants XUR-BLT (B)</u>** and **<u>UWYO-A (D)</u>** using synthetic brine of 200,000 ppm salinity, a foam quality of 85%, a concentration of 0.4 wt%, and 10% S_{oi} in oil-wet proppant packs.

Foam Evaluation Tests (Cont'd)

Foam Generation Tests on Oil-wet Proppant Packs using Bakken Produced Water from En-Ortloff and En-Anderson Pads

An image of Bakken-produced brine from **En-Ortloff pad** (as received)

An image of Bakken-produced brine from **En-Anderson pad** (as received)

- Produced brine salinity range: 295,000 - 323,000 ppm
- Presence of solids. Solid particles gradually settle down at the bottom of the container
- Amount of TOC (~9,000 ppm)
- Aqueous solutions of surfactant XUR-BLT in both brines show good stability
- The salinity of En-Anderson water is ~30,000 ppm lower than En-Ortloff water

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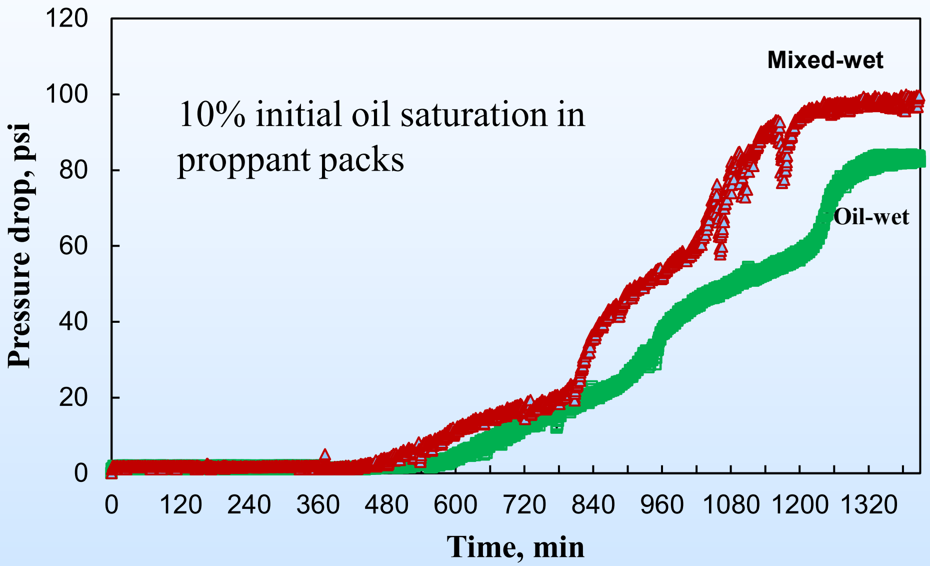
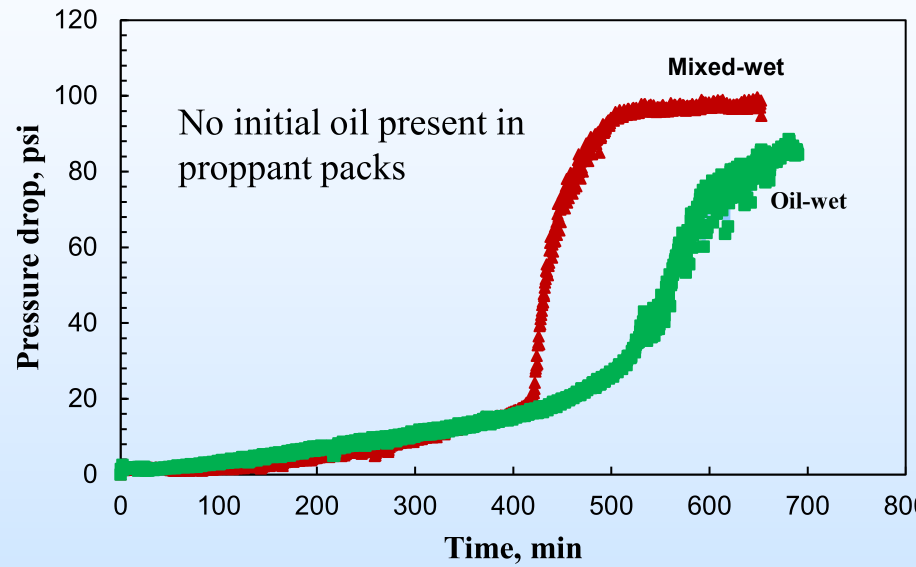
Foam Evaluation Tests (Cont'd)

<u>Foam Generation Tests using Bakken Produced Water from En-Ortloff Pad in Mixed-wet and Oil-wet Proppant Packs</u>

Reservoir Conditions



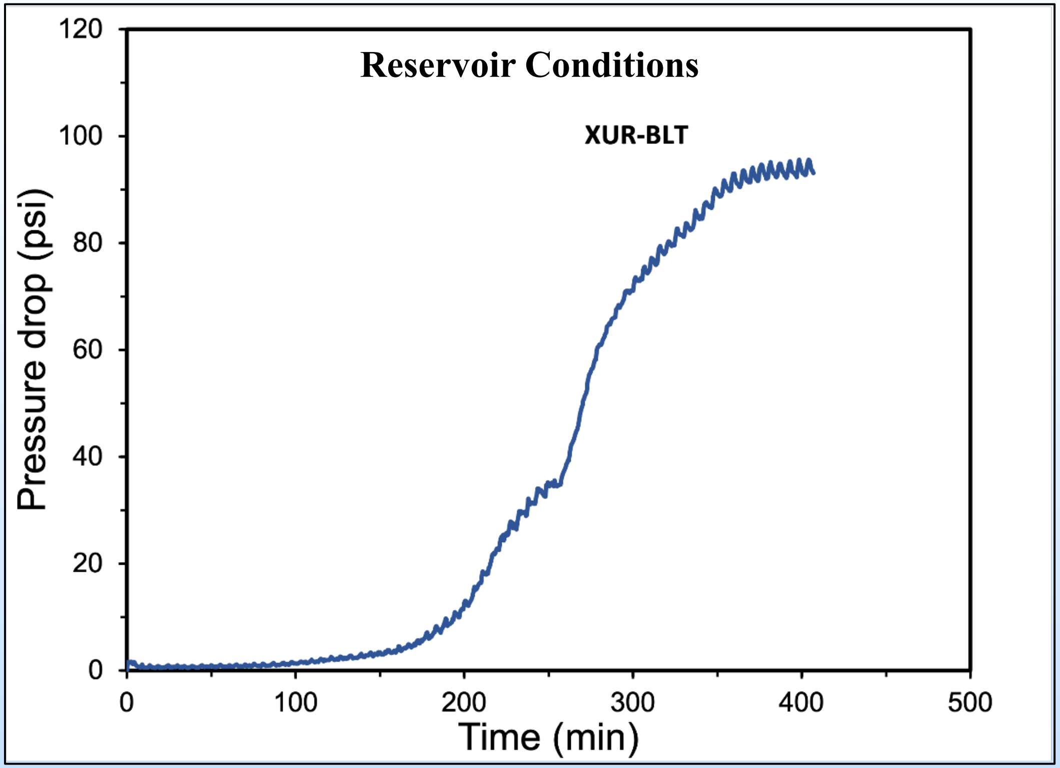


Pressure vs time profiles during foam generation for surfactant B (XUR-BLT) using **En-Ortloff produced water** in **<u>mixed-wet and oil-wet sandpacks with and without initial oil saturation</u>** at 1 cc/min total injection rate, 85% foam quality, and 0.4wt% surfactant concentration.

- Presence of initial oil delays foam generation
- Steady-state foam strength does not show sensitivity to initial oil saturation
- Surfactant B delivers promising foam performance with En-Ortloff-produced water
- Mixed-wet wetting media promotes slightly superior foam performance

Foam Evaluation Tests (Cont'd)

<u>Foam Generation Tests using Bakken Produced Water from En-Anderson Pad in Oil-wet Proppant Packs</u>

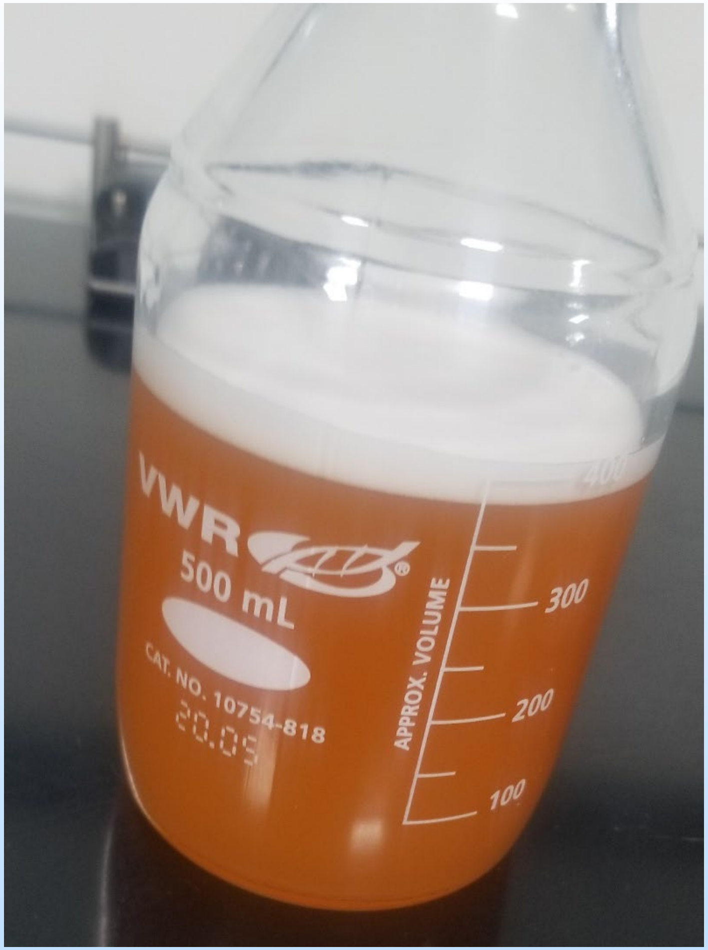


Pressure vs time profile during foam generation for surfactant B (XUR-BLT) using **En-Anderson produced water** in **<u>oil-wet sandpacks</u>** at 1 cc/min total injection rate, 85% foam quality, 0.4wt% surfactant concentration, and 10% Soi.

- Surfactant B produces **<u>remarkable foam strength</u>** with produced water from **<u>En-Anderson pad</u>**.

Foam Evaluation Tests (Cont'd)

Foam Generation Tests on Oil-wet Proppant Packs using Bakken Produced Water from En-Eva Joyce Pad

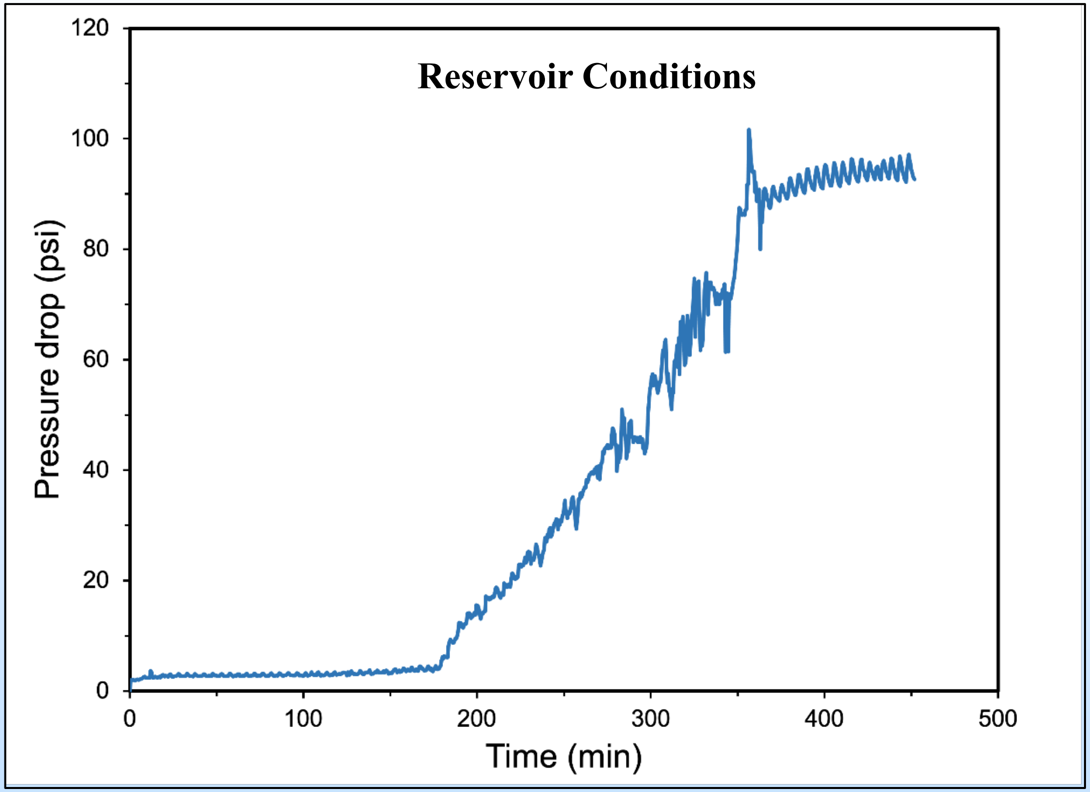


An image of Bakken-produced brine from **En-Eva Joyce pad** (as received)

- Produced brine salinity: **266,000 ppm.**
- **30,000 – 60,000 ppm lower** salinity than other produced brines
- Presence of solids. Solid particles gradually settle down at the bottom of the container
- A much smaller amount of TOC (approximately 3,000 ppm) compared to En-Anderson and En-Ortloff.
- The aqueous solutions of surfactant XUR-BLT show good stability

Foam Evaluation Tests (Cont'd)

<u>Foam Generation Tests using Bakken Produced Water from En-Eva Joyce Pad in Oil-wet Proppant Packs</u>



Pressure vs time profile during foam generation for surfactant B (XUR-BLT) using **En-Eva Joyce produced water** in **<u>oil-wet sandpacks</u>** at 1 cc/min total injection rate, 85% foam quality, 0.4wt% surfactant concentration, and 10% Soi.

- Surfactant B produces **<u>foams of significant strength</u>** with produced water from the **<u>En-Eva Joyce pad</u>**.

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Foam Evaluation Tests (Cont'd)

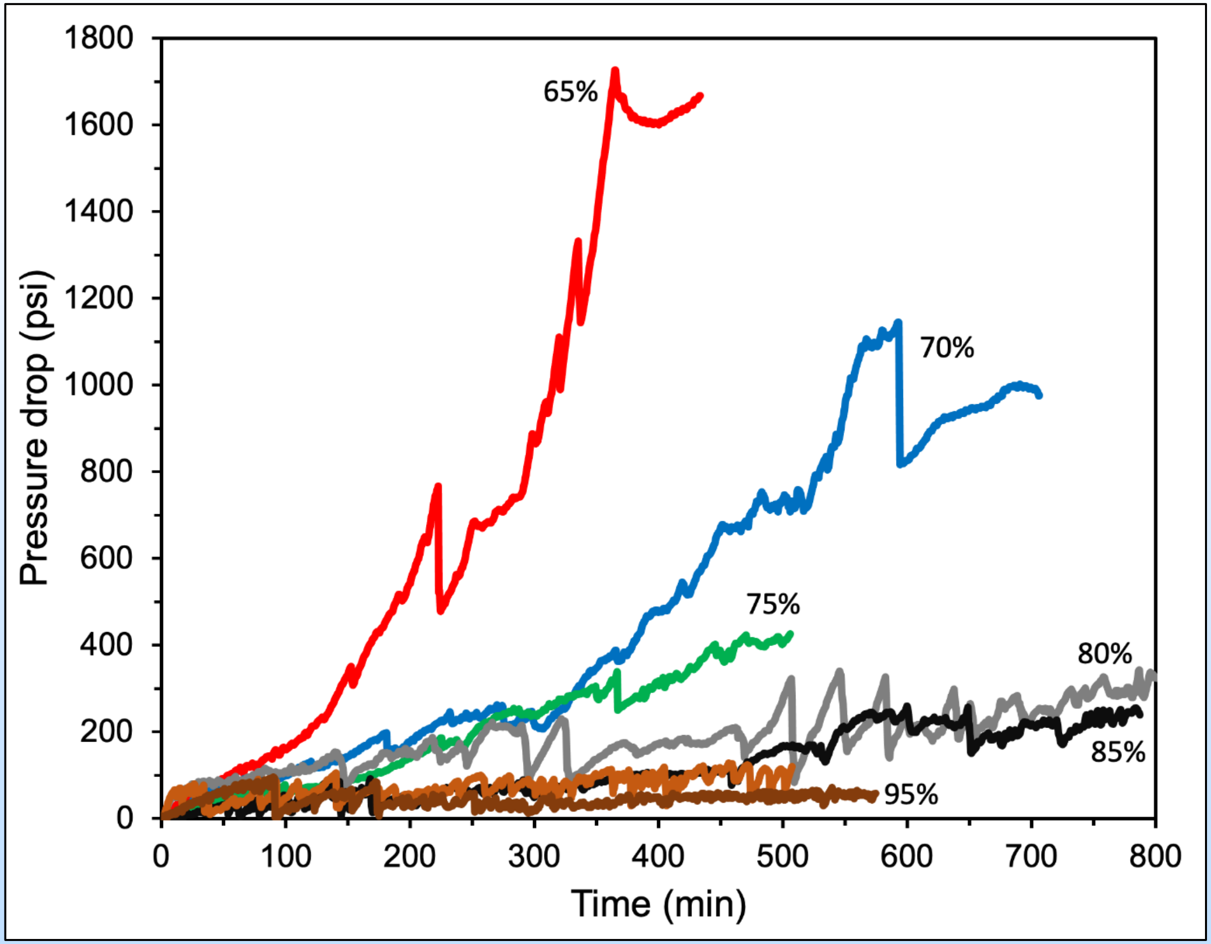
Comparison of the Foam Performance of Produced Water Samples.

Produced Water	**Salinity**	**Steady-state Pressure Drop**
En-Ortloff	340,000 ppm	81.7 psi
En-Anderson	296,000 ppm	88.6 psi
En-Eva Joyce	266,000 ppm	92 psi

Foam Evaluation Tests (Cont'd)

Silica Nanoparticle-stabilized Foam Performance in Oil-wet Proppant Packs

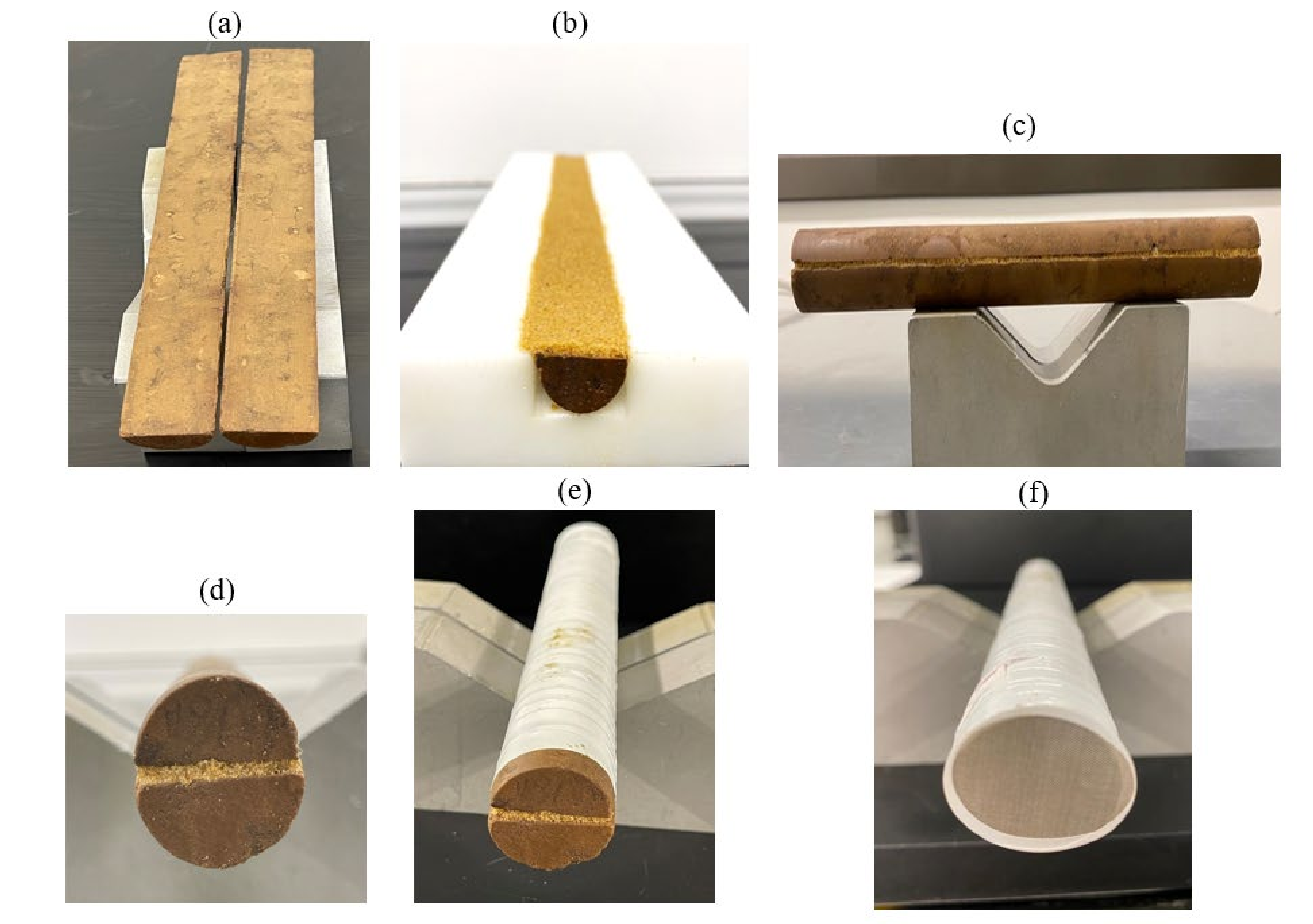
Reservoir Conditions



Pressure vs time profile during foam generation for surfactant UWYO-A using synthetic brine in **oil-wet sandpacks** at 1 cc/min total injection rate, 0.4 wt% surfactant concentration, and 10% S_{oi}.

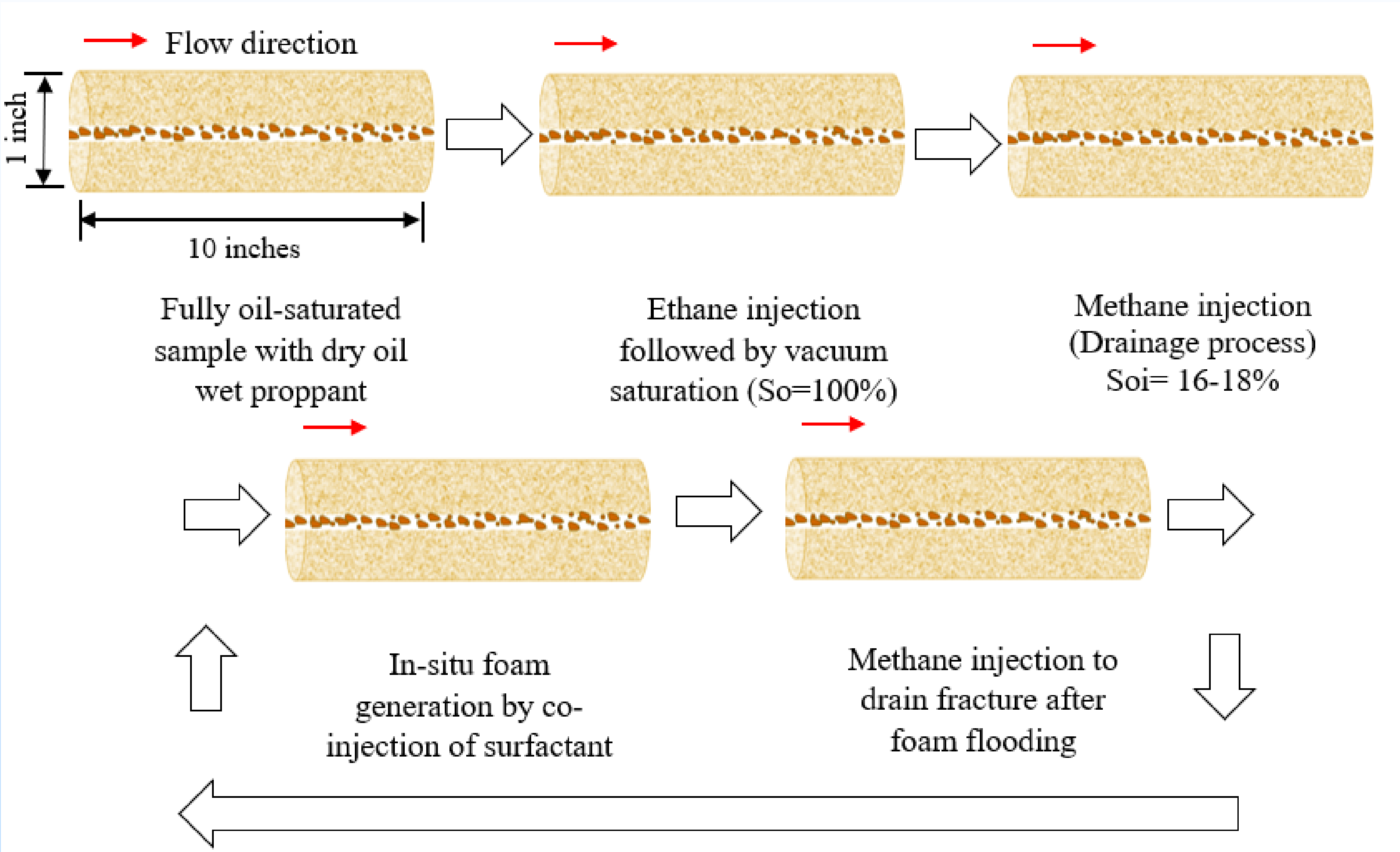
Foam Evaluation Tests (Cont'd)

<u>Macroscale Foam Flooding in Propped Fractured Oil-wet Cores</u>



Foam Evaluation Tests (Cont'd)

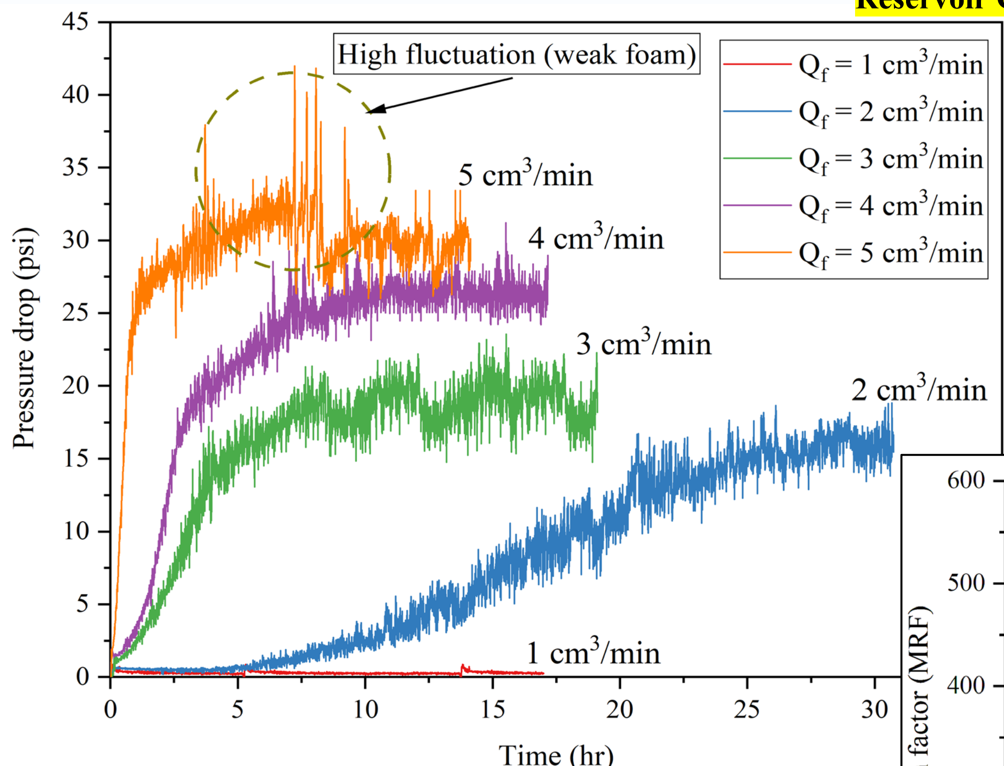
Macroscale Foam Flooding in Propped Fractured Oil-wet Cores



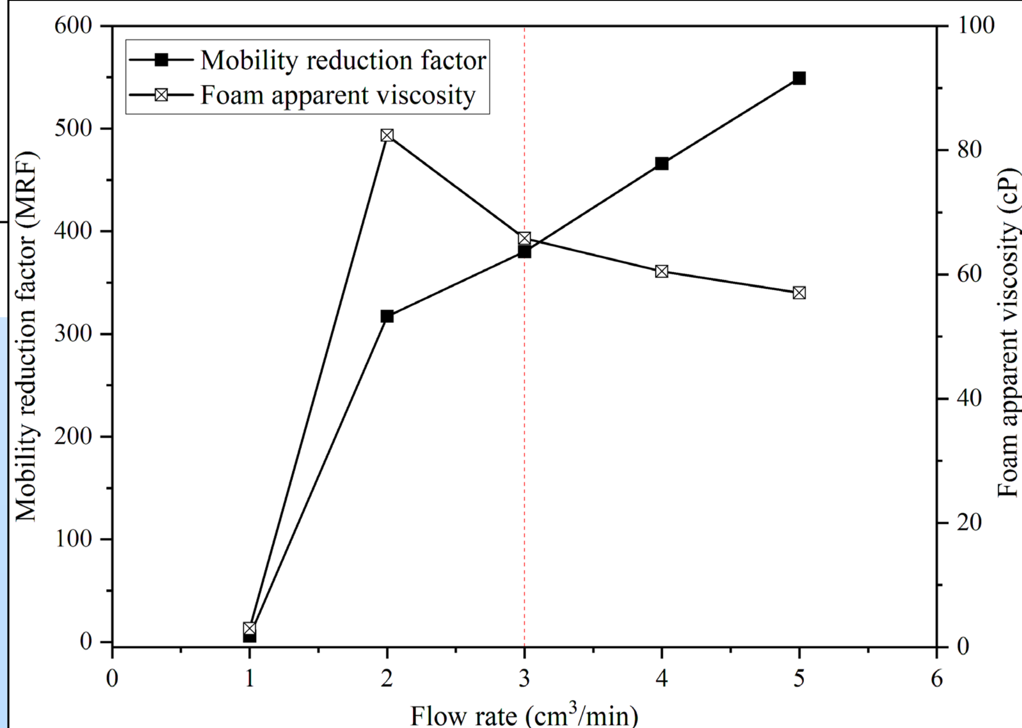
Foam Evaluation Tests (Cont'd)

Foam Generation and Performance Evaluation in Propped Fractured Oil-wet Cores

Reservoir Conditions



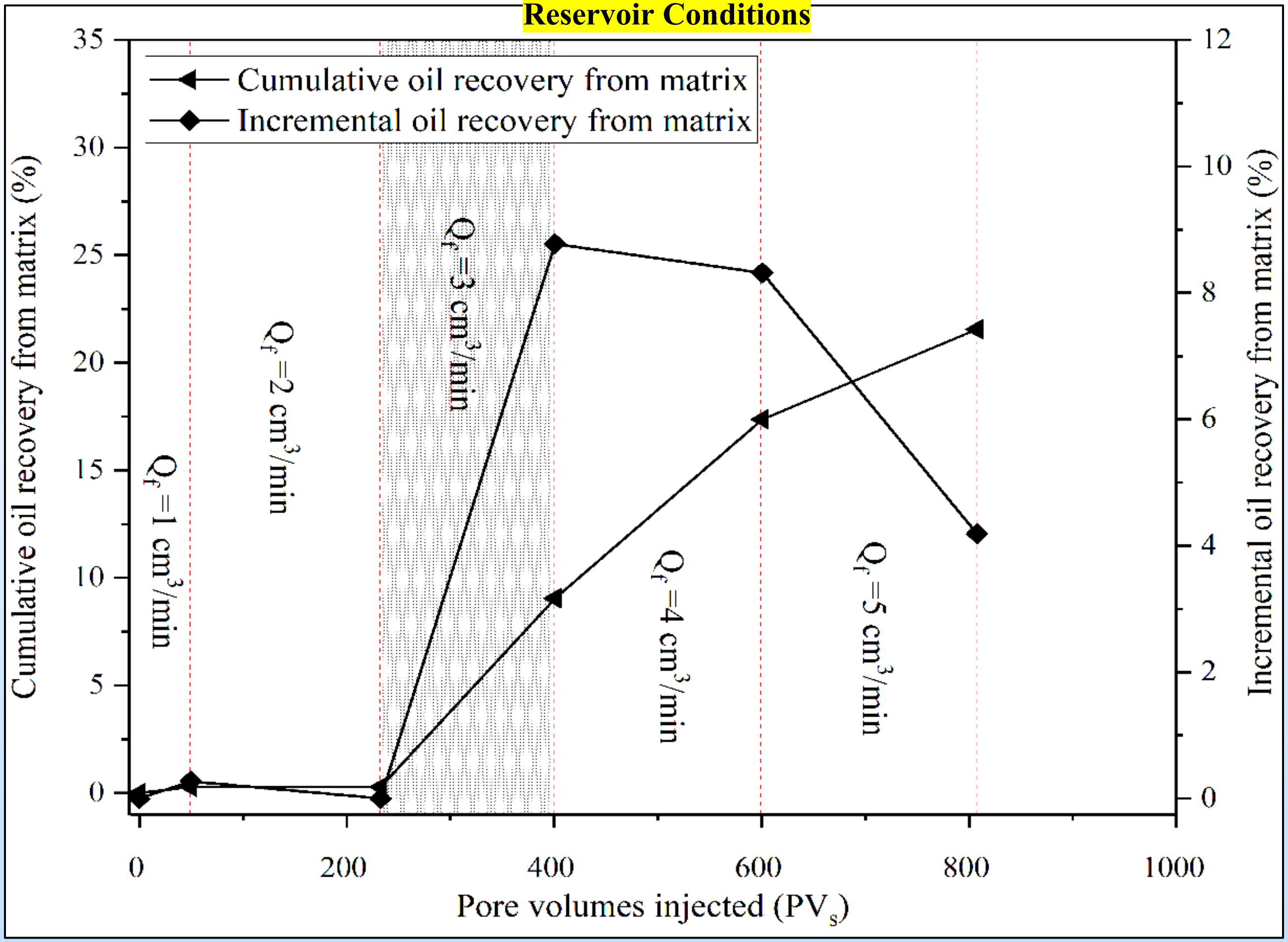
Pressure drop history during foam flooding at different injection rates and 85% foam quality using surfactant XUR-BLT



Variations in the mobility reduction factor (MRF) and foam apparent viscosity at varying flow rates for surfactant XUR-BLT.

Foam Evaluation Tests (Cont'd)

Foam-induced Oil Recovery in Propped Fractured Oil-wet Cores

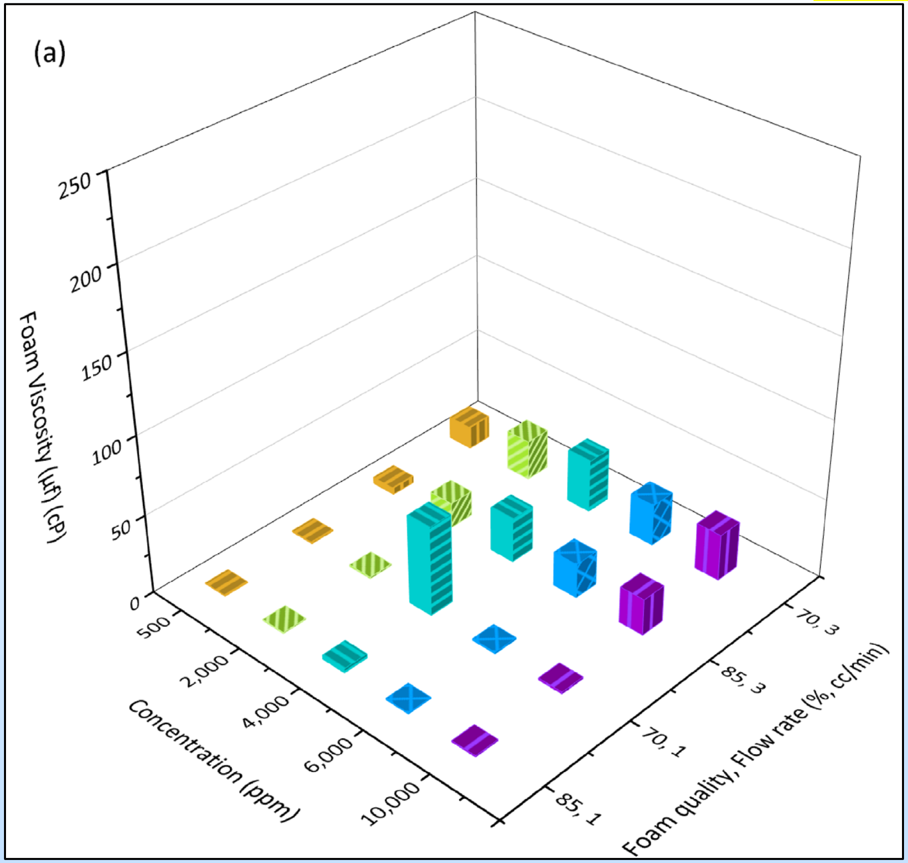


Cumulative and incremental oil recoveries at the end of foam flooding using surfactant XUR-BLT at varying flow rates and 85% foam quality.

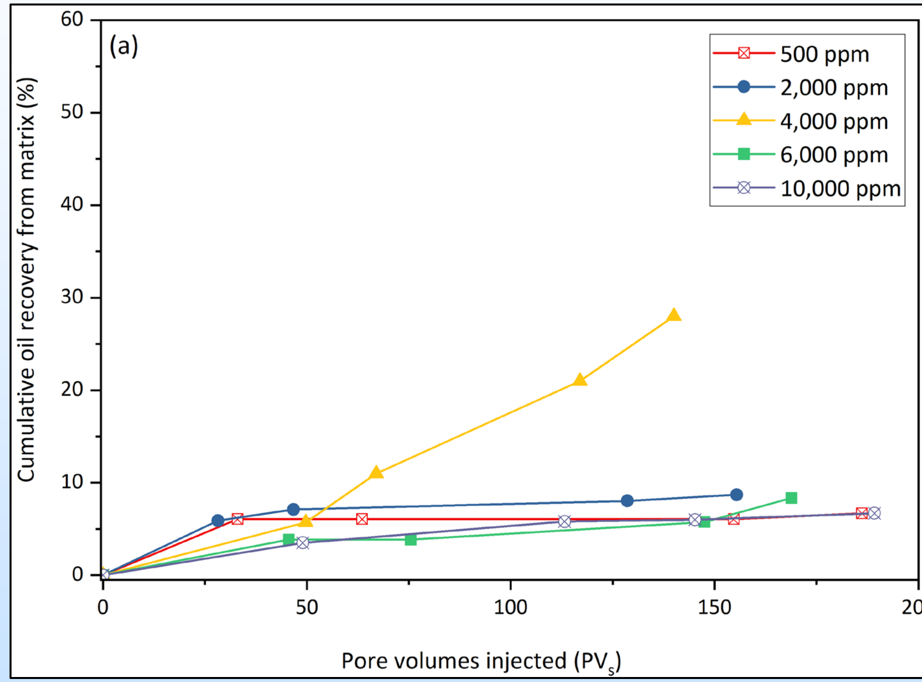
Foam Evaluation Tests (Cont'd)

Effect of Foam Parameters on Foam Performance in Propped Fractured Oil-wet Cores

Reservoir Conditions



Variation in the foam's apparent viscosity with changes in concentrations, flow rates, and foam qualities for Surfactant XUR-BLT.



Oil recovery from the matrix at the end of foam flooding at varying concentrations of Surfactant XUR-BLT.

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PROJECT SPIRO
HESS

Project Spiro Overview

8

Huff-n-Puff cycles

Inject into one well
Produce from all

4

Injection Wells

30 days injection
45 days production

2

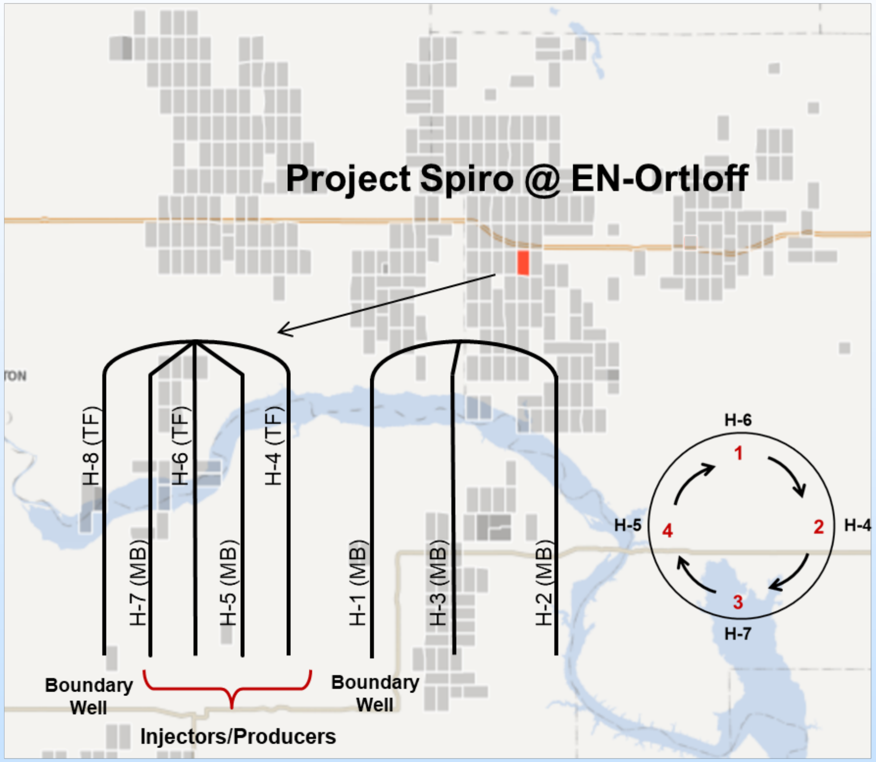
Years

30 days injection
45 days production

250

MMSCF

per well injection
~2 BCF over 8 cycles



Status of the Project

Introducing the gas to the pad for the first time
August 8

- Key updates
  - Site commissioned (Jul)
  - Baseline data gathering completed (Aug)
  - Pre-injection tests highlighted critical compressor issues (Sep)
  - Compressor upgrade completed (Dec)
  - Site recommissioned (Jan)

- Cycle #1
  - Injection started in January
  - Injection stopped in February due to check-valve failures
  - Repairs to be completed by April 4
  - Production cycle to begin April 4-10

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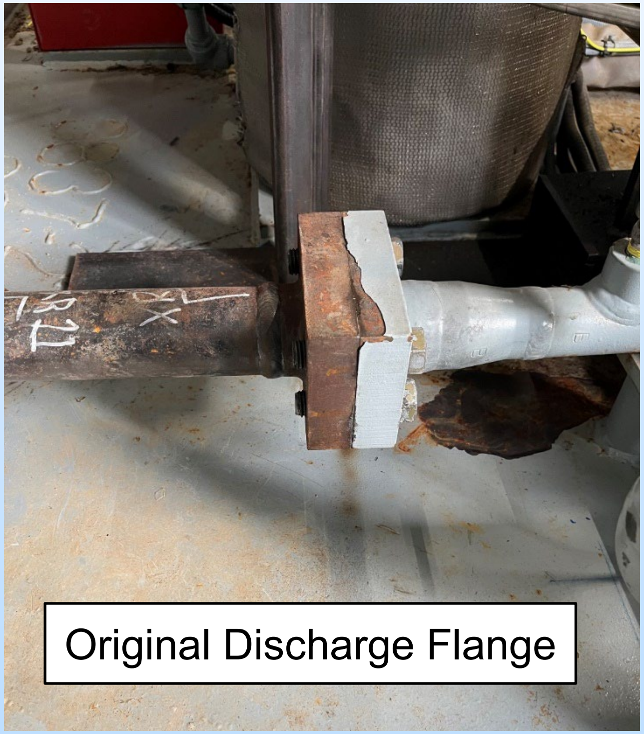
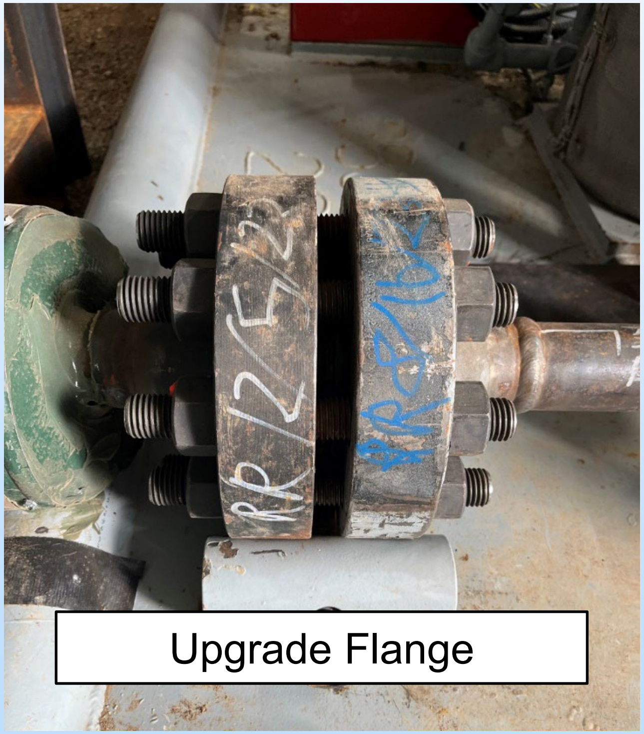
Major Compressor Upgrade

- Pre-injection tests in September identified issues with compressors
  - A potential weak point was the type of flanges used in the discharge piping
  - Upgrade required extensive modifications including long lead-time items



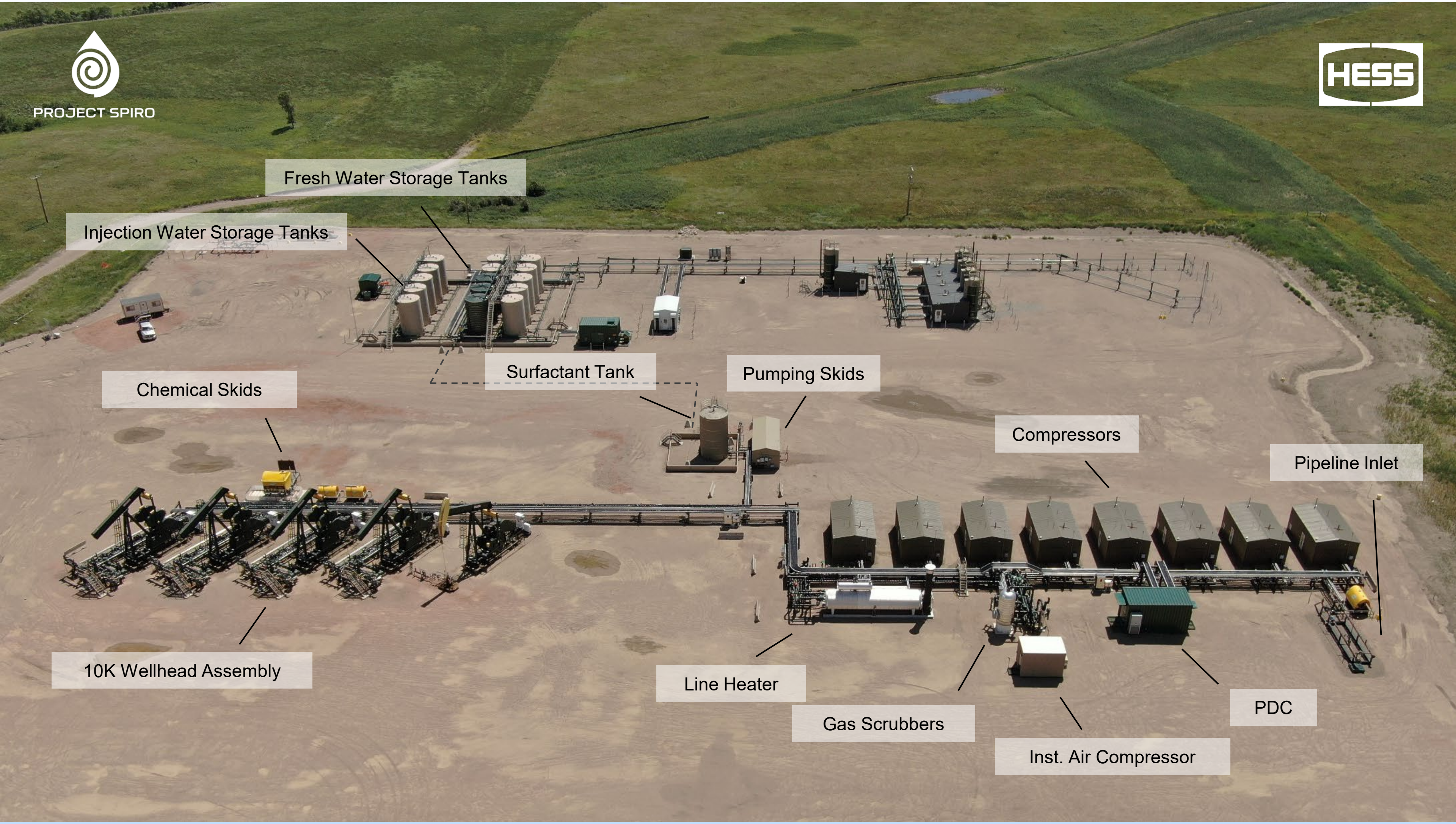
Original Discharge Flange

→



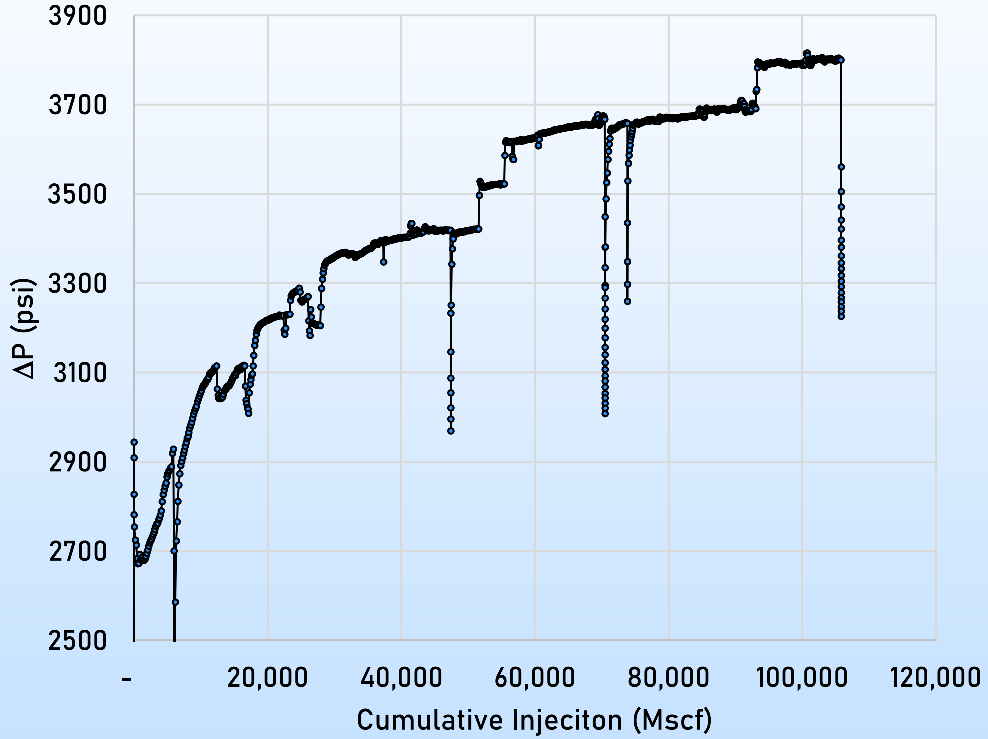
Upgrade Flange

The Site


PROJECT SPIRO
HESS
Fresh Water Storage Tanks
Injection Water Storage Tanks
Chemical Skids
Surfactant Tank
Pumping Skids
Compressors
Pipeline Inlet
10K Wellhead Assembly
Line Heater
Gas Scrubbers
Inst. Air Compressor
PDC

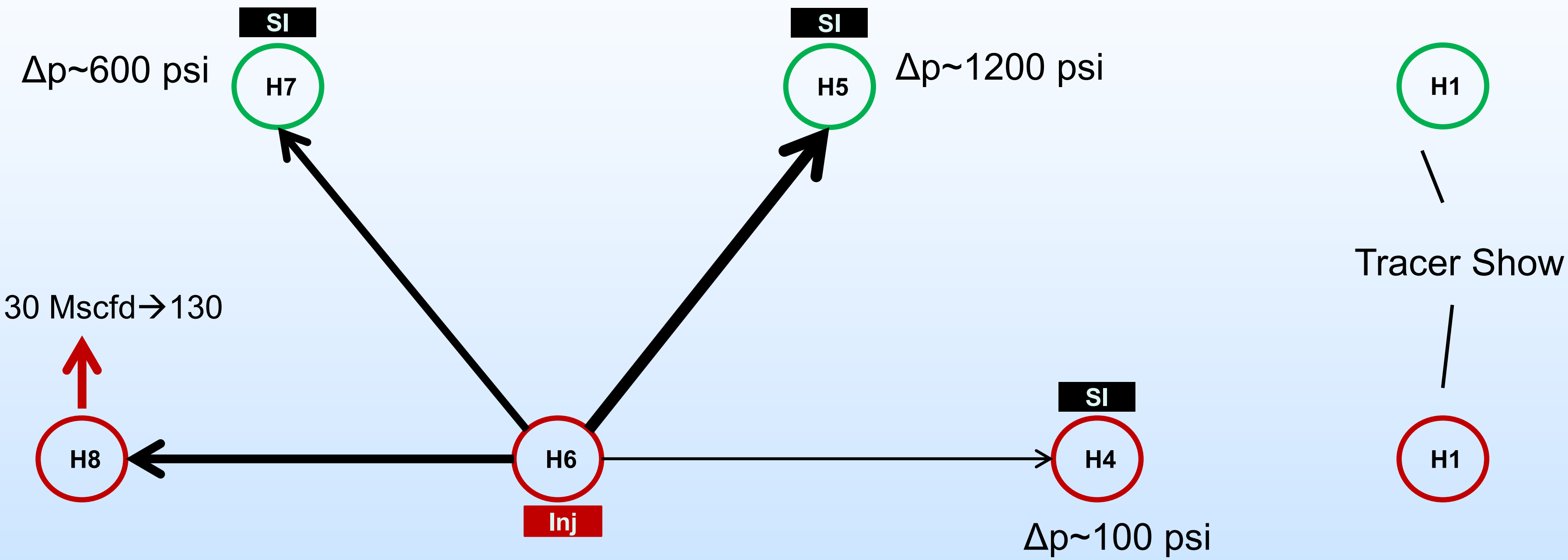
Cycle #1 Injection

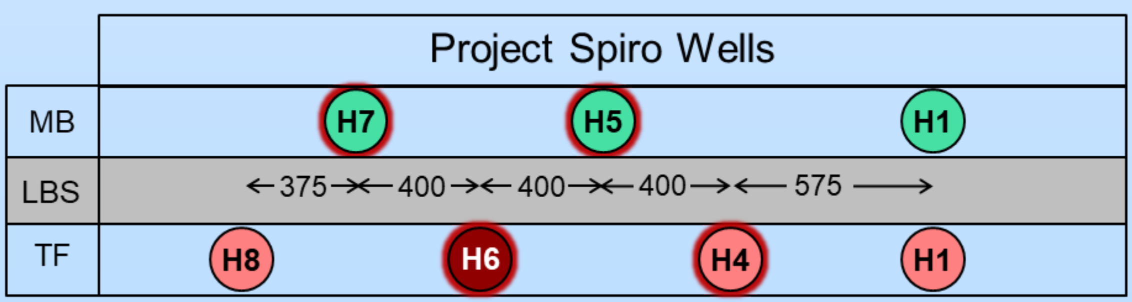
- Injected ~100 MMscf (gas-only)
  - One well only (H-6)
  - Replaced 20-30% of the well production
- Early pressure response in neighboring wells
- Early breakthrough in H-8
- Injected tracers in 3 intervals
  - Possible tracer show in an offset pad
  - Resampled fluid for verifications
- Pressure analysis suggests
  - Limited leaks out of the well
  - Matrix is pressurized



BHP Pressure Increase with Cumulative Injection

Communication to Neighboring Wells





Current Status

- Site is shut-in due to check valve failures; two root causes are identified

  (1) Compressor pulsation → all check valves were replaced

  (2) Debris in the discharge piping → piping removed and hydro-washed

Damaged swing check-valve

Debris seen in discharge pipe

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The Schedule

Item	Date
Cycle #1 Production	April 8
Fluid Sampling	April 8 – April 31
Cycle #2 Injection	May 1 – 10
Cycle #2 Production	June 15 – 25

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What is Next

- Production cycle will generate valuable insights

Category	Learning	Favorable Outcome
HP Production	Test the facility, procedure, and the site logic.	No issue
Production Rates	Fine tune the sim model	Fall within the modeled response
Pressure Responses	Baseline to foam; connectivity in the pad	Slow decline toward the pre-injection pressure
Production GOR	Gas dissolution into oil	Stabilized GOR is higher than 1400 scf/day
Fluid Sampling	Effectiveness of gas/oil mixing	Enriched produced gas composition with the lighter components of oil


PROJECT SPIRO

Summary

- Characterized the chemical and petrophysical properties of Bakken and Three Forks reservoir rocks and their interactions with brine/oil/surfactants.
- Completed the fabrication of a state-of-the-art foam generation system. This high-throughput foam generation system includes six modules, housing eighteen (18) foam generators in total.
- Fabricated and commissioned an experimental setup with two core flooding systems to probe the performance of several foam injection schemes in propped fractured oil-wet cores.
- Identified best-performing 3 phase-stable, freeze-protected, low-adsorbing, low-viscosity, and non-emulsifying foaming formulations for the harsh Bakken field conditions.
- Conducted more than **1,850** foam evaluation tests on water-wet, oil-wet, and mixed-wet sandpacks at reservoir conditions using surfactants from Dow Chemical Company and UW.
- Foam performance sensitivities of the chosen surfactants were evaluated with respect to various foam generation parameters, including, salinity, total flow rate, foam quality, concentration, oil saturation, and operating condition such as pressure.
- Identified the optimized values of foam parameters and operating conditions that result in optimum foam performance.

Summary (Cont'd)

- Evaluated the foam performance of selected surfactants in the produced water from Bakken formation pads, including En-Ortloff, En-Anderson, and En-Eva Joyce, on proppant packs of different wettability and probed the feasibility of using produced water for aqueous solution during the foam pilot.
- Performed FAGI tests on propped fractured cores under different conditions. Using macro-scale core-flooding experiments, we investigated the effect of foam injection into the fracture on oil recovery, and study the interactions between the matrix and fracture under different flow conditions.
- Probes on foam generation and performance evaluation of nanofluids of selected chemicals and silica nanoparticles are ongoing.
- First cycle started in January
  - Injected gas without foam as a baseline to future foam injection
  - Production cycle to begin in early April

Future Plans

- Optimizing the injection strategy towards the desired production enhancement during the foam pilot.
- Producing large quantities of the foaming formulation required for the field trial.
- Continue HPHT foam evaluation tests and optimization of foam performance of selected surfactants for cycle #2 using produced water from different pads from Bakken field on oil-wet proppant packs and evaluate the consistency in the foam performance.
- Performing FAGI tests on aged propped fractured cores under different conditions. Using macro-scale core-flooding experiments, we will investigate the effect of foam injection into the fractures of varying conductivities on oil recovery, and study the interactions between the matrix and fracture under different flow conditions.
- Complete the cycle #1 with production cycle
  - Production cycle to bring valuable insight regard the gas injection EOR
  - Compare the simulation model with the field data and update the model
  - Evaluate and update the injection plan for the second cycle

Thank you!

Gantt Chart

		Oct 2019 – Sep 2020				Oct 2020 – Sep 2023											
Task #	Description	Budget Period 1				Budget Period 2 (Including No Cost Time Extension)											
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
1	Project Management and Planning	4%	8%	12%	16%	20%	24%	28%	32%	36%	40%	44%	48%	52%	56%	60%	64%
2	Reservoir Rock and Fluid Properties	27%	50%	75%	95%	98%	99%	100%									
3	Surfactant Screening and Foam Optimization	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%
4	Multi-scale Core-flooding Experiments of Foam-assisted Gas Injection in Fractured Rock	4%	8%	11%	16%	20%	24%	27%	32%	36%	40%	43%	48%	52%	55%	59%	64%
5	Multi-scale Modeling, Simulation, and Optimization	4%	8%	12%	16%	20%	24%	28%	32%	36%	40%	44%	48%	52%	56%	60%	64%
6	Field Operations and Optimization	25%	50%							60%	70%	80%	85%	90%	95%	95%	100%
7	Field Pilot Test in Bakken																

Delays due to COVID-19 pandemic

Adjusted schedule due to COVID-19 pandemic

Gantt Chart (Cont'd)

		Oct 2023 – Sep 2024				Oct 2024 – Sep 2025			
Task #	Description	Budget Period 3				Budget Period 4			
		Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24
1	Project Management and Planning	68%	72%						
2	Reservoir Rock and Fluid Properties								
3	Surfactant Screening and Foam Optimization	85%	90%						
4	Multi-scale Core-flooding Experiments of Foam-assisted Gas Injection in Fractured Rock	68%	72%						
5	Multi-scale Modeling, Simulation, and Optimization	68%	72%						
6	Field Operations and Optimization								
7	Field Pilot Test in Bakken								

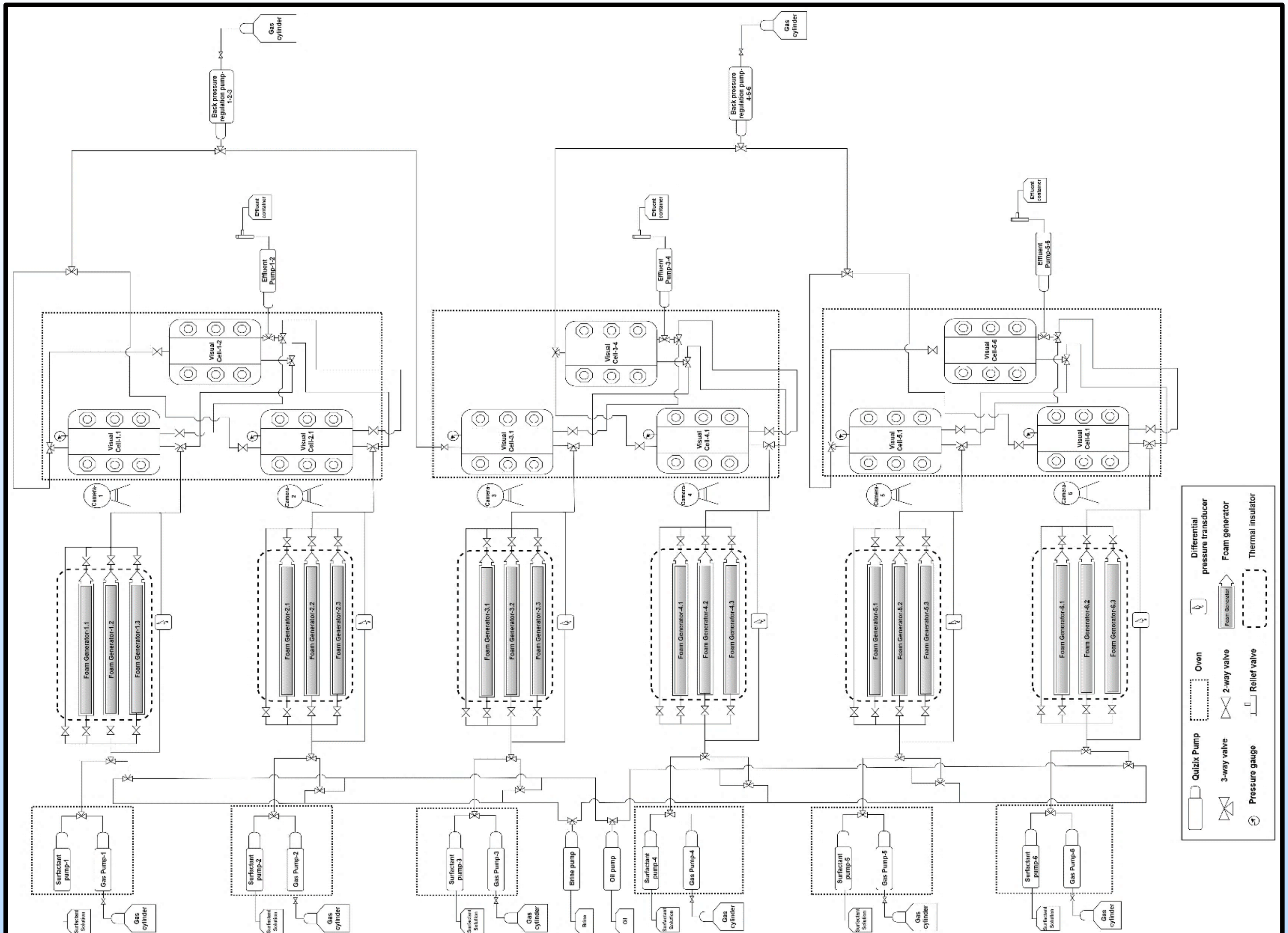
Appendix

The following items are included in the Appendix

I. Schematic of the state-of-the-art foam generation platform
II. Schematic of the miniature core-flooding apparatus
III. Wettability characterization of proppants
IV. Additional foam evaluation results

Appendix-I

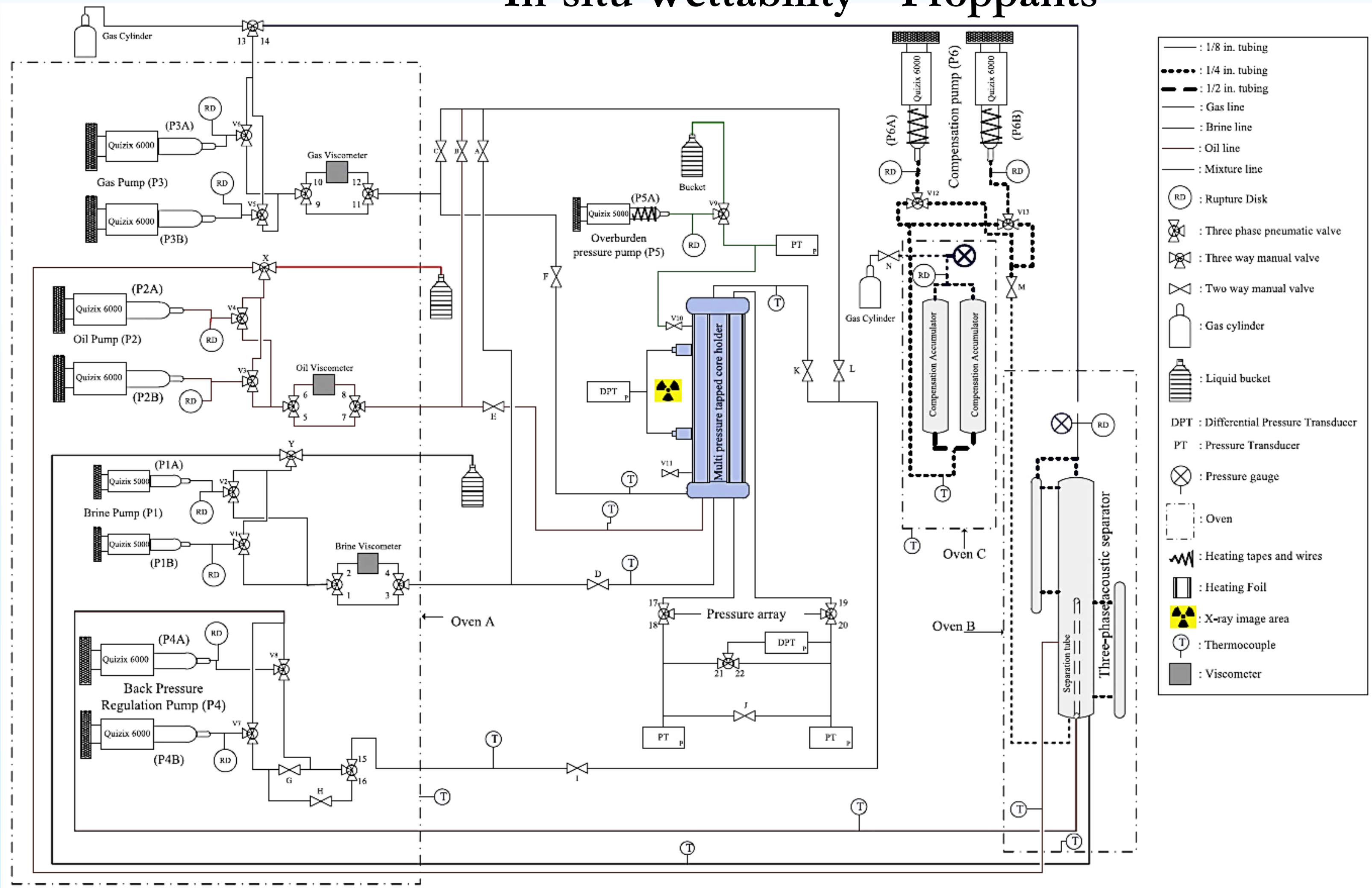
- State-of-the-art foam generation system design:



Appendix-II

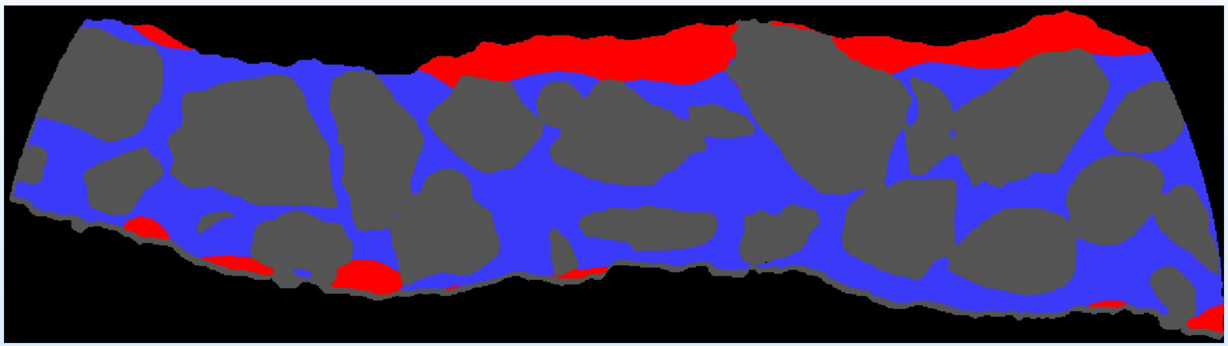
- A typical core-flooding apparatus used in this project:

In-situ Wettability – Proppants

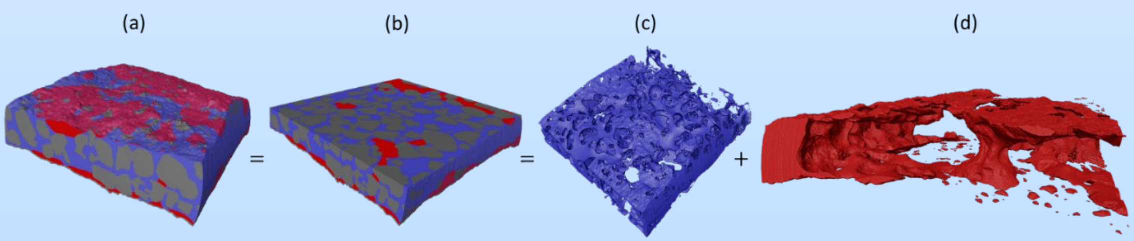


Appendix-III

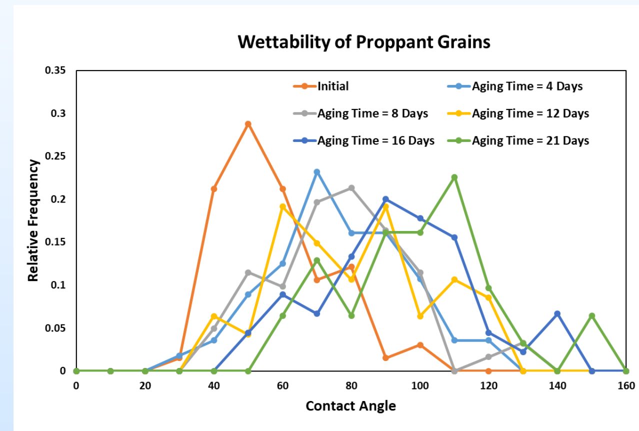
- A HPHT three-phase miniature core-flooding system integrated with a high-resolution x-ray micro-CT scanner was used to perform core-flooding tests on a miniature fractured reservoir rock sample for the purpose of proppant and fracture wall in-situ wettability characterization.

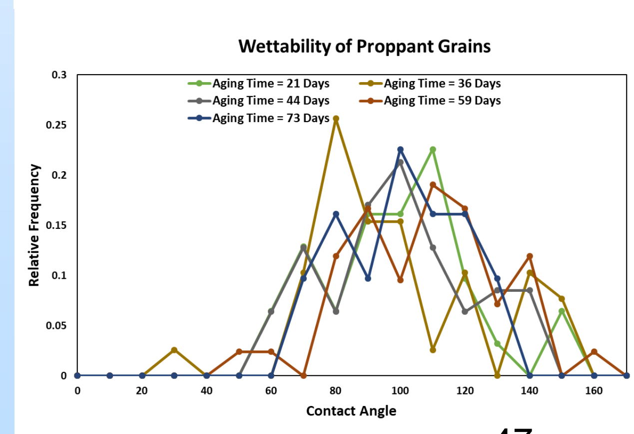


A segmented image of a slice obtained after introducing the doped oil into the proppant pack (red, blue, and gray represent oil, brine, and and proppant grains, respectively).



(a) Segmented fluid occupancy map, (b) fluid distribution in the middle of the fracture, (c) preferential fluid occupancy for brine, and (d) distribution of oil in the proppant pack.

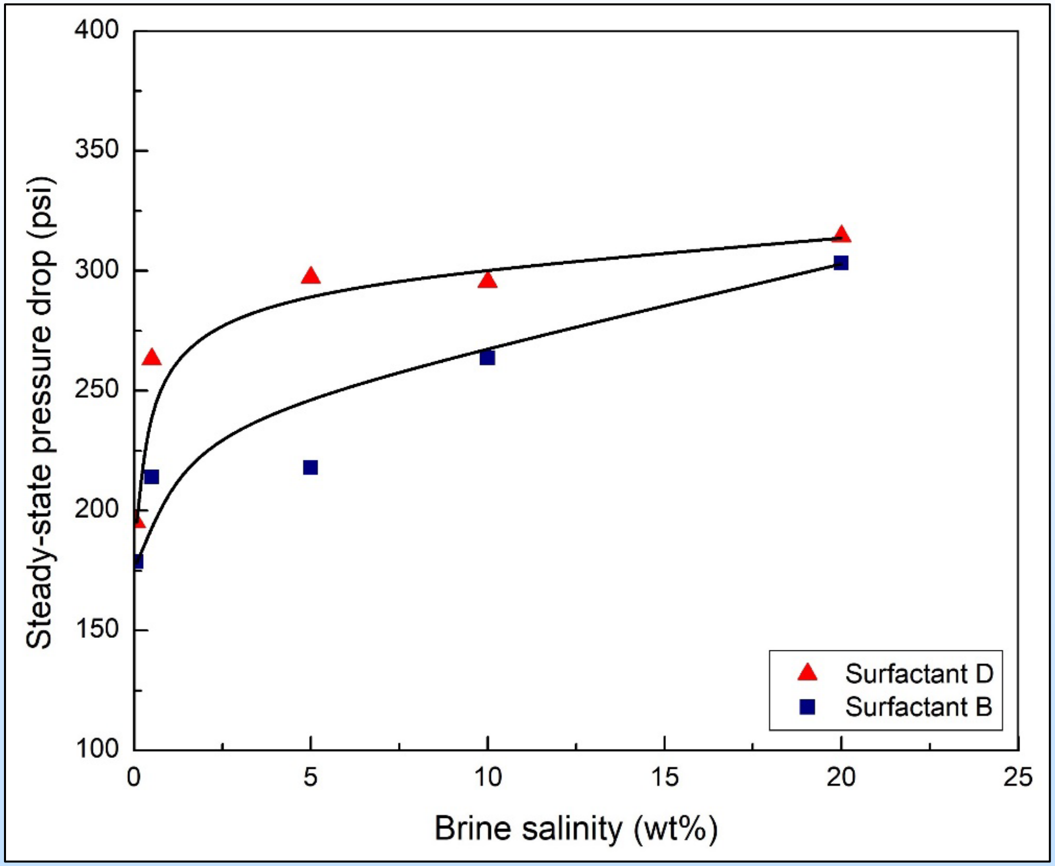




Appendix-IV

Salinity Sensitivity -- Water-wet Proppant Packs

Reservoir Conditions



- An increase in brine salinity causes less ionic repulsions among the surfactant's anionic headgroups and improves electrical double-layer (EDL) structures, resulting in enhanced foam strength.

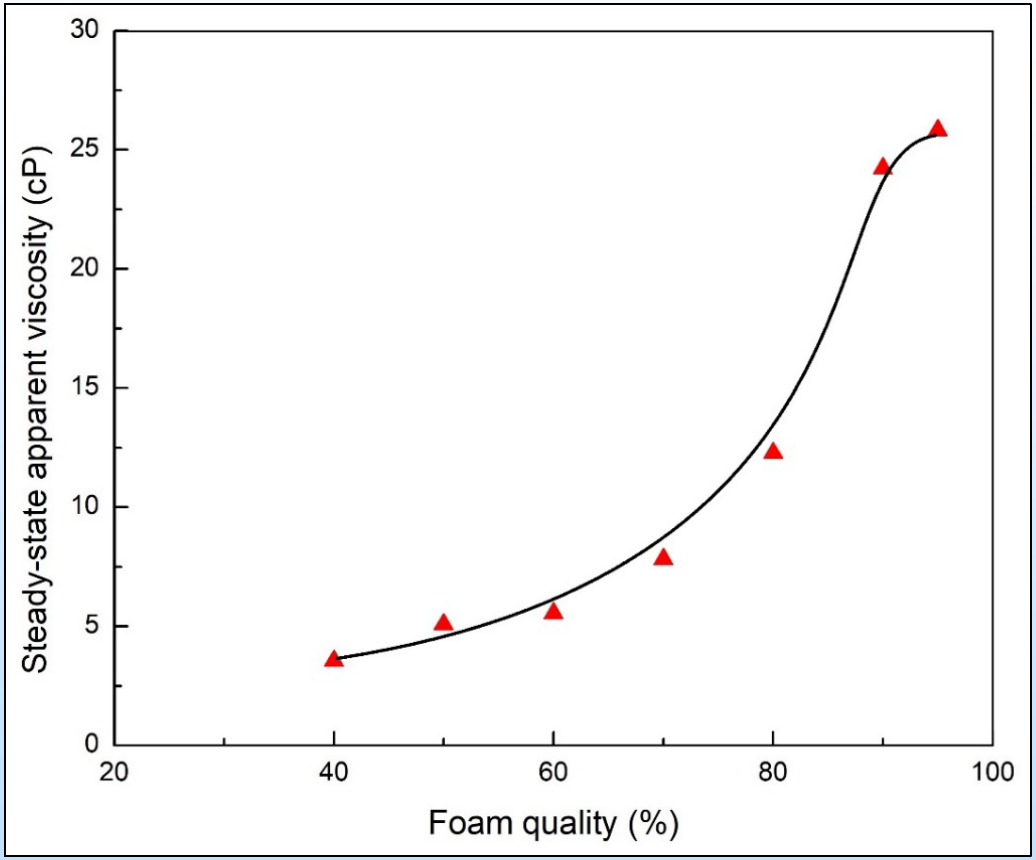
- Amphoteric surfactant D contains cations and anions along with foam stabilizers that provide more stability to foam lamella even at low salinities and increases the foam strength.

Steady-state pressure drop (foam strength) variation with changes in aqueous solution salinity for surfactants UWYO-A (D) and XUR-BLT (B) using synthetic brine at a foam quality of 90%, a concentration of 0.7 wt%, and the total injection rate of 5 cc/min in water-wet proppant packs.

Appendix-IV (Cont'd)

Foam Quality Sensitivity -- Water-wet Proppant Packs

Reservoir Conditions



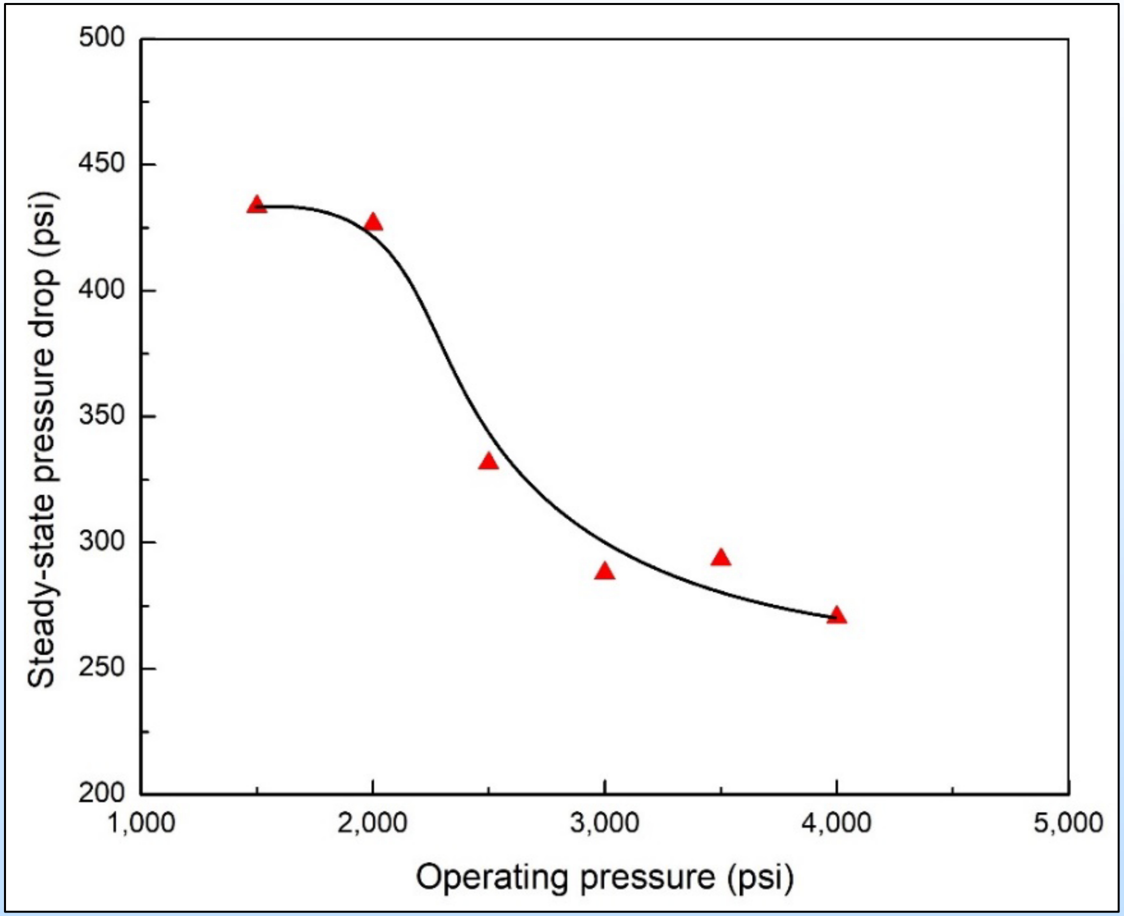
Variations of steady-state apparent viscosity with increasing foam quality for **surfactant D** at a total injection rate of 5 cm^3/min and a surfactant concentration of 0.4 wt%.

- Amphoteric surfactant D generates foams with remarkable strength at high foam qualities, extending the transition gas fraction to above 90%.

Appendix-IV (Cont'd)

Operating Pressure Sensitivity -- Water-wet Proppant Packs

Reservoir Conditions



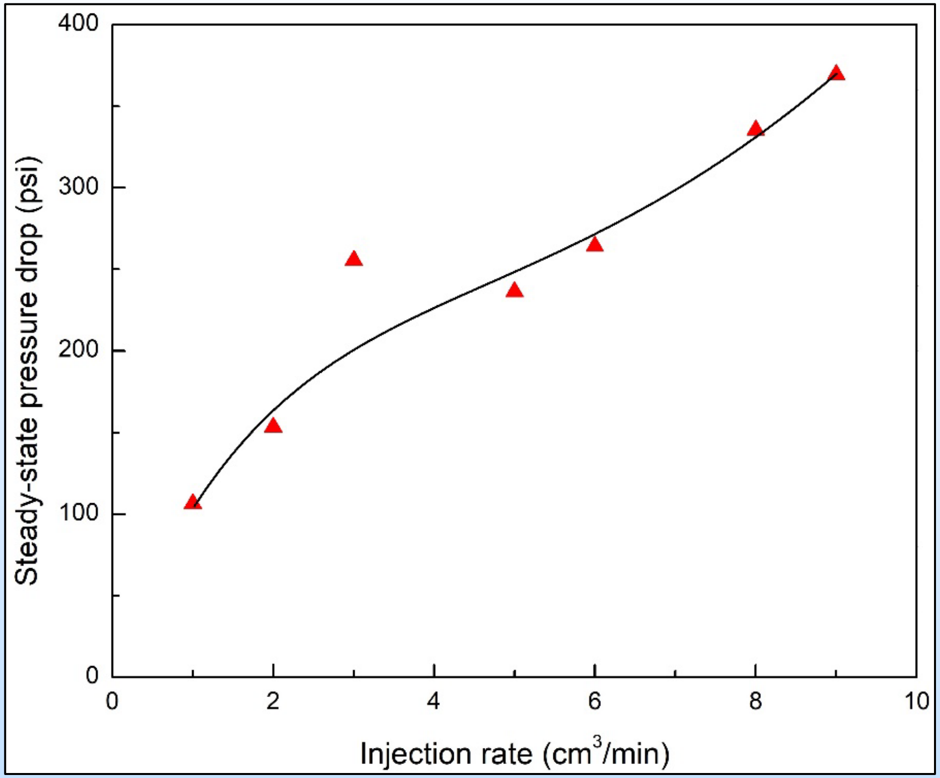
- Due to changes in the physical properties of methane at high pressure, enhanced interactions between surfactant solution and gas phase affect the foam strength.

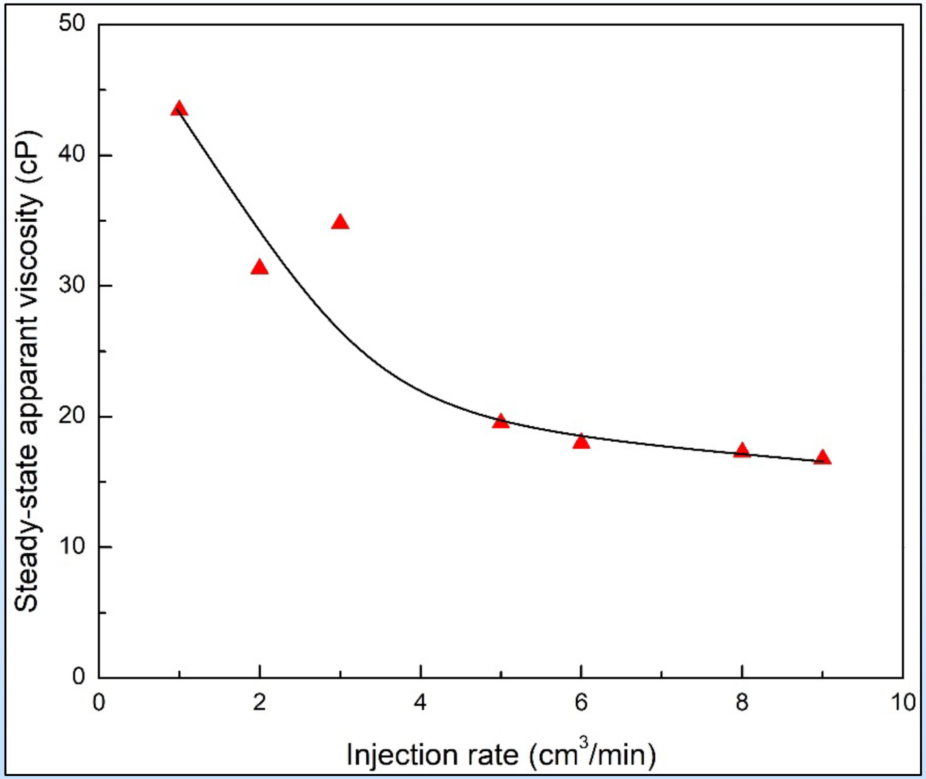
Variations in steady-state pressure drop with changes in operating pressure for **surfactant D**. Experiments were conducted at foam quality of 90%, a total injection rate of 5 cm^3/min, and a surfactant concentration of 0.4 wt%.

Appendix-IV (Cont'd)

Injection Rate Sensitivity -- Water-wet Proppant Packs

Reservoir Conditions



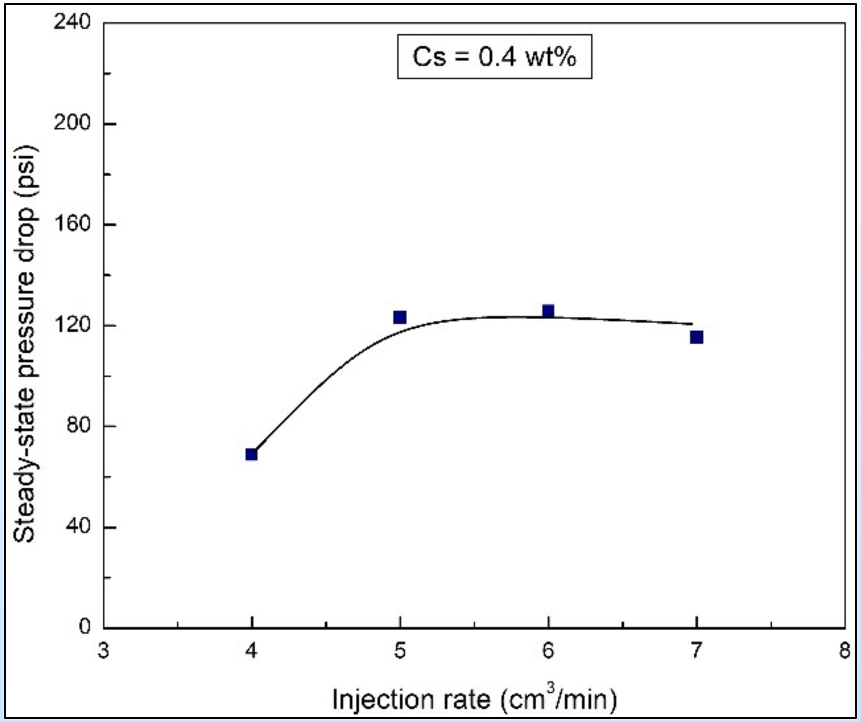


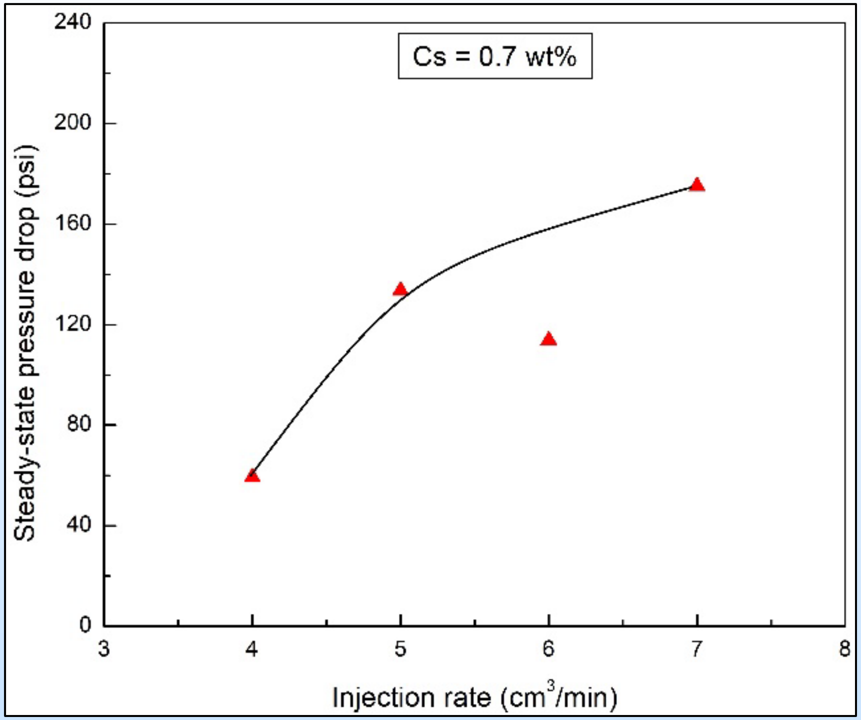
Variations of steady-state pressure drop (left) and steady-state apparent viscosity (right) with changes in the total injection rate for **amphoteric surfactant D**. Tests were conducted at foam quality of 90% and a surfactant concentration of 0.4 wt%.

Appendix-IV (Cont'd)

Injection Rate Sensitivity -- Water-wet Proppant Packs

Reservoir Conditions



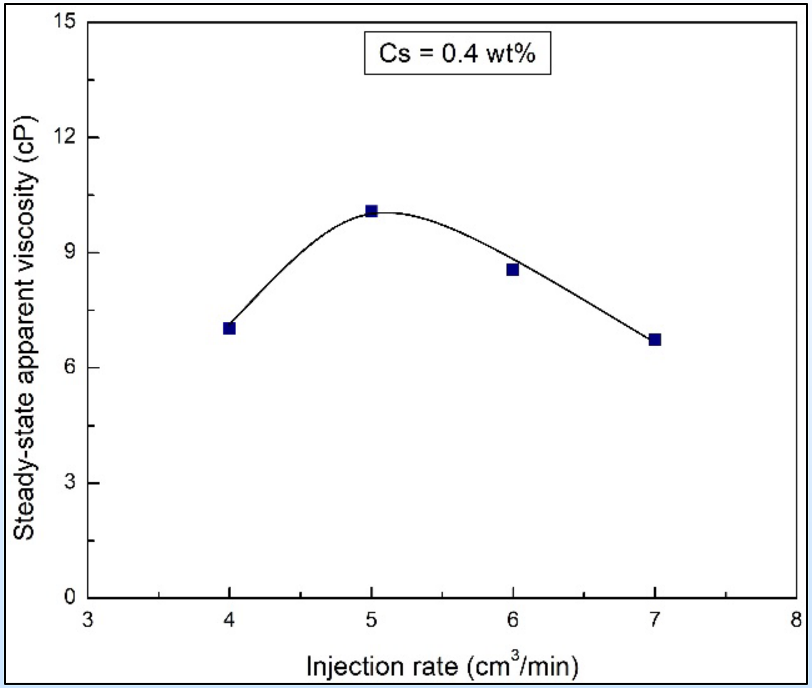


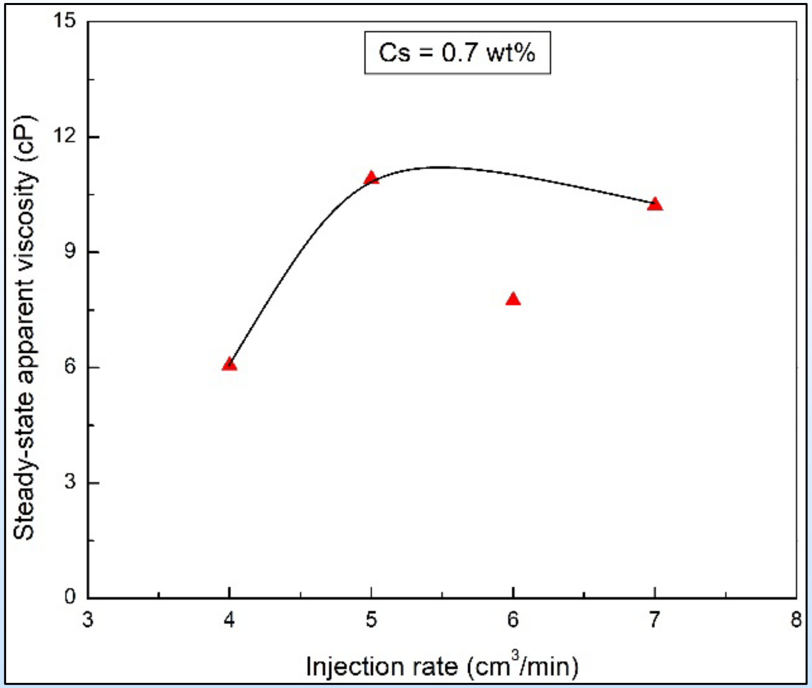
Variations of steady-state pressure drop with changes in the total injection rate for **surfactant C** at two different concentrations of 0.4 and 0.7 wt% and foam quality of 90%.

Appendix-IV (Cont'd)

Injection Rate Sensitivity -- Water-wet Proppant Packs

Reservoir Conditions





Variations of steady-state apparent viscosity with changes in the total injection rate for **surfactant C** at two different concentrations of 0.4 and 0.7 wt% and foam quality of 90%.

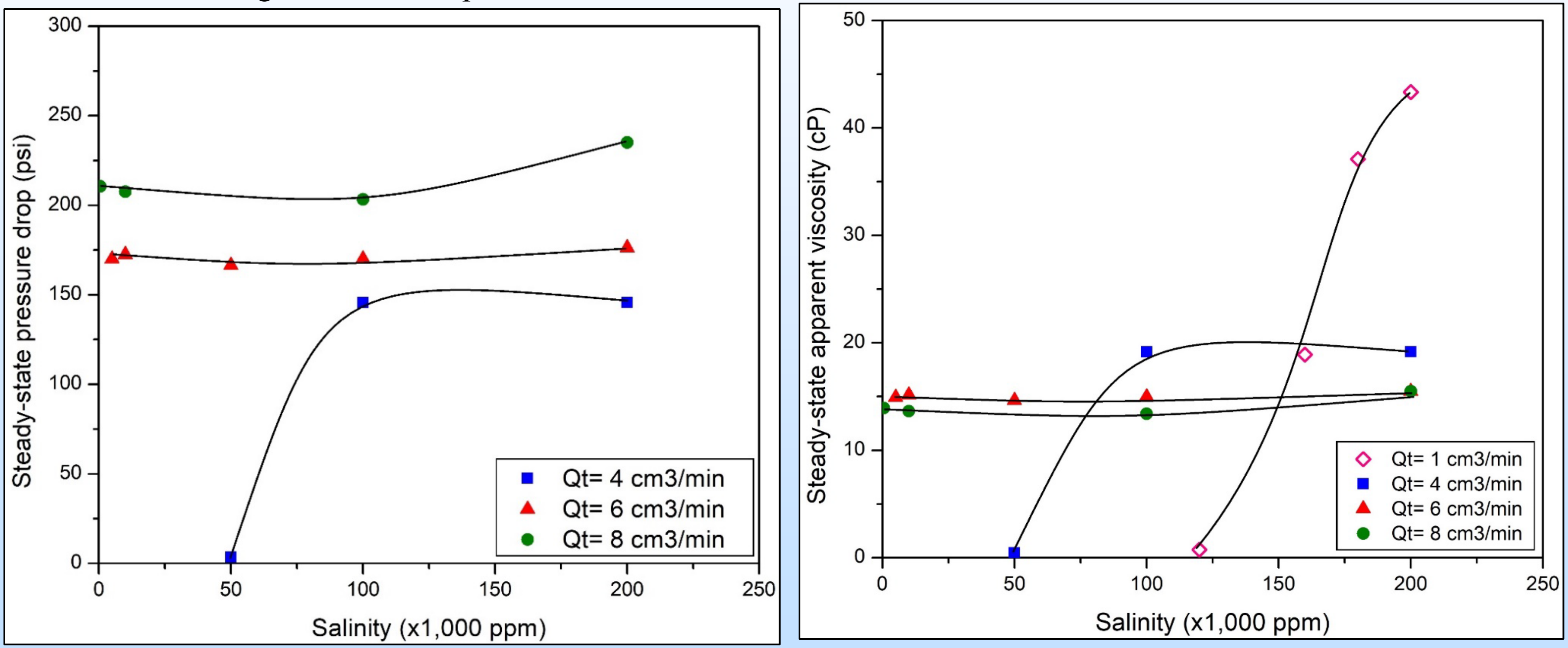
- An increase in the population of surfactant molecules at the interface can mitigate the adverse effect of high injection rates, known as shear thinning.

Foam Evaluation Tests (Cont'd)

Effects of Salinity and Total Flow Rate on Foam Performance -- Oil-wet Proppant Packs

Reservoir Conditions

For anionic surfactant B, high shear rates improve the foamability (pressure drop) by quickly removing the in-situ oil and altering the wetting conditions, and supporting bubble generation through enforced snap-off.



Steady-state pressure drop (left) and apparent viscosity (right) variations with changes in aqueous solution salinity for **surfactant XUR-BLT (B)** **at varying total injection rates** using synthetic brine with a foam quality of 85%, concentration of 0.4 wt%, and 10% S_{oi} in oil-wet proppant packs.

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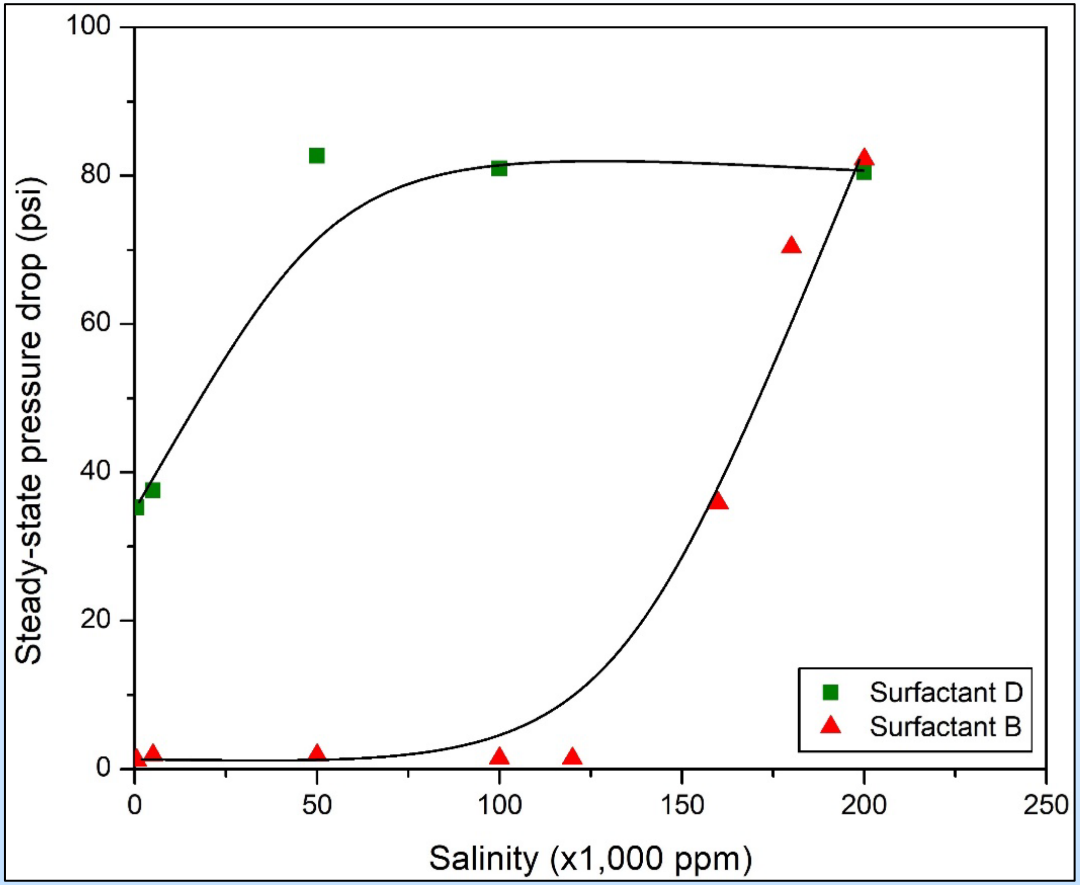
Foam Evaluation Tests (Cont'd)

Salinity Sensitivity -- Oil-wet Proppant Packs

Reservoir Conditions



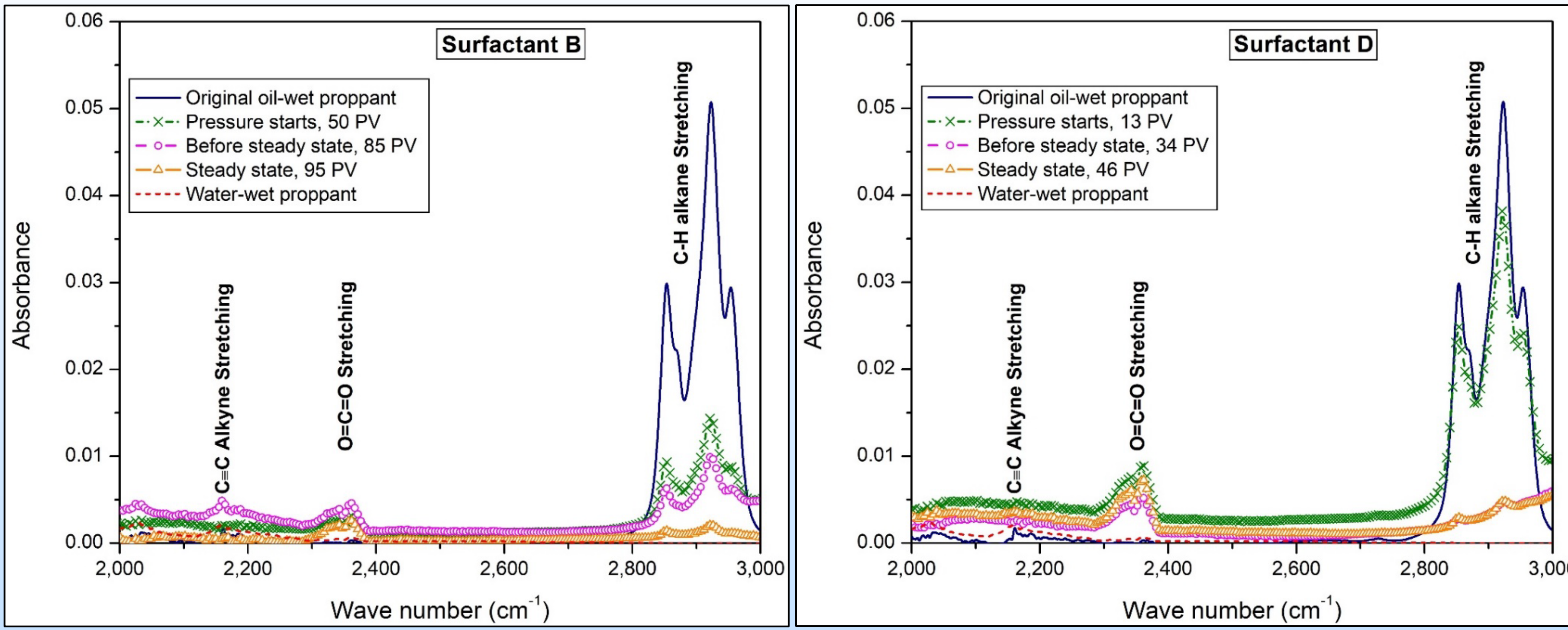
- Anionic surfactant B exhibits poor foamability at low salinity conditions due to in-situ oil and adverse wettability conditions, which dampen the ability of surfactant molecules to accumulate at the solid-liquid interfaces and create favorable wetting conditions for foam generation. This effect is mitigated at high salinity.
- Amphoteric surfactant D delivers strong foam at low salinities as it possesses more tolerance to oil due to foam stabilizers and its ionic nature facilitating the formation of stable EDLs, providing improved viscoelasticity.

Steady-state pressure drop (foam strength) variation with changes in aqueous solution salinity for surfactants UWYO-A (D) and XUR-BLT (B) using synthetic brine at a foam quality of 85%, a concentration of 0.4 wt%, the total injection rate of 1 cc/min, and 10% S_{oi} in oil-wet proppant packs.

Appendix-IV (Cont'd)

Effect of Surfactant Flooding on Oil Wetness of Proppant Packs during Foam Generation

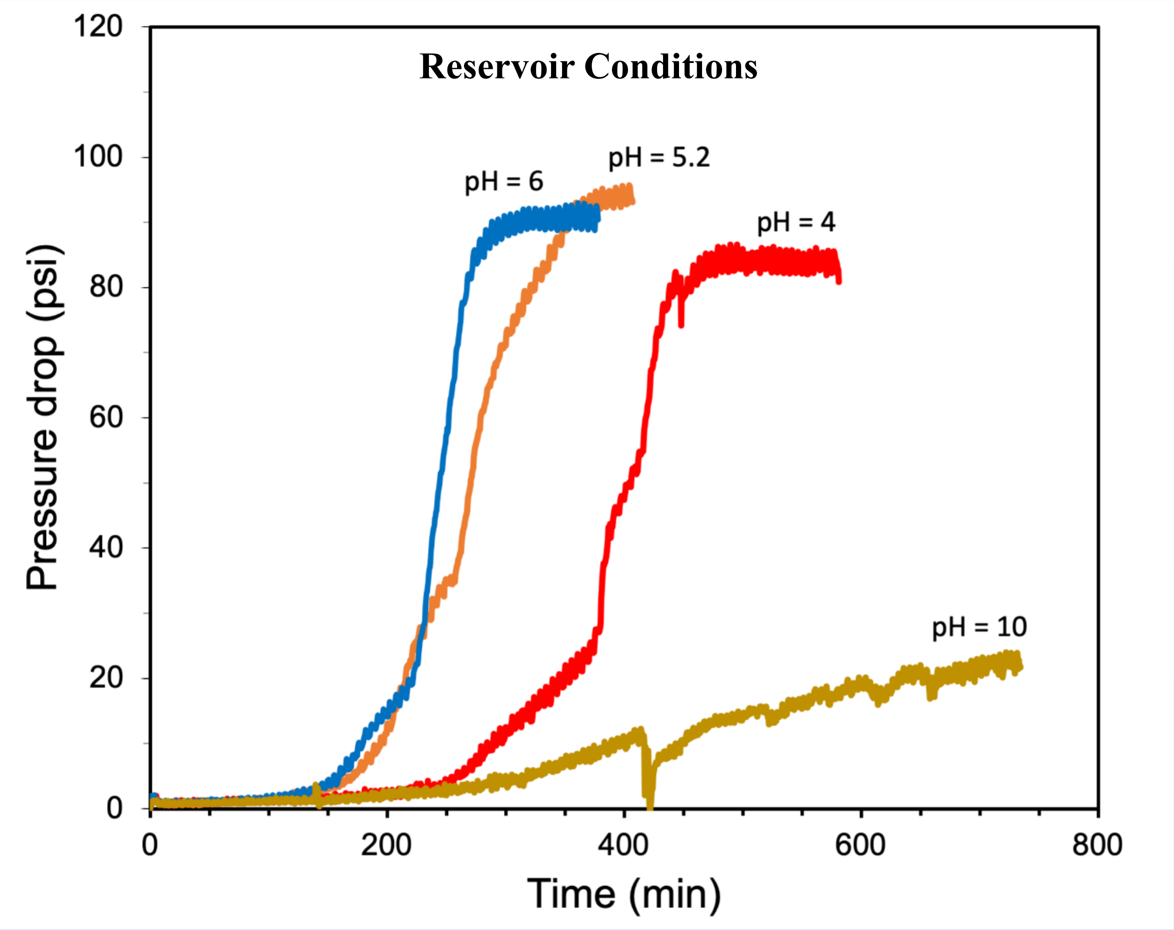
Reservoir Conditions



FTIR profiles of the proppant sand samples from different stages of foam generation using **surfactants B (left) and D (right)** performed at a total injection rate of 1 cm^3/min, 85% foam quality, 200,000 ppm salinity, and 4,000 ppm concentration.

Foam Evaluation Tests (Cont'd)

Effect of pH on Foam Performance of XUR-BLT using Bakken Produced Water from En-Anderson Pad in Oil-wet Proppant Packs



Surfactant B shows promising foam performance in acidic aqueous solutions of produced water from the **En-Anderson pad**.

Pressure vs time profile during foam generation for surfactant B (XUR-BLT) using **En-Anderson produced water** in **oil-wet sandpacks** at 1 cc/min total injection rate, 85% foam quality, 0.4 wt% surfactant concentration, and 10% S_{oi}.