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

DOE Award Number: DE-FE0031787

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Center of Innovation for Flow through Porous Media (COIFPM)

University of Wyoming, Hess Corporation, and Dow Chemical

U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability
Project Review Meeting
2022

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). Two years of no-cost time extension has been incorporated.

Project Participants

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

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

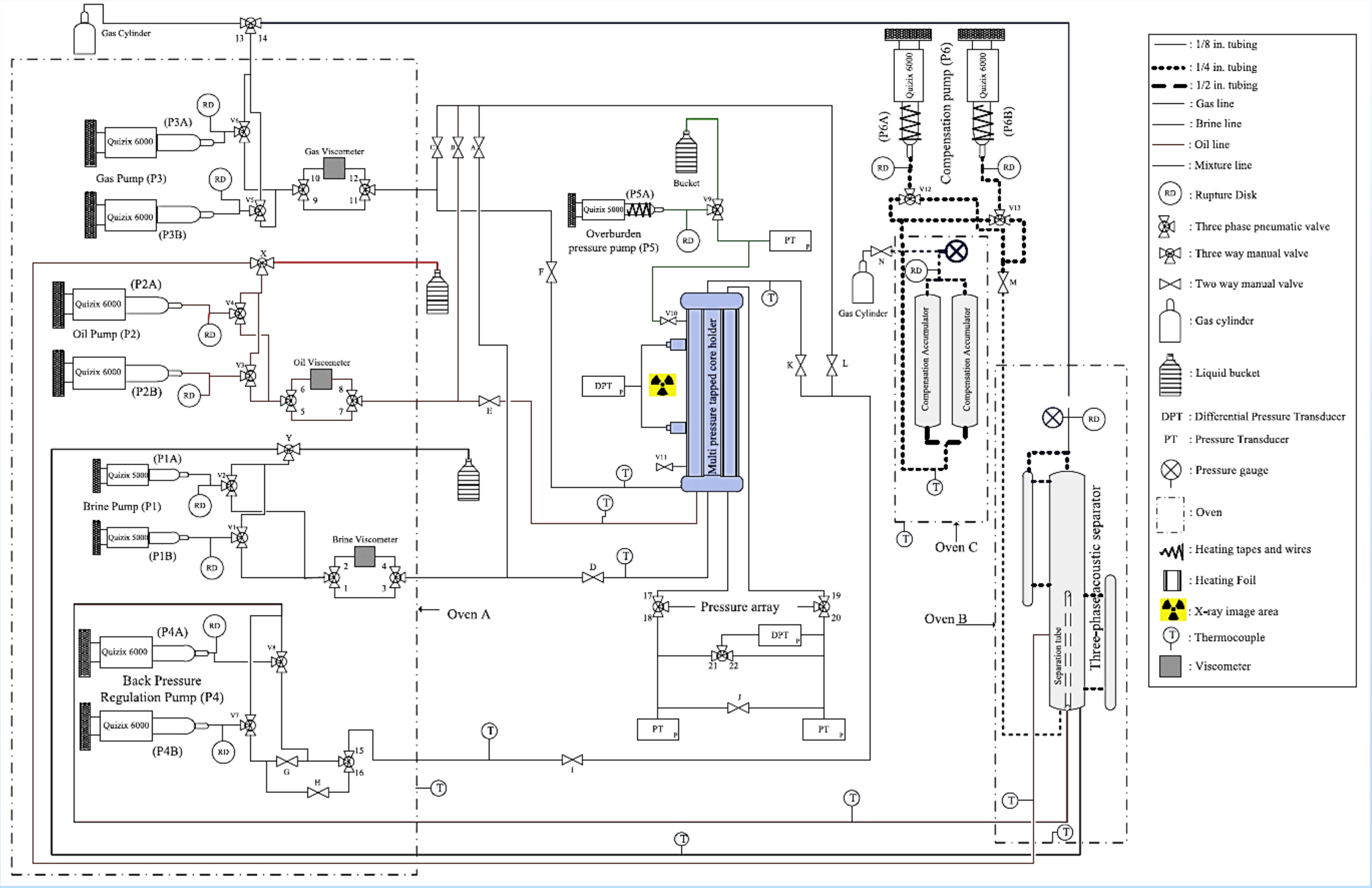
	Budget Period 1		Budget Period 2		Budget Period 3		Budget Period 4		Total	
	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share
Applicant	$665,063	$201,166	$1,411,665	$217,689	$585,087	$182,968	$338,184	$150,456	$3,000,000	$752,280
Hess Corporation	$0	$0	$0	$182,000	$1,207,375	$169,000	3,792,625	$99,000	$5,000,000	$450,000
Dow Chemicals	-	$299,808	-	$275,244	-	$111,614	-	$114,341	-	$801,007
FFRDC/NL, if proposed	-	-	-	-	-	-	-	-	-	-
Total ($)	$665,063	$500,974	$1,411,665	$674,933	$1,792,462	$463,582	$4,130,810	$363,798	$8,000,000	$2,003,287
Total Cost Share %		42.96%		32.34%		20.54%		8.10%		20.0%

Technical Approach

- 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.

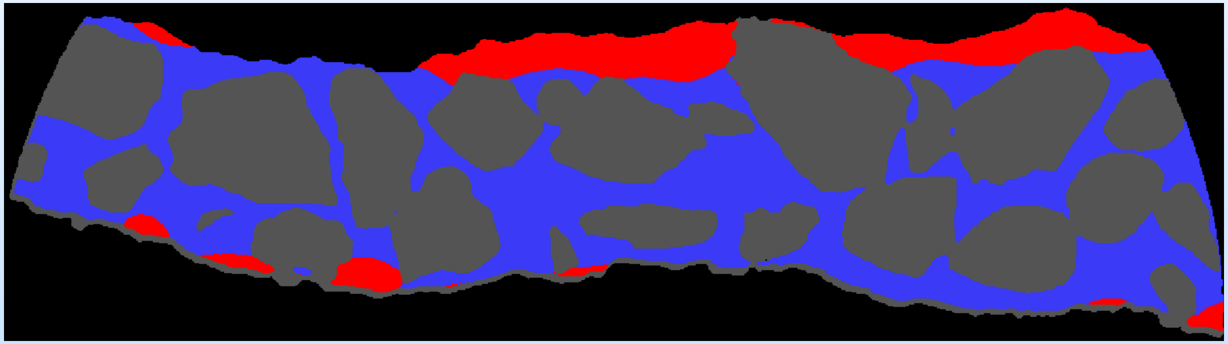
In-situ Wettability – Proppants

A typical miniature core-flooding apparatus:

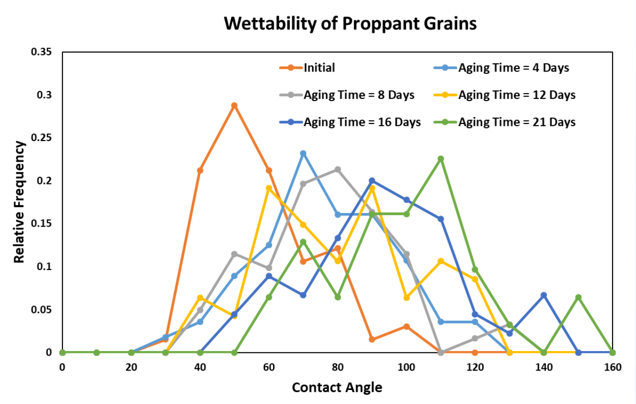


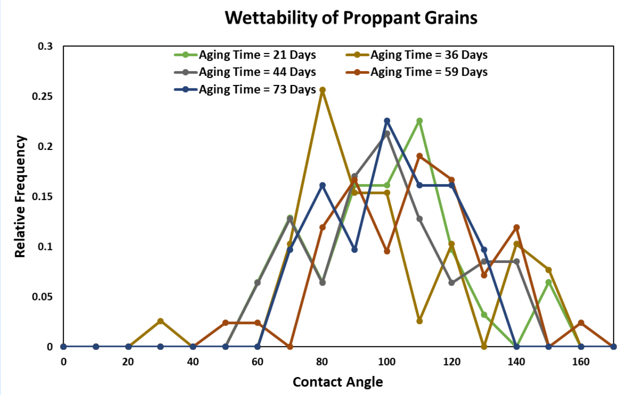
In-situ Wettability – Proppants (Cont'd)

- 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.



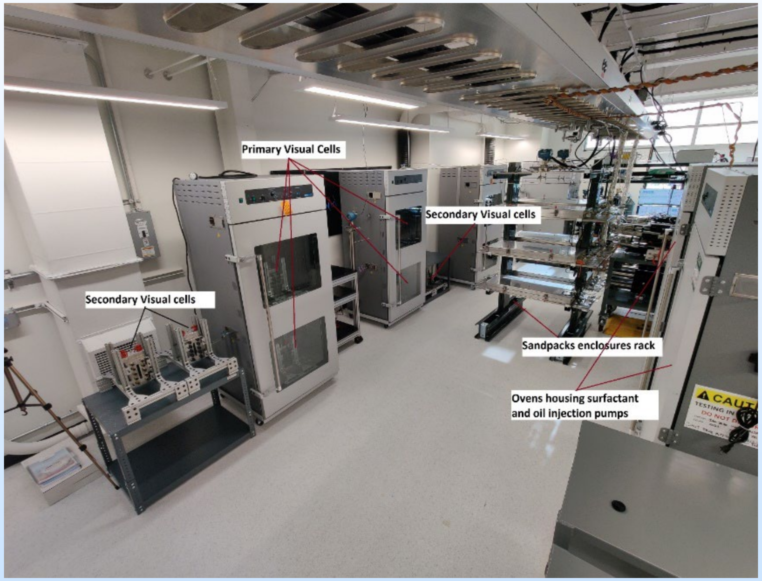
A segmented image of a slice obtained after introducing the doped oil into the proppant pack (red, blue, and gray represent oil, brine, and and proppant grains, respectively).

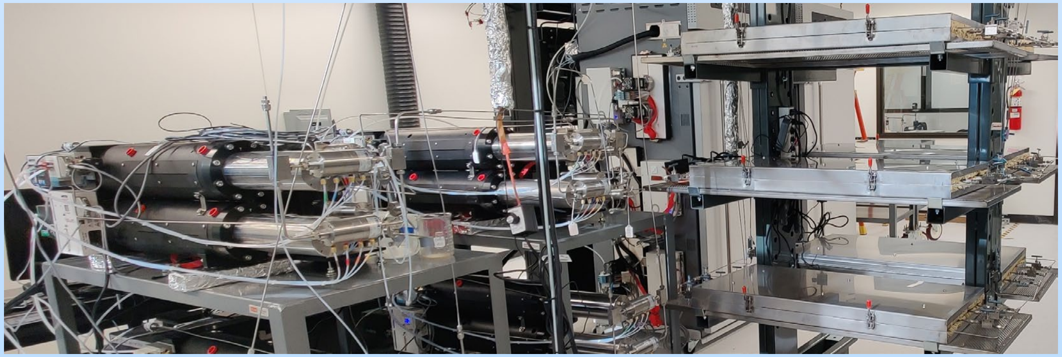




Foam Evaluation Facility

- A state-of-the-art HPHT foam generation and evaluation system was fabricated from scratch. A total of **Eighteen (18)** foam generation experiments can be conducted simultaneously on **proppant packs with different wettability states.** The platform consists of Hastelloy components, Quizix precision pumping systems, Visual cells, Methane detection sensors, etc.).





- HC gas foam generation and evaluation for different surfactants at high-pressure and high-temperature conditions.
- Studies of the impacts of surfactant concentration, gas/water flow rate ratio, total flow rate, and initial saturation on foam properties.
- Evaluate foam stability and strength by measuring foam half-life and the pressure drop (apparent viscosity) generated across proppant packs.
- Identify superior surfactants and optimum operating parameters for field applications.
- The foam is generated by co-injecting the surfactant and gas into the sandpack.
- High-pressure (3,500 psi) and temperature (115 °C) conditions.

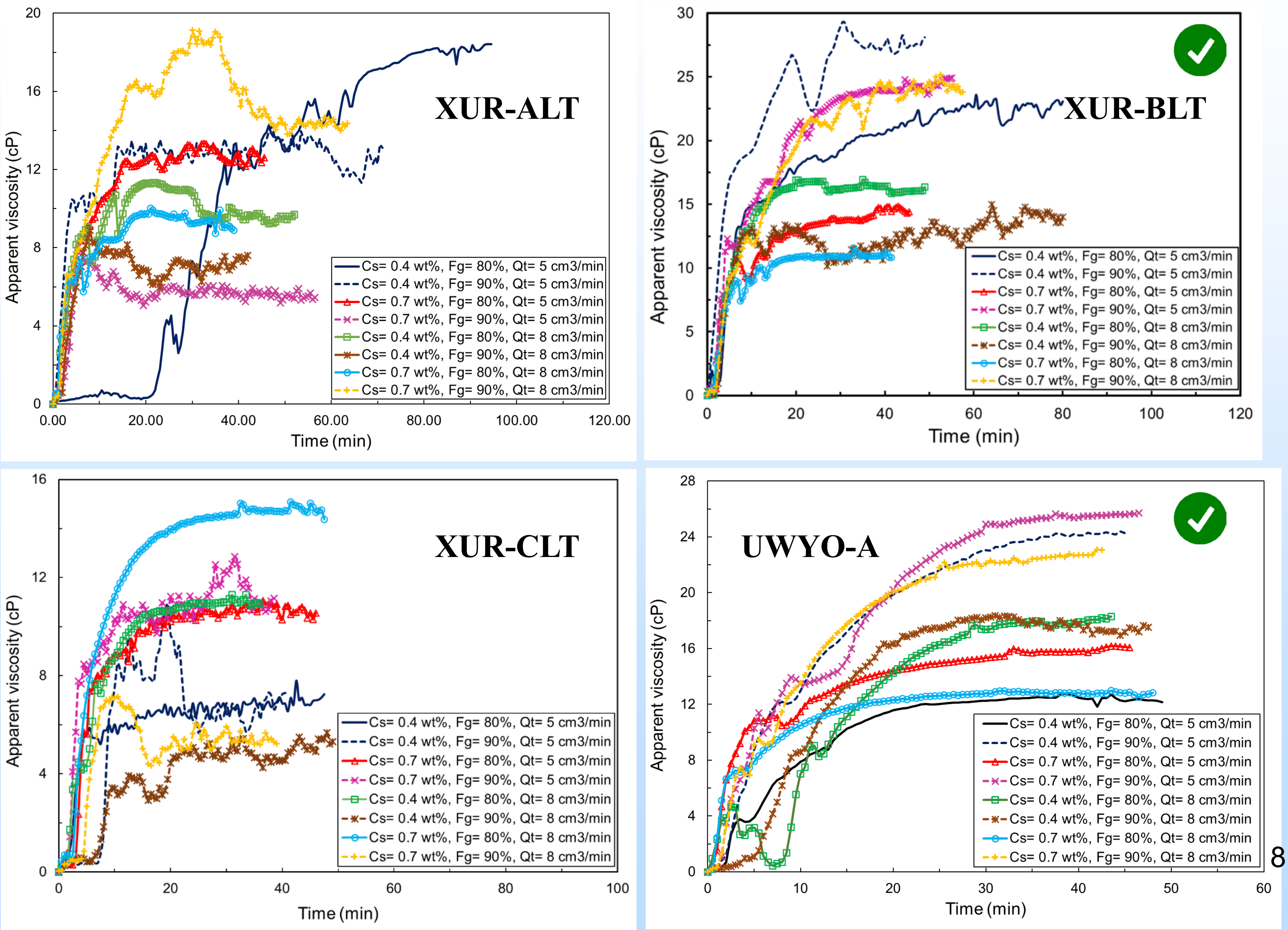
Foam Evaluation Tests

- Approximately **1,000** 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)

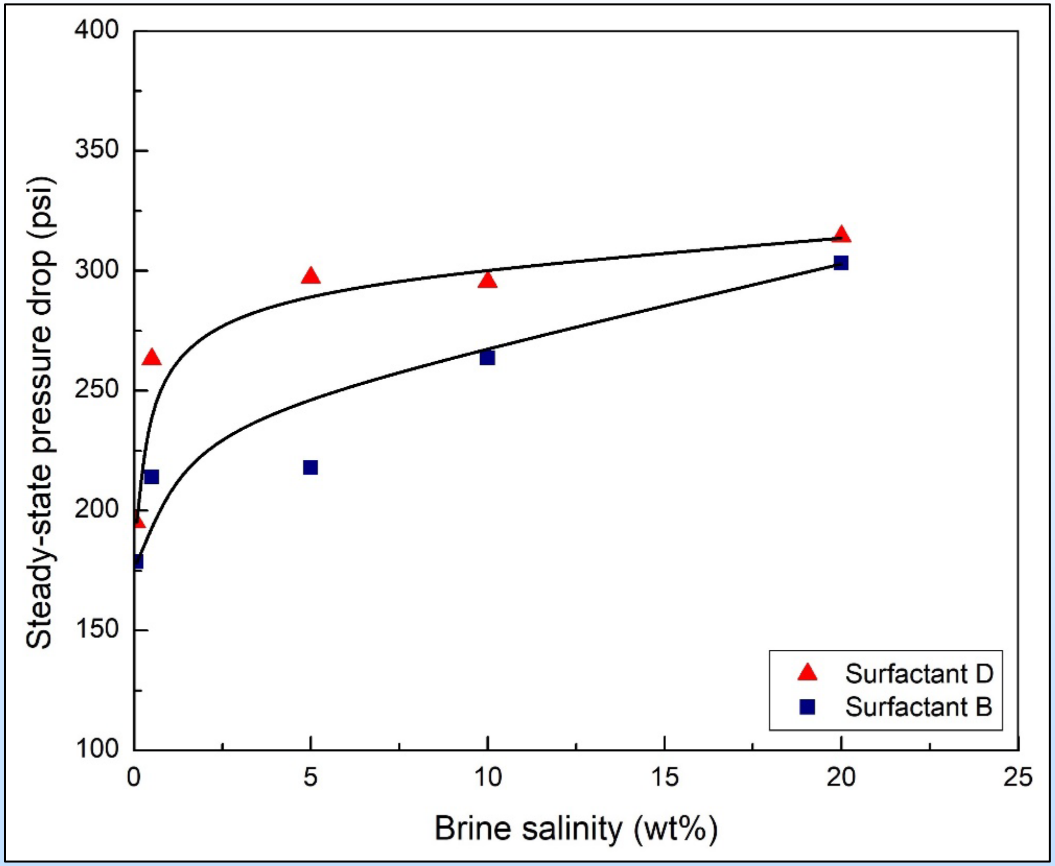
Foam-induced pressure profiles for different surfactants on water-wet proppant packs



Foam Evaluation Tests (Cont'd)

Salinity Sensitivity -- Water-wet Proppant Packs

Reservoir Conditions



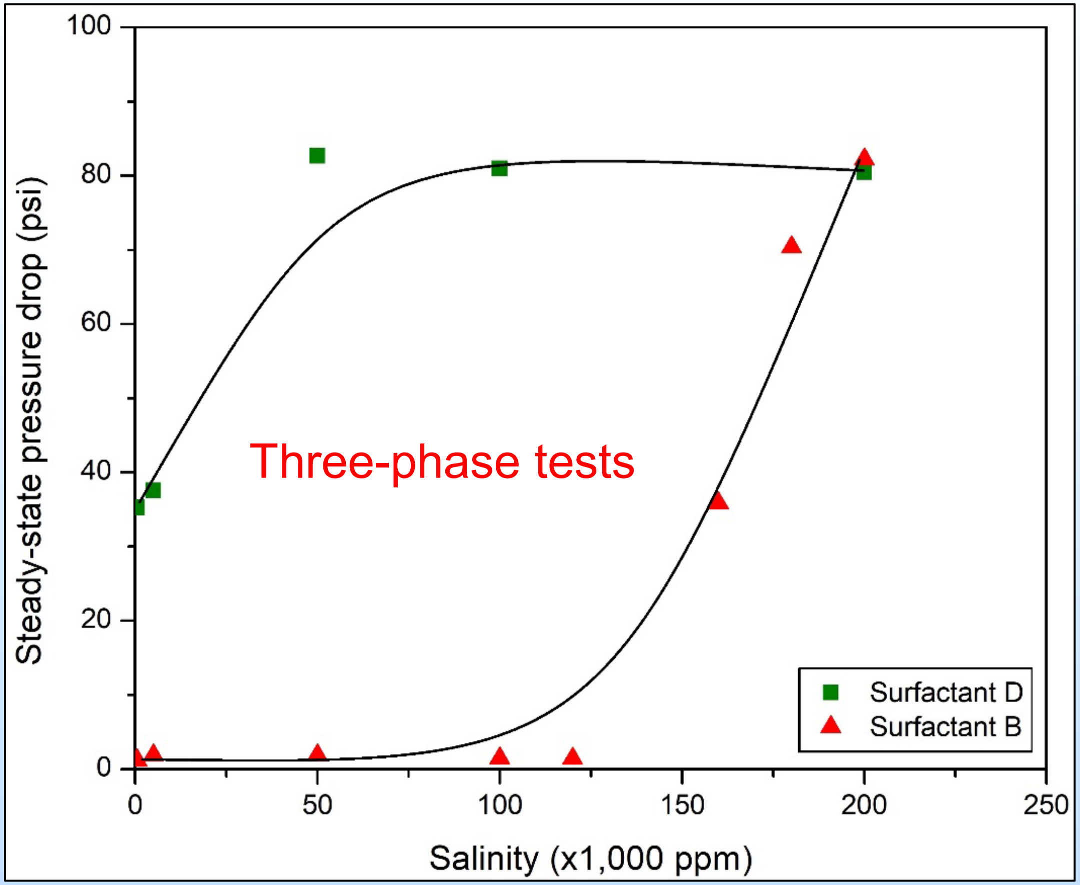
- An increase in brine salinity causes less ionic repulsion among the surfactant's anionic headgroups and improves electrical double-layer (EDL) structures, resulting in enhanced foam strength.
- Amphoteric surfactant D contains cations and anions along with foam stabilizers that provide more stability to foam lamellae 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.

Foam Evaluation Tests (Cont'd)

Salinity Sensitivity -- Oil-wet Proppant Packs

Reservoir Conditions



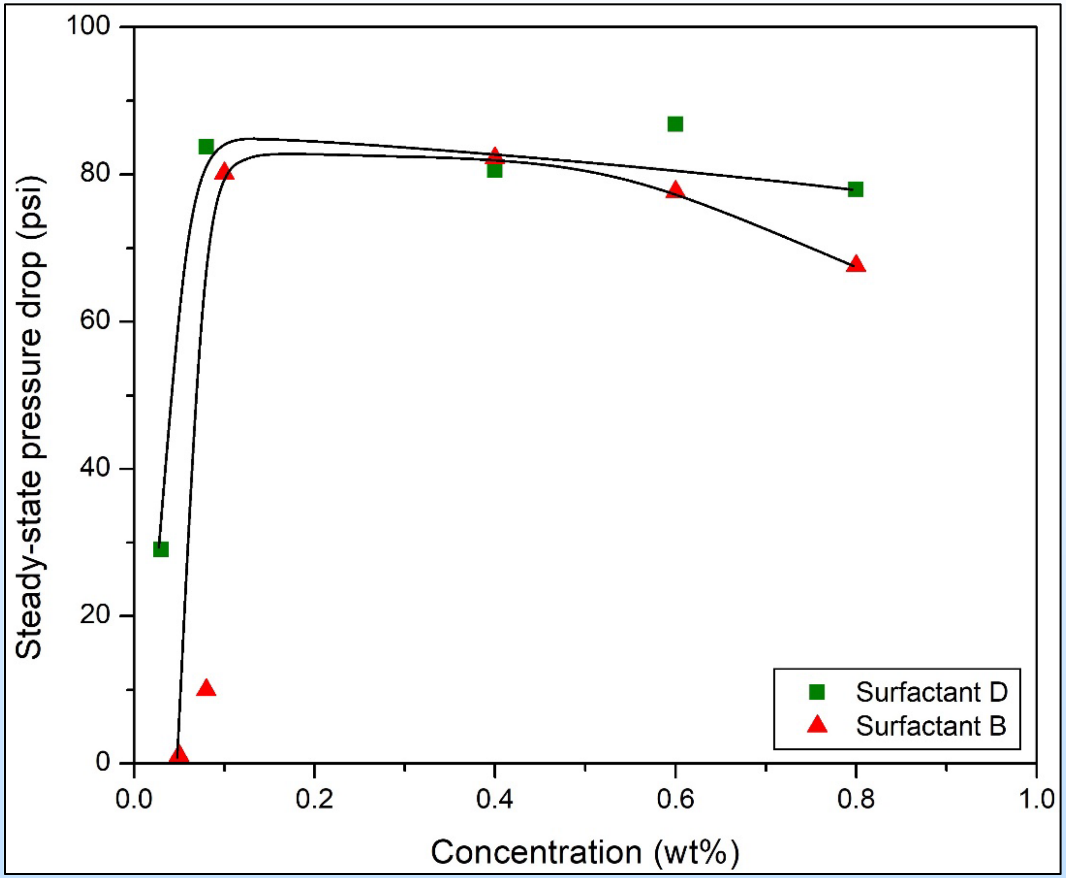
- Anionic surfactant B exhibits low foamability at low salinity conditions due to presence of oil saturation and adverse wettability conditions, which dampen the ability of surfactant molecules to accumulate at the solid-liquid interfaces and create favorable wetting conditions for foam generation. This 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.

Foam Evaluation Tests (Cont'd)

Surfactant Concentration Sensitivity -- Oil-wet Proppant Packs

Reservoir Conditions



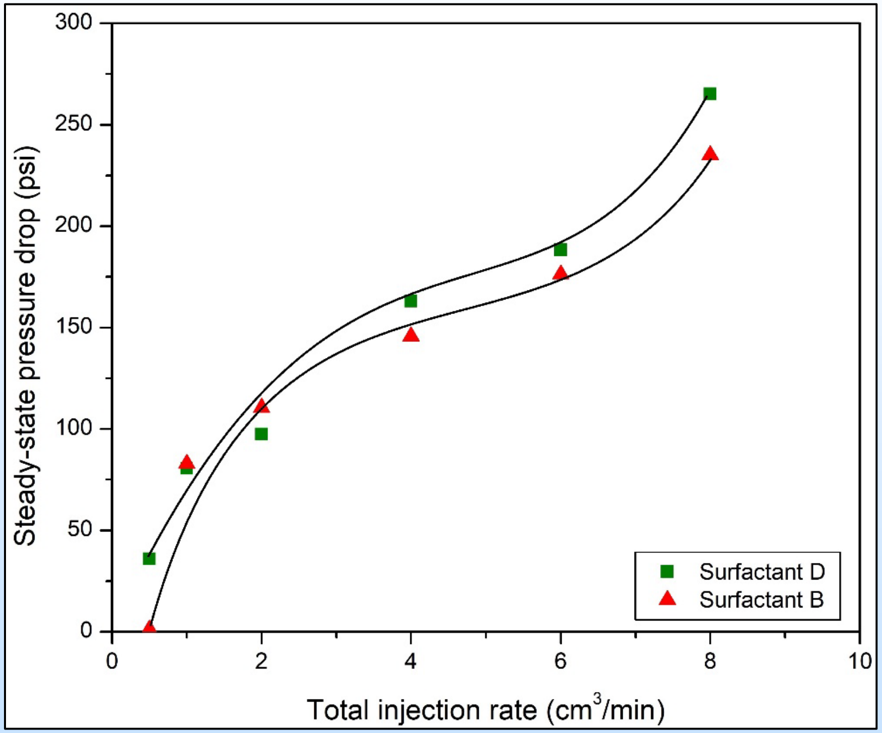
- Foam performance sensitivity to concentration shows similar trends and optimum concentration range for both surfactants.
- Specifically, for anionic surfactant B, foam strength decreases at higher concentrations due to the increased population of surfactant molecules at the interfaces, causing destabilization of the lamella.
- Amphoteric surfactant D provides better viscoelasticity which makes lamella films more resistant to rupture due to the high population of surfactant molecules and leads to increased foam strength at higher concentrations.

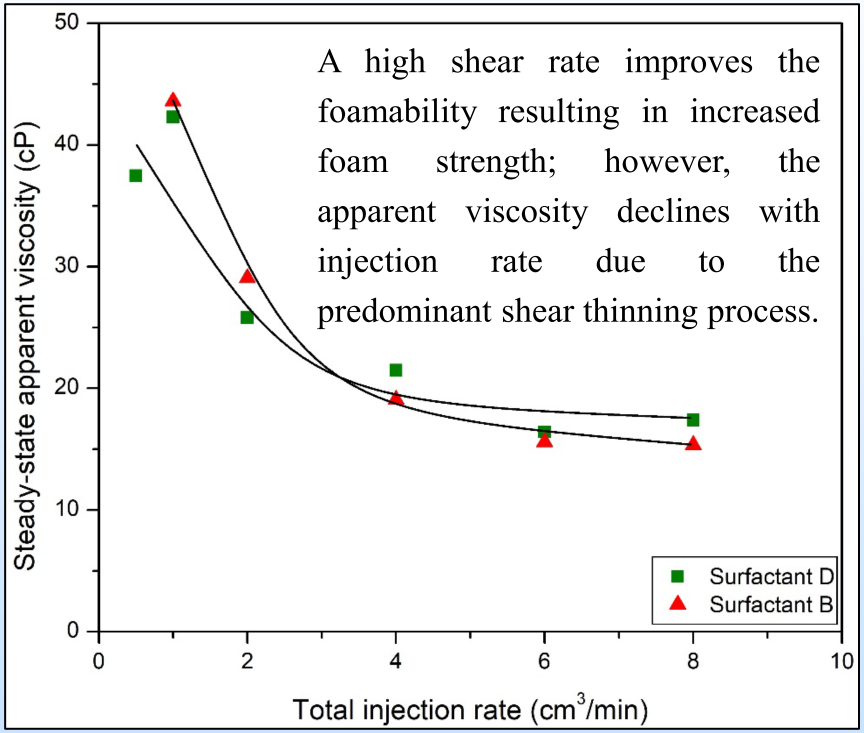
Steady-state pressure drop variations with changes in the surfactant concentration for **surfactants XUR-BLT (B)** and **UWYO-A (D)** using synthetic brine of 200,000 ppm salinity, a foam quality of 85%, 1 cc/min total flow rate, and 10% S_{oi} in oil-wet proppant packs.

Foam Evaluation Tests (Cont'd)

Total Injection Rate Sensitivity in Oil-wet Proppant Packs

Reservoir Conditions



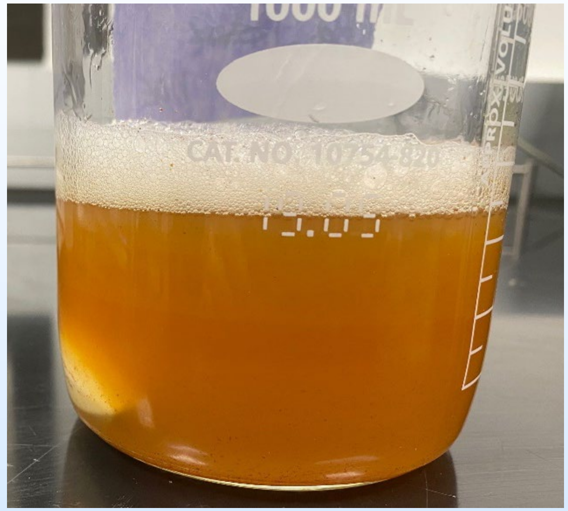


Steady-state pressure drop (left) and foam's apparent viscosity (right) variations with changes in the total injection rate for **surfactants XUR-BLT (B)** and **UWYO-A (D)** using synthetic brine of 200,000 ppm salinity, a foam quality of 85%, a concentration of 0.4 wt%, and 10% S_{oi} in oil-wet proppant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

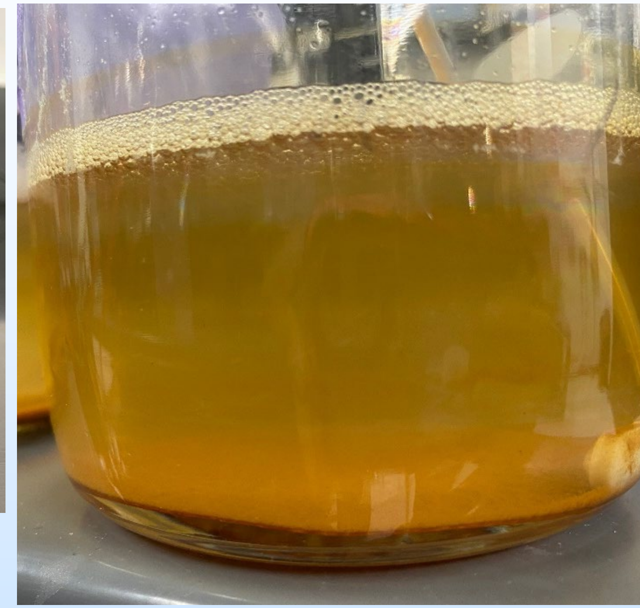
Foam Evaluation Tests (Cont'd)

Foam Generation Tests on Oil-wet Proppant Packs using Bakken Produced Water

An image of Bakken produced brine (as received)



Surfactant B solution immediately after preparation



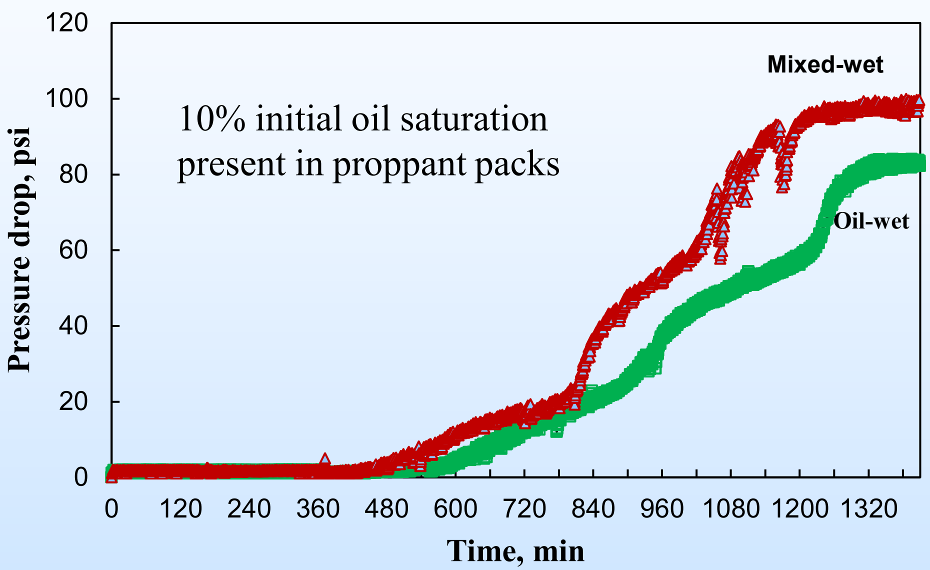
Surfactant B solution after 14 hours of preparation

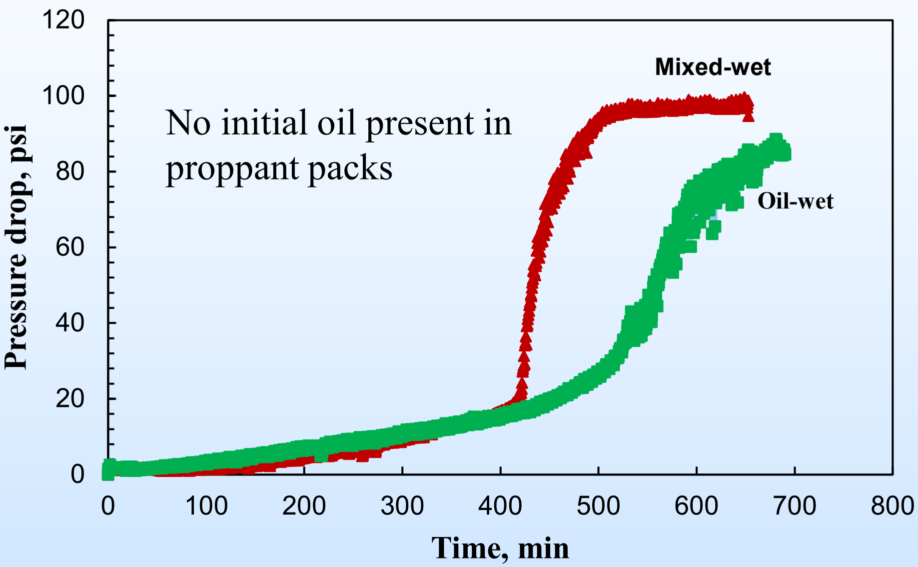
- Produced brine salinity: **313,000 ppm**
- Presence of solids. Solid particles settle down at the bottom of the container
- Negligible amount of TOC (~50 ppm)
- Aqueous solution with surfactant B shows stability

Foam Evaluation Tests (Cont'd)

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

Reservoir Conditions



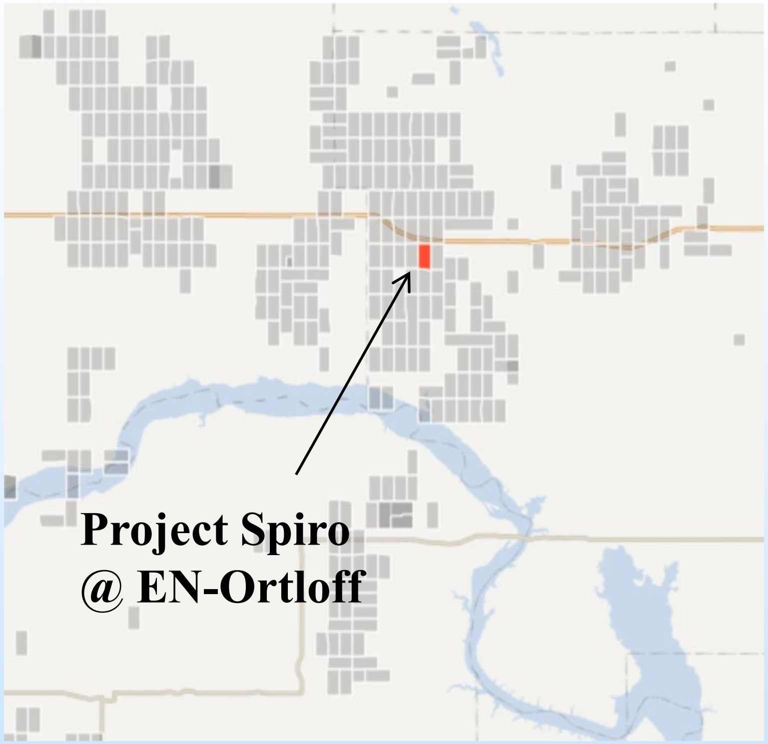


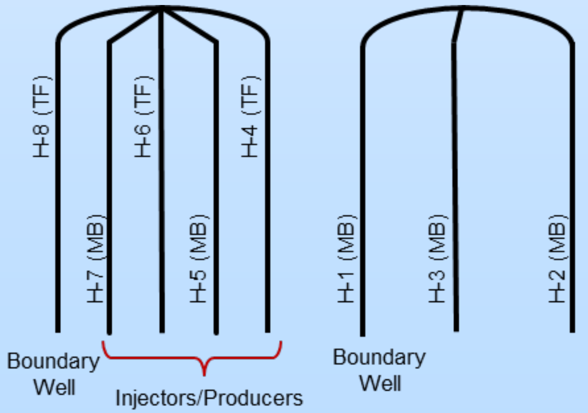
Pressure vs time profiles during foam generation for surfactant B (XUR-BLT) using Bakken produced water in **<u>mixed-wet and oil-wet sandpacks with and without initial oil saturation</u>** at 1 cc/min total injection rate, 85% foam quality, and 0.4wt% surfactant concentration.

- Presence of initial oil delays foam generation
- Steady-state foam strength does not show sensitivity to initial oil saturation
- Mixed-wet media show slightly superior foam performance

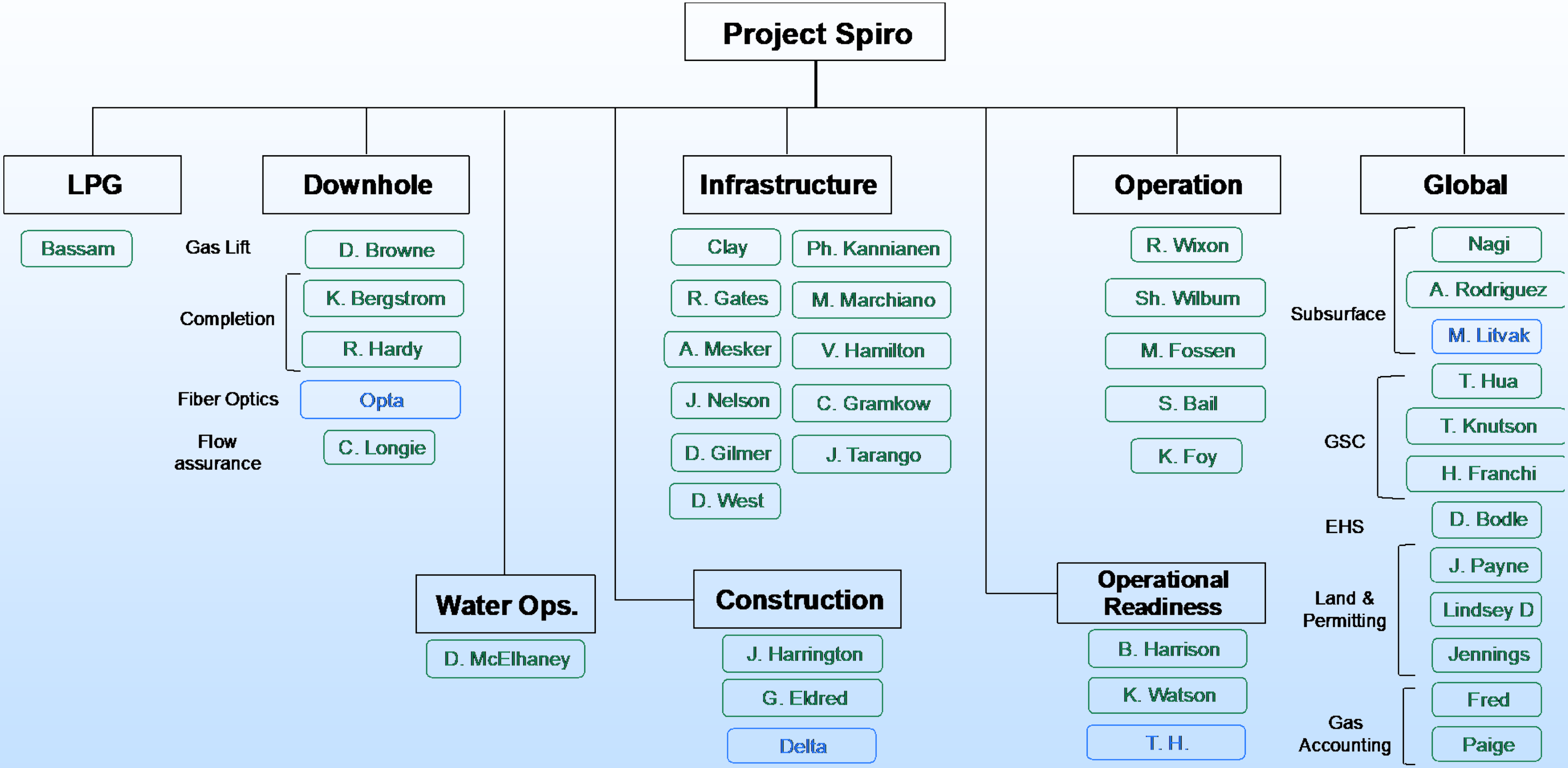
Project Spiro Overview

- Foam Assisted Gas Injection (Conformance Control)
- Hess-UW-Dow Project – Co-funded by DOE
- Injection into 4 horizontal wells over 2 years
- Pipeline supplied field gas (2 miles, 6”)
- Foaming agents from Dow
- Hess-UW Laboratory tests foam behavior and generates data to calibrate Hess in-house model
- Scheduled for 2020 deployment, moved to 2022
  - –Scheduled for startup mid-December





Project Spiro Team

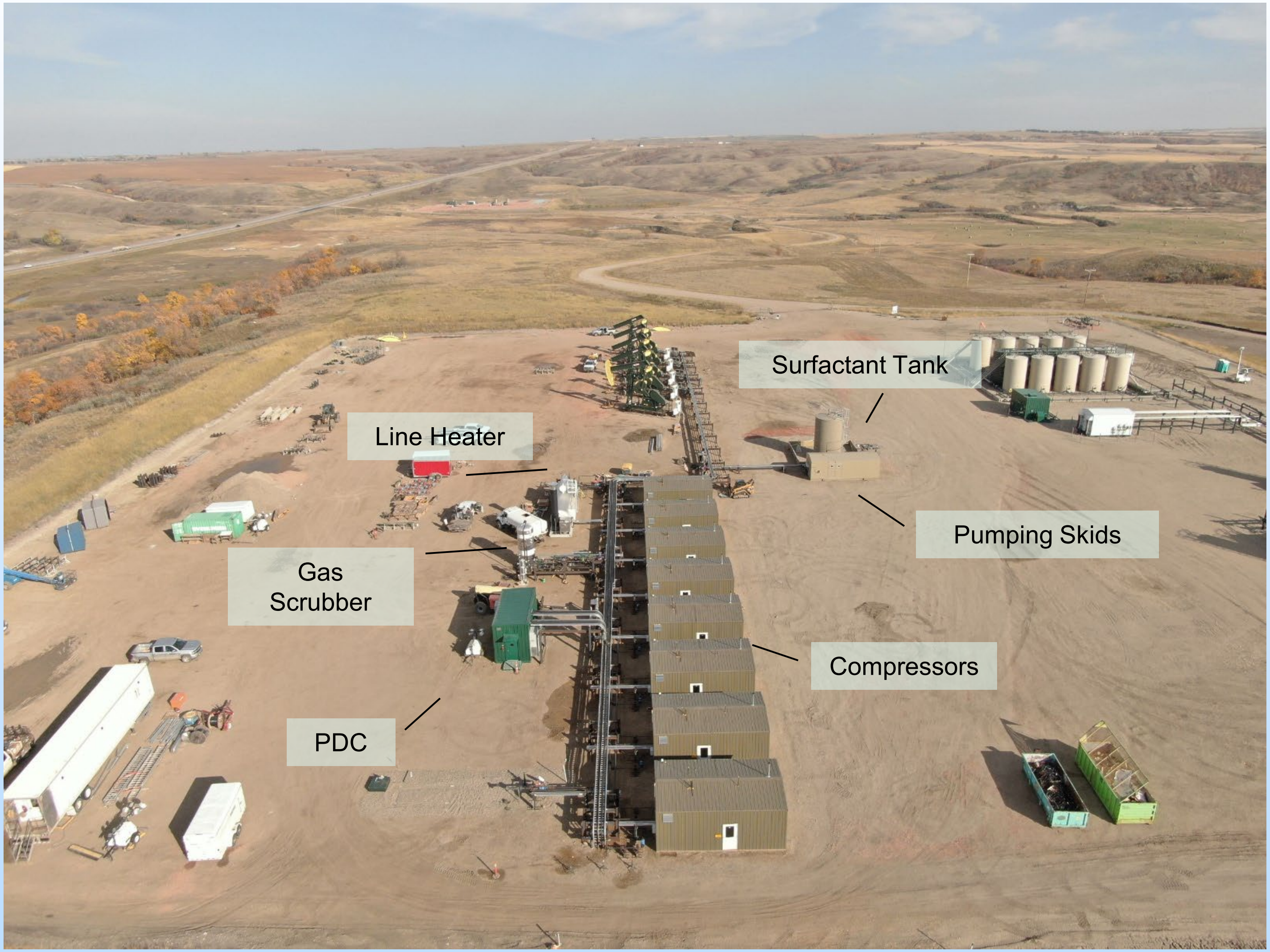


Project Spiro Construction Progress

- Key update
  - Scheduled Dec 16 startup
  - Startup delayed due to faulty equipment; long replacement lead time

- Progress
  - Eight compressors, pumps, and tanks are installed
  - Two miles of pipeline constructed to bring gas to the pad
  - Well upgrade is near completed
  - Wellhead is upgraded to 10k
  - Corrosion resistant gas-tight tubing installed
  - Operation procedures are developed and under review

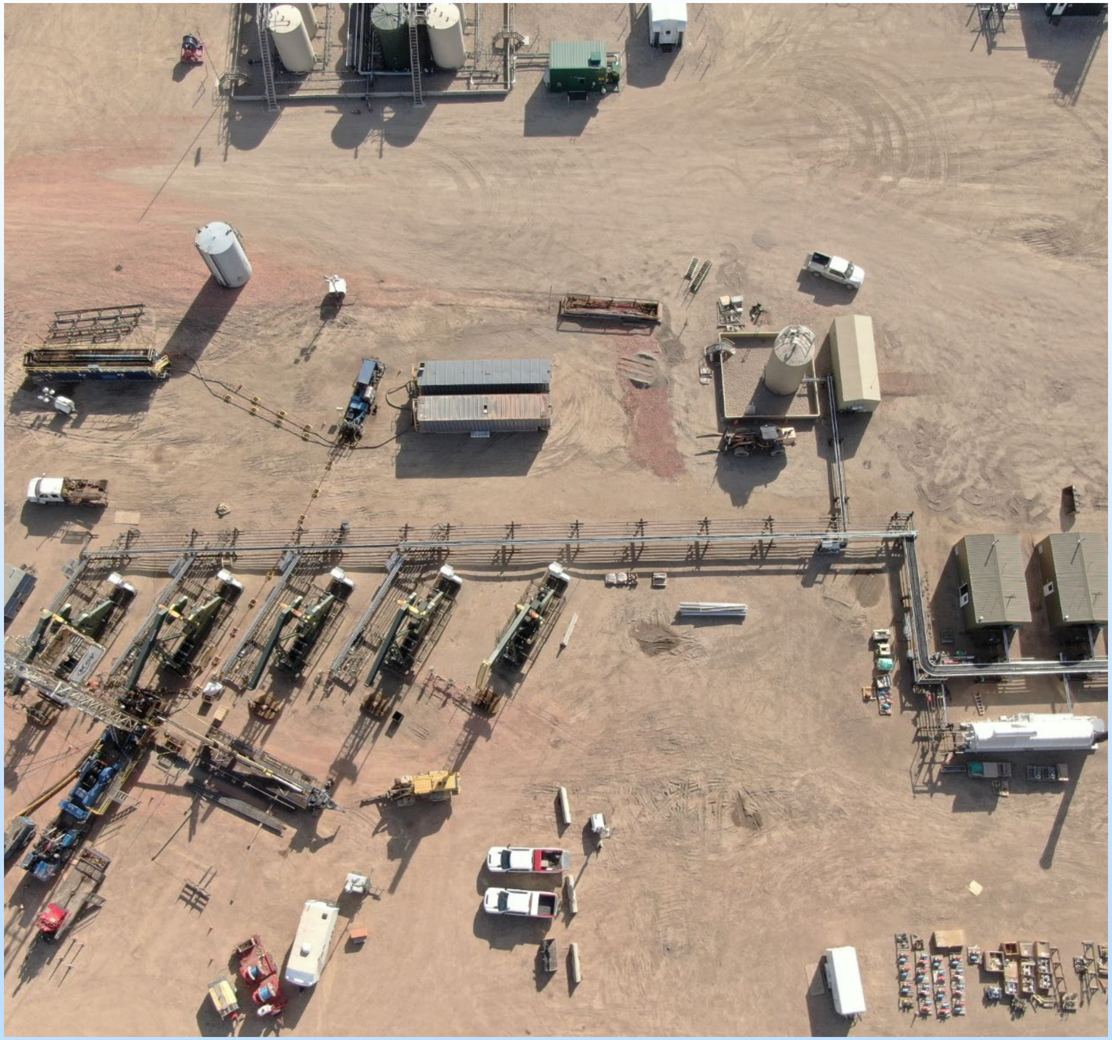
Project Spiro Construction Site



Project Spiro Construction Site (Cont'd)

Project Spiro Construction Site (Cont'd)

What is Next?



- Completion of facility construction
- Commissioning the facility
- Soft startup and troubleshooting
- Baseline data gathering
- First cycle of injection

Future Plans

- Produce large quantities of the foaming formulation required for the field trial.
- Perform compositional analysis and aqueous solution stability tests on Bakken produced water collected from different pads.
- Conduct HPHT foam evaluation tests on oil-wet and mixed-wet proppant packs using Bakken produced water obtained from different pads and evaluate the consistency in the foam performance.
- Perform FAGI tests on aged fractured cores under different conditions. Using macro-scale core-flooding experiments, we will investigate the effect of foam injection into the fracture on oil recovery, and study the interactions between the matrix and fracture under different flow conditions.
- Continue to calibrate the simulation model with field surveillance and production data as and when they become available.
- Optimize the injection strategy towards the desired production enhancement during the foam pilot. Several improvements in regards to the injection strategy are planned for implementation in the simulation studies: (a) gravity override, (b) gravity drainage of injected water/aqueous surfactant solutions, and (c) foam injection strategy.

Thank you!

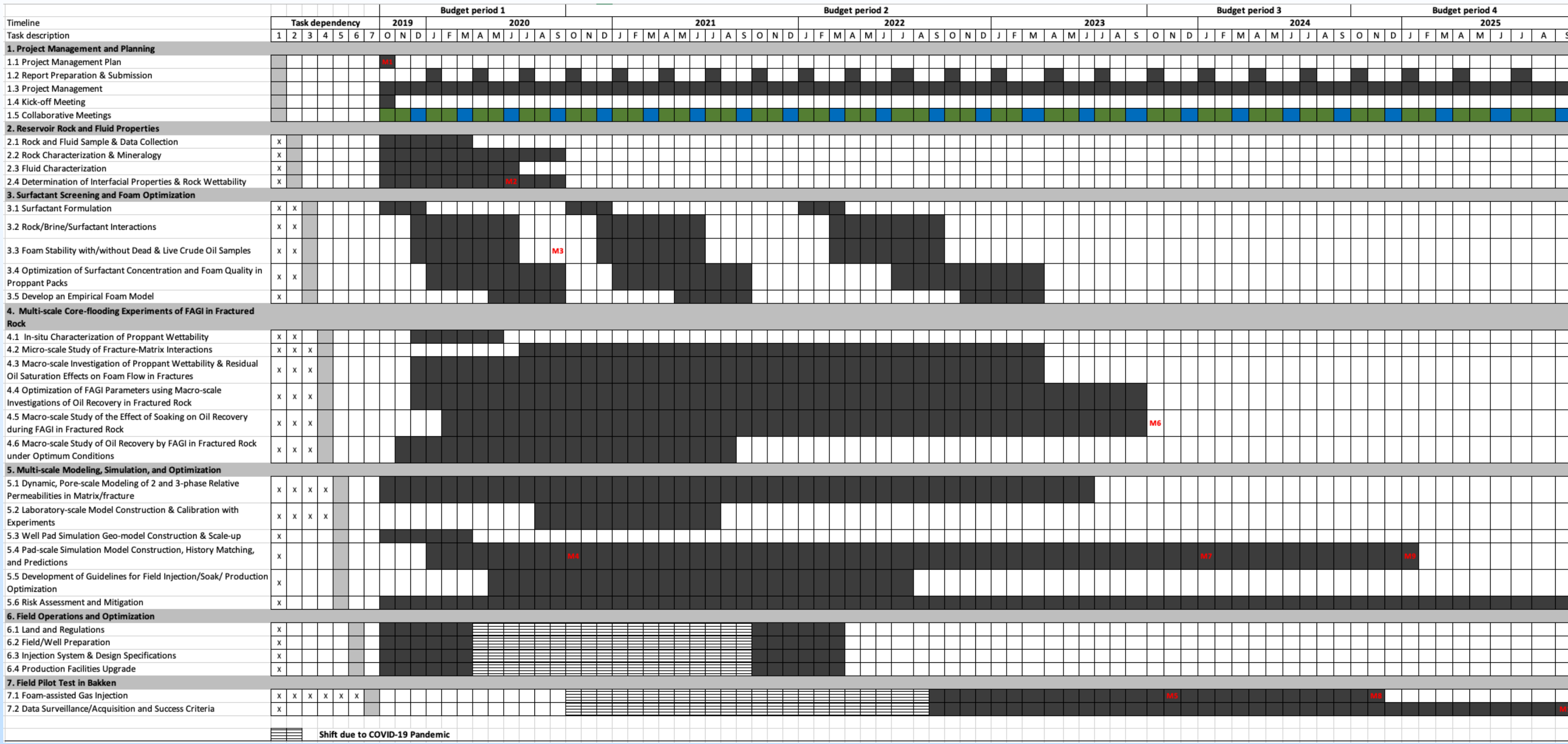
Appendix

The following items are included in the Appendix

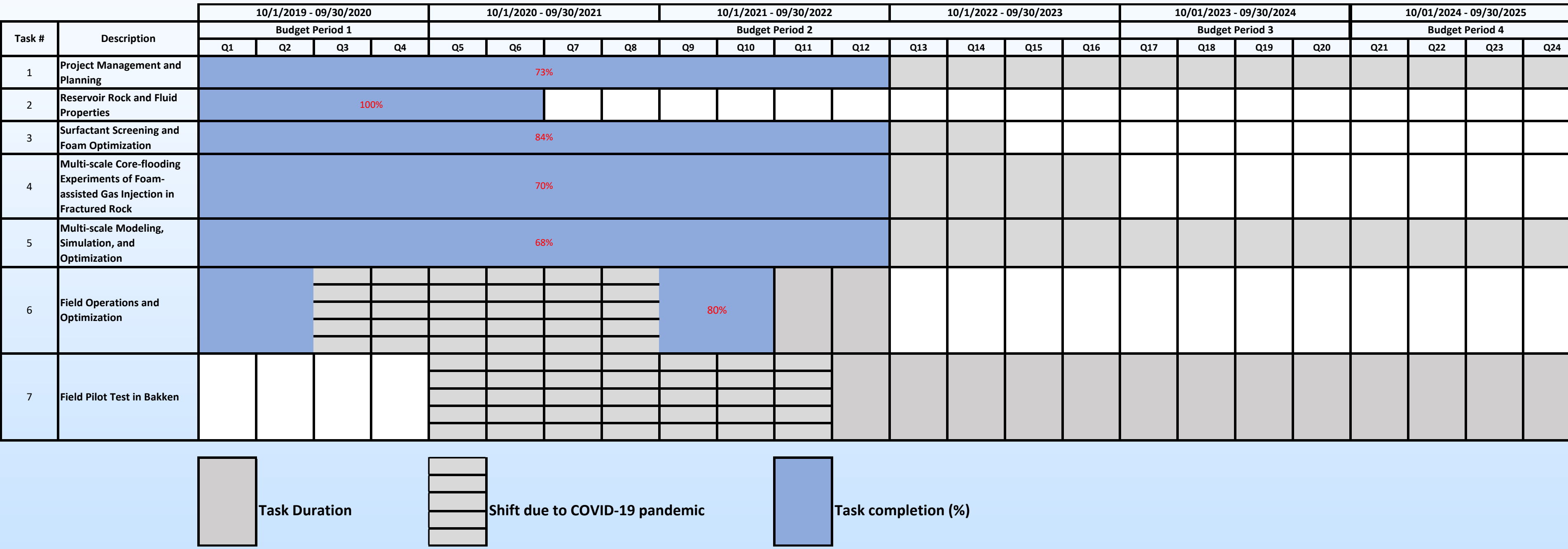
I. Schematic of the state-of-the-art foam generation platform

II. The Injection/Soak/Production Strategy for FAGI operation

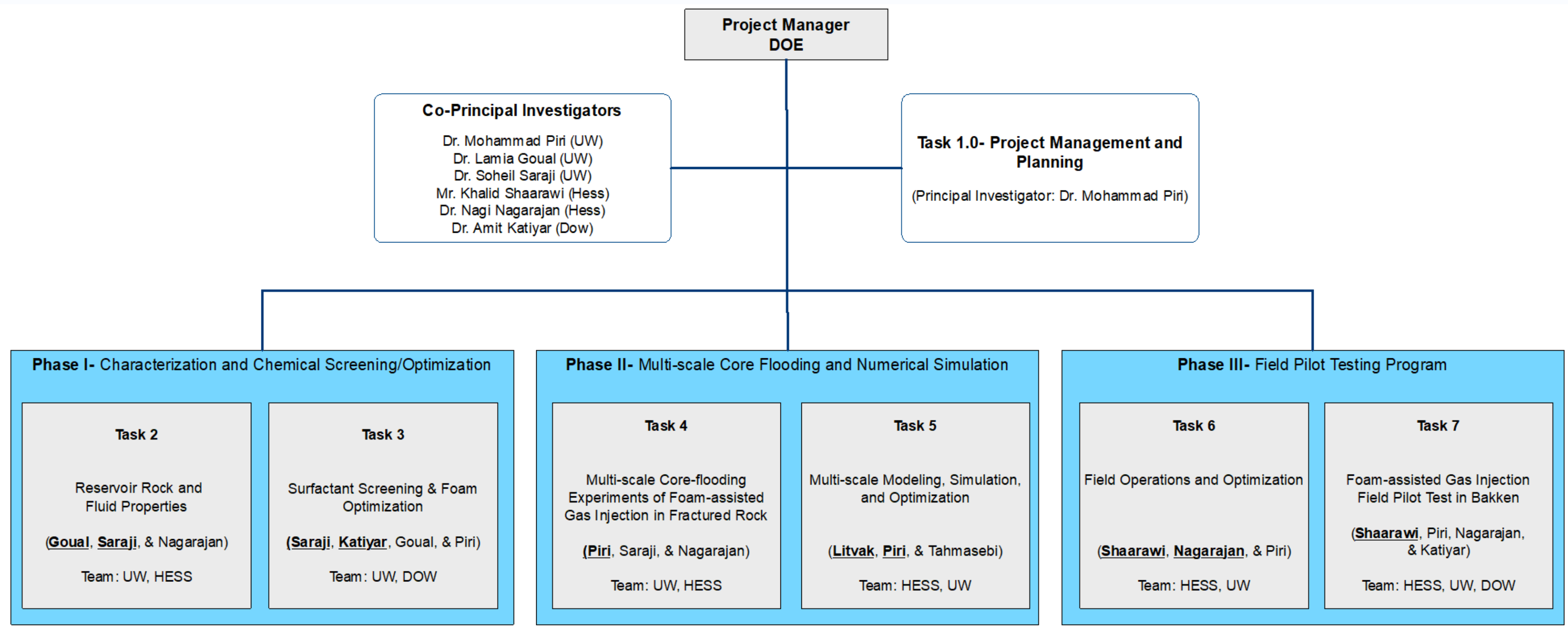
Gantt Chart


Budget period 1
Budget period 2
Budget period 3
Budget period 4
Timeline
Task dependency
Task description
2019
2020
2021
2022
2023
2024
2025
1. Project Management and Planning
1.1 Project Management Plan
1.2 Report Preparation & Submission
1.3 Project Management
1.4 Kick-off Meeting
1.5 Collaborative Meetings
2. Reservoir Rock and Fluid Properties
2.1 Rock and Fluid Sample & Data Collection
2.2 Rock Characterization & Mineralogy
2.3 Fluid Characterization
2.4 Determination of Interfacial Properties & Rock Wettability
3. Surfactant Screening and Foam Optimization
3.1 Surfactant Formulation
3.2 Rock/Brine/Surfactant Interactions
3.3 Foam Stability with/without Dead & Live Crude Oil Samples
3.4 Optimization of Surfactant Concentration and Foam Quality in Proppant Packs
3.5 Develop an Empirical Foam Model
4. Multi-scale Core-flooding Experiments of FAGI in Fractured Rock
4.1 In-situ Characterization of Proppant Wettability
4.2 Micro-scale Study of Fracture-Matrix Interactions
4.3 Macro-scale Investigation of Proppant Wettability & Residual Oil Saturation Effects on Foam Flow in Fractures
4.4 Optimization of FAGI Parameters using Macro-scale Investigations of Oil Recovery in Fractured Rock
4.5 Macro-scale Study of the Effect of Soaking on Oil Recovery during FAGI in Fractured Rock
4.6 Macro-scale Study of Oil Recovery by FAGI in Fractured Rock under Optimum Conditions
5. Multi-scale Modeling, Simulation, and Optimization
5.1 Dynamic, Pore-scale Modeling of 2 and 3-phase Relative Permeabilities in Matrix/fracture
5.2 Laboratory-scale Model Construction & Calibration with Experiments
5.3 Well Pad Simulation Geo-model Construction & Scale-up
5.4 Pad-scale Simulation Model Construction, History Matching, and Predictions
5.5 Development of Guidelines for Field Injection/Soak/ Production Optimization
5.6 Risk Assessment and Mitigation
6. Field Operations and Optimization
6.1 Land and Regulations
6.2 Field/Well Preparation
6.3 Injection System & Design Specifications
6.4 Production Facilities Upgrade
7. Field Pilot Test in Bakken
7.1 Foam-assisted Gas Injection
7.2 Data Surveillance/Acquisition and Success Criteria
M3
M6
Shift due to COVID-19 Pandemic

Gantt Chart (Cont'd)



Organization Chart

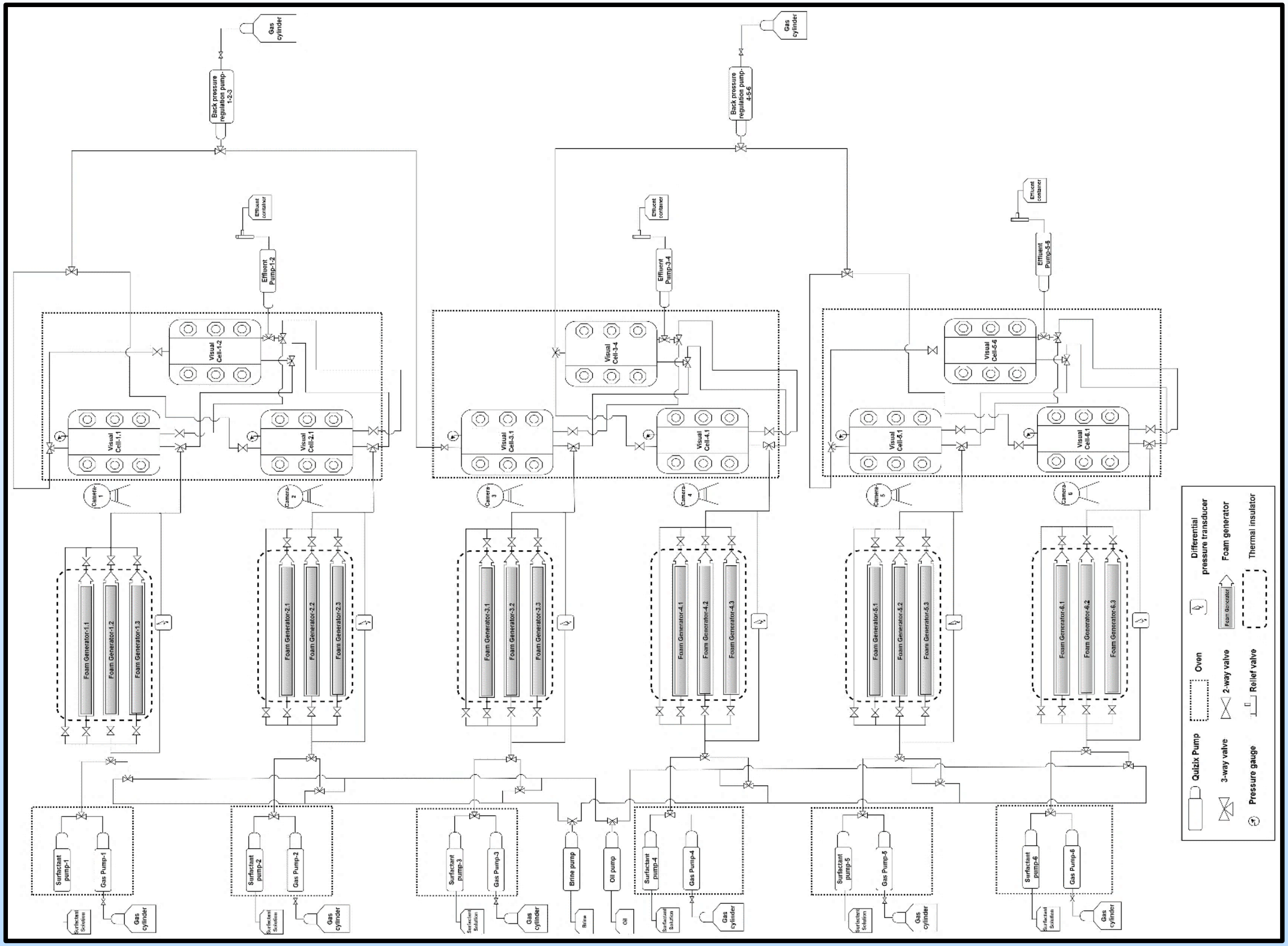


The organizational structure of the project integrates

- 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).

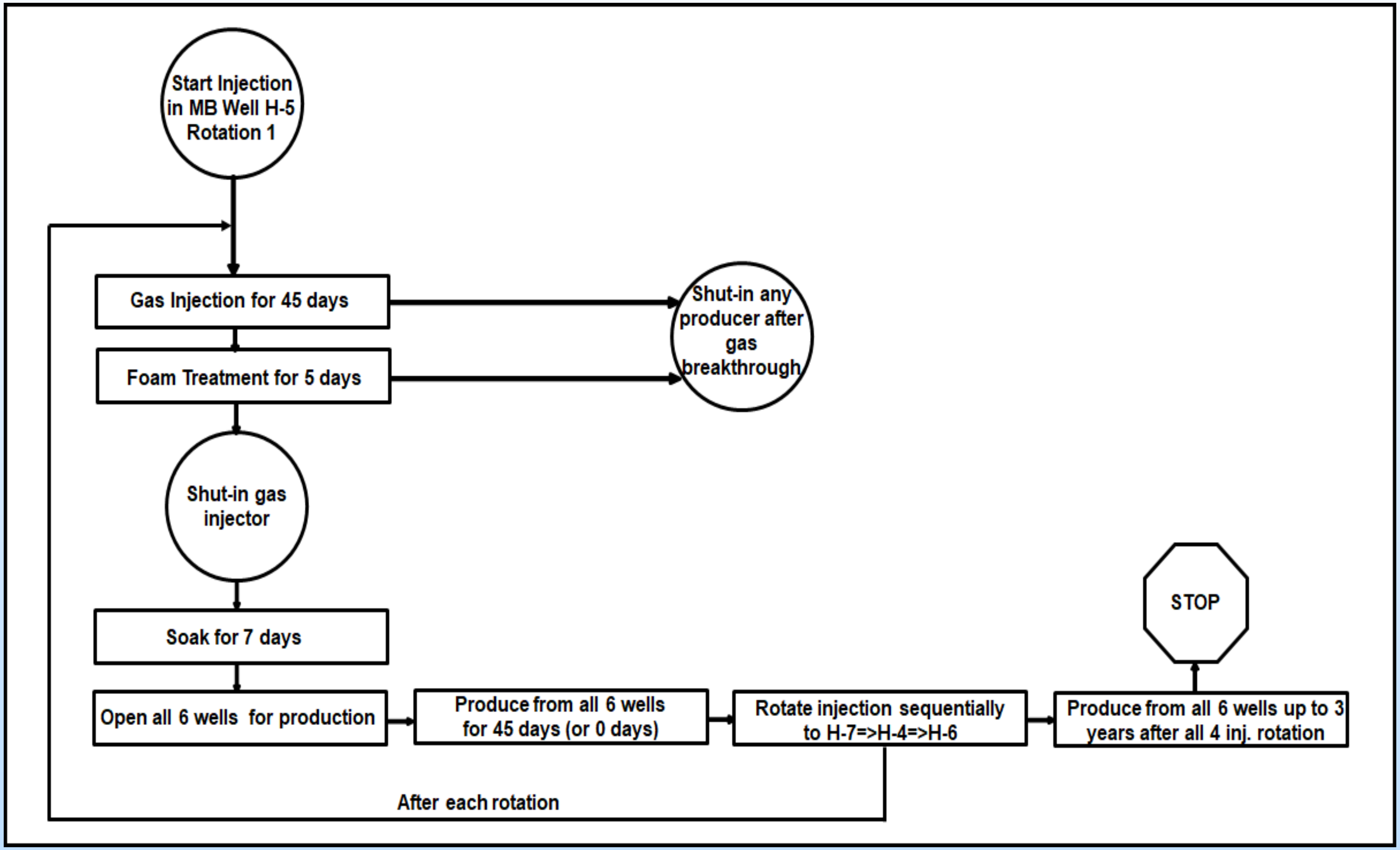
Appendix-I

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



Appendix-II

- Strategy of Injection/Soak/Production for FAGI operation:



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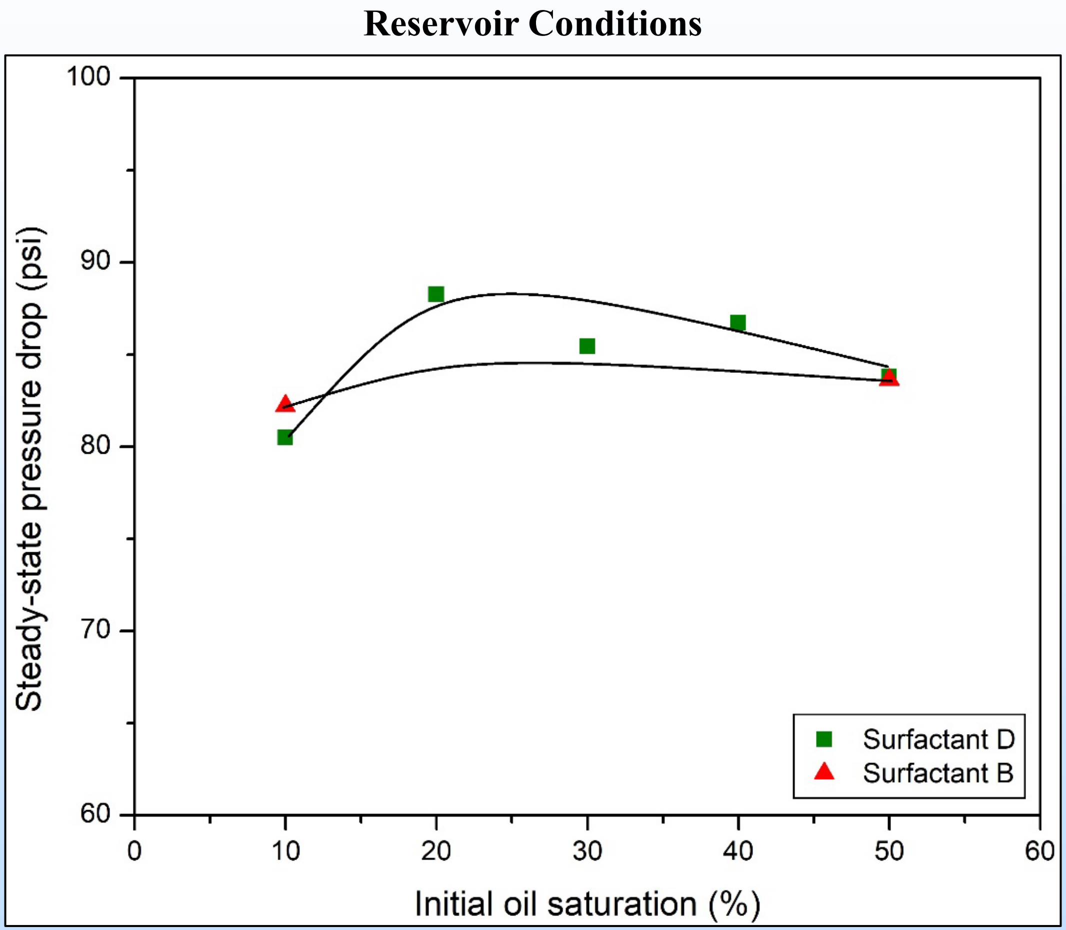
Foam Evaluation Tests (Cont'd)

<u>Initial Oil Saturation Sensitivity in Oil-wet Proppant Packs</u>



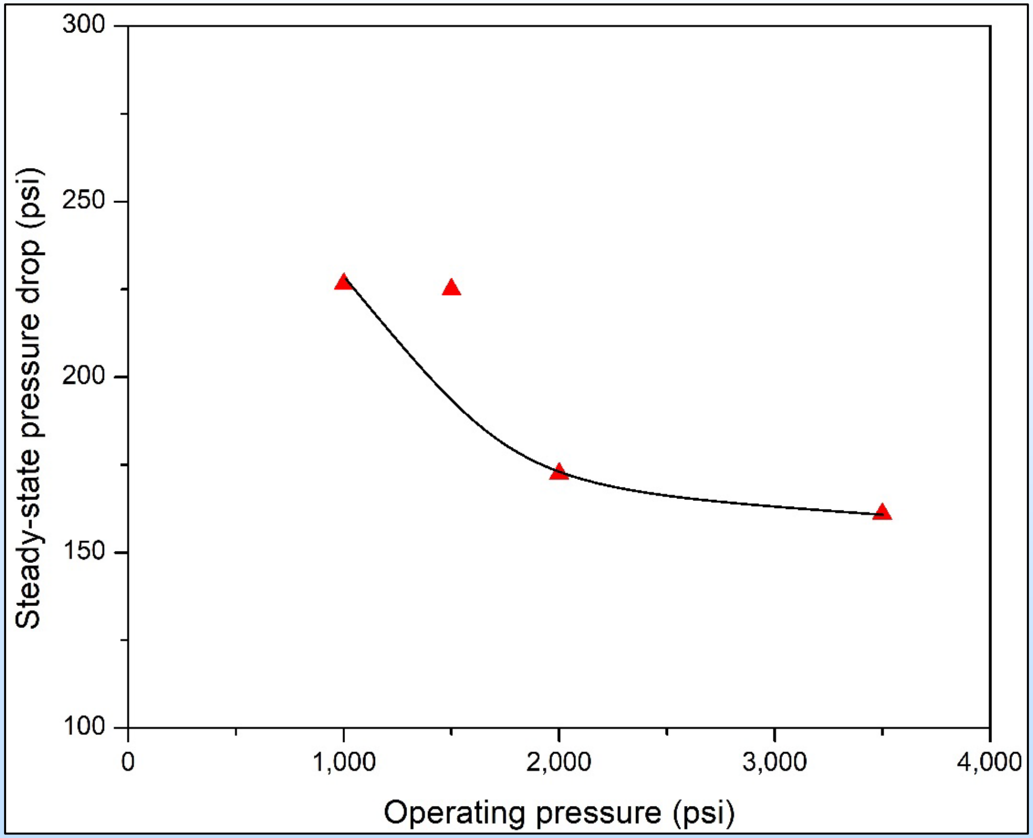
Steady-state pressure drop variations with changes in the initial oil saturation for **<u>surfactants XUR-BLT (B)</u>** and **<u>UWYO-A (D)</u>** using synthetic brine of 200,000 ppm salinity, a foam quality of 85%, a concentration of 0.4 wt%, and 1 cc/min total flow rate in oil-wet proppant packs.

University of Wyoming

Foam Evaluation Tests (Cont'd)

Mitigation of the Effect of Low Operating Pressure on Anionic Surfactant B in Oil-wet Proppant Packs

Reservoir Conditions



Steady-state pressure drop variation with changes in operating pressure for **surfactants XUR-BLT (B)** using synthetic brine of 200,000 ppm salinity, a foam quality of 85%, 0.4 wt% concentration, **5 cc/min total flow rate**, and 10% Soi in oil-wet proppant packs.

Summary

- An efficient and adaptable project management plan in place to ensure continuous progress.
- Followed guidelines from CDC and UW to address the safety of the staff during the pandemic COVID-19, and reported significant technical and scientific progress.
- Characterized the chemical and petrophysical properties of Bakken and Three Forks reservoir rocks and their interactions with brine/oil/surfactants.
- Developed various fluid models with varying number of components with high consistency in predicting PVT properties for EN Ortloff.
- 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.
- Conducted more than **1,000** foam evaluation tests on water-wet, oil-wet, and mixed-wet sandpacks at reservoir conditions using surfactants from Dow chemical company and UW.
- Identified best performing 3 phase-stable, freeze-protected, low-adsorbing, low-viscosity, and non-emulsifying foaming formulations for the harsh Bakken field conditions.
- 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.

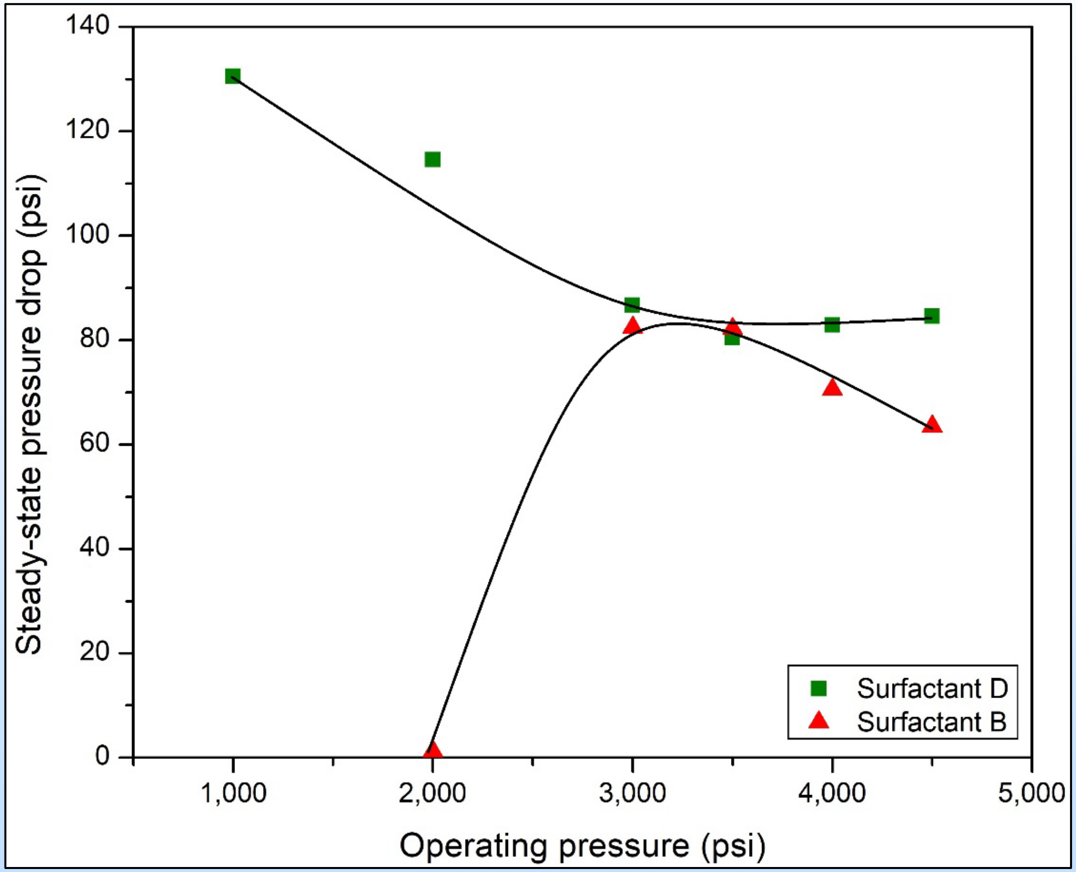
Summary (Cont'd)

- Evaluated the foam performance of selected surfactants in the produced water from Bakken formation 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 aged 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.
- Developed various fluid models with varying number of components with high consistency in predicting PVT properties for EN Ortloff.
- Functionality of the seamless pore network extraction platform was further expanded to produce enhanced pore networks. The platform was then used to obtain conventional sized enhanced pore networks of sandstone and carbonate rock samples.
- Designed an empirical foam model from prior core-flood foaming studies to enable early reservoir simulation studies conducted by the team towards production enhancement with the field pilot.
- Constructed a simplified sector model for the foam simulation evaluation. The history match of the simplified sector model was conducted based on the primary production data.
- Several large uncertainties in both subsurface and foam modeling input parameters were identified, and the expected uncertainty ranges were estimated.
- Started operation readiness to review the procedures for field operations and optimization.

Foam Evaluation Tests (Cont'd)

Operating Pressure Sensitivity -- Oil-wet Proppant Packs

Reservoir Conditions

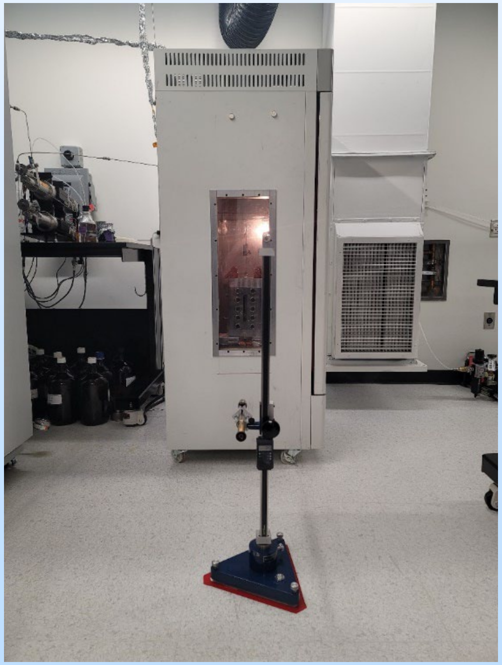


- For anionic surfactant B, a rise in operating pressure mitigates the adverse effect of low pressure as it increases the density of methane, making it more hydrophobic, which improves the interactions between hydrophobic tails of surfactants and gas at the gas-water interfaces, resulting in the generation of stable foams.
- Amphoteric surfactant D shows insensitivity to low operating pressure due to its stabilizers which provide stable interfaces at lower pressures and better tolerance to oil.

Steady-state pressure drop variations with changes in operating pressure for **surfactants XUR-BLT (B)** and **UWYO-A (D)** using synthetic brine of 200,000 ppm salinity, a foam quality of 85%, concentration of 0.4 wt%, 1 cc/min total flow rate, and 10% Soi in oil-wet proppant packs.

Foam Evaluation Facility (Cont'd)

- An experimental setup consisting of **two core-flooding systems** was fabricated and commissioned to conduct Gas-Alternating-Foam Injection experiments on oil-wet fractured core samples.
- Various injection scenarios, including gas flooding followed by foam injection and gas-alternating foam injection, are studied.



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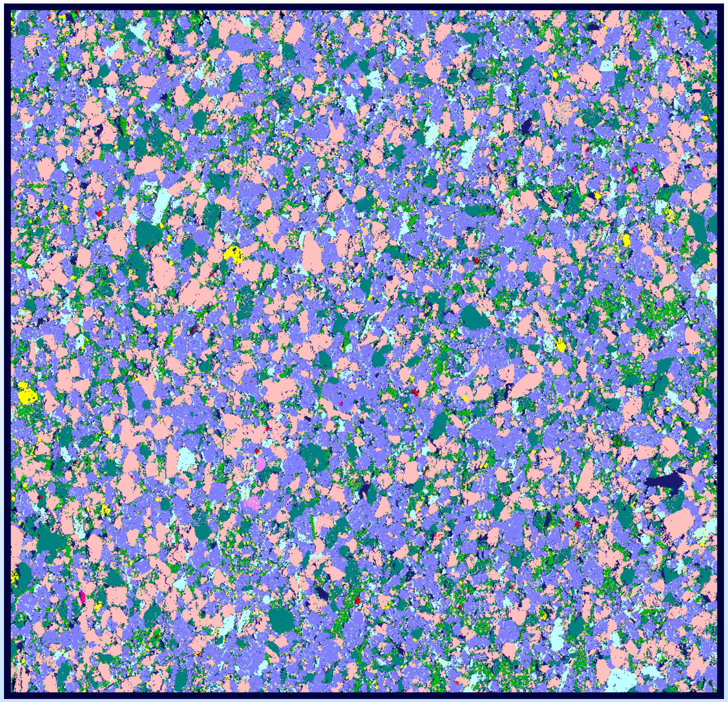
Technical Approach (Cont'd)

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	10/01/2023*	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	01/01/2024*	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 1 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.

Reservoir Rock Mineralogy



	Mineral	Area Percent
	Dolomite	32.59
	Quartz	27.72
	Feldspars	13.61
	Pores	9.81
	Calcite	8.41
	Mica Minerals	6.35
	Pyrite	1
	Rutile	0.12
	Apatite	0.11
	Trace Minerals	0.07
	Gypsym/Anhydrite	0.07
	Chamosite	0.06
	Clinochlore	0.04
	Zircon	0.02
	Expansible Clays	0.01
	Kaolinite	0.01

QEMSCAN mineralogy map of Middle Bakken reservoir core samples show the dominance of dolomite and quartz on a 3 mm^2 area.

- Whole core samples, flow-through cleaning, and salt removal
- Crude oil samples: dynamic aging & core-flooding tests
- Proppants used in the pad

Technology Background

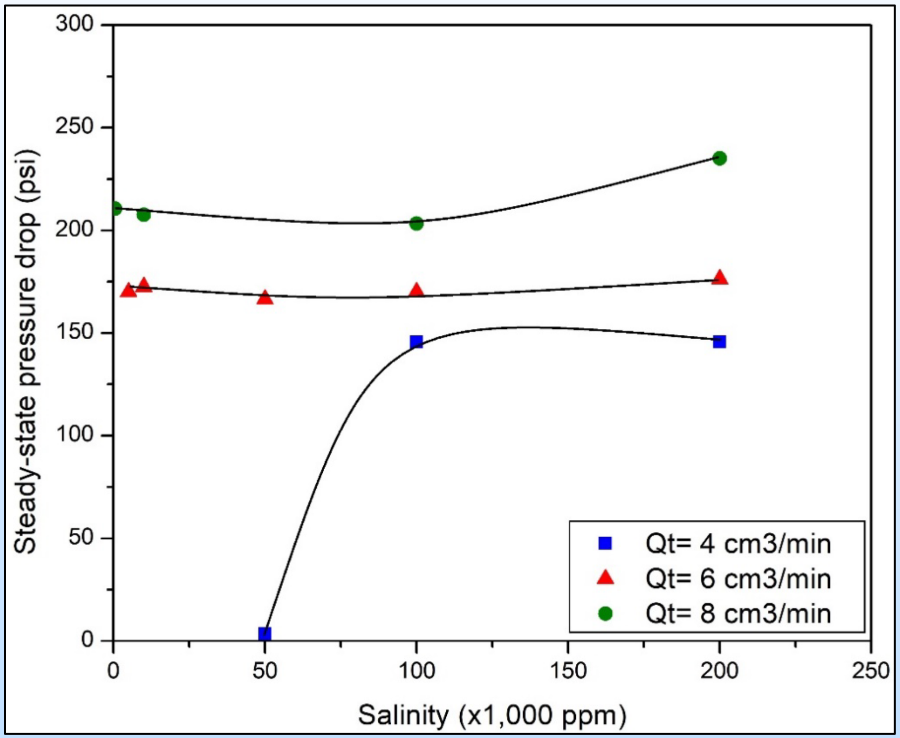
- Enhanced oil recovery (EOR) processes are of paramount importance to address the problem of low primary recovery of hydrocarbons from unconventional reservoirs.
- The proliferation of hydraulic fracturing further compliments to the success of the EOR processes by providing a larger surface area to 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.

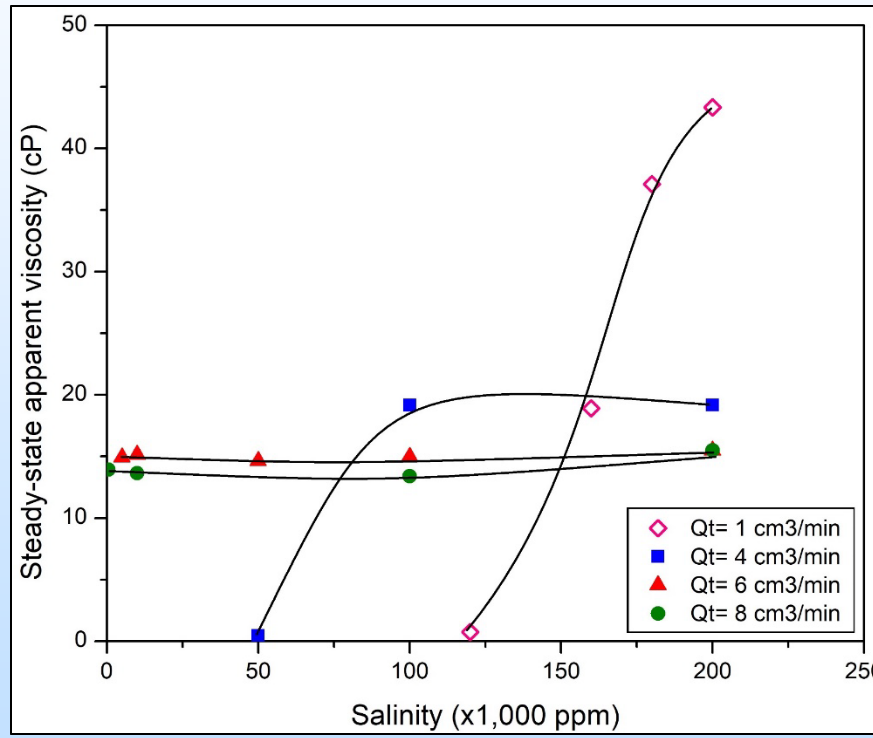
Foam Evaluation Tests (Cont'd)

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.