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

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U.S. Department of Energy
National Energy Technology Laboratory
Oil & Natural Gas
2020 Integrated Review Webinar

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 novel Enhanced Oil Recovery (EOR) technology. Additionally, we aim at resolving some of the pivotal issues associated with gas containment in this field.

- The initial project duration is four years (Oct. 1, 2019 to Sep. 30, 2023).

Project Participants

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

Funding (DOE and Cost Share)

	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%

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.
- The foam can enhance the macro-scale sweep efficiency by mitigating the effect of heterogeneity, gas segregation, and viscous instability which are profound in gas only injection strategies.

Technical Approach

- A detailed project management plan is developed to sketch a clear path to accomplish the project deliverables.
- Reservoir rock and fluid samples are acquired and their chemical and physical properties are characterized.
- A rigorous surfactant screening is performed to identify 3-5 potential candidates for the field application.
- A state-of-the-art foam generation system is fabricated for evaluation of the selected chemicals and optimization of the foam parameters.
- Multiscale core-flooding and numerical simulations are 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 is developed to address critical issues such as land and regulations, field/well preparation, injection systems, and design specifications.

Technical Approach (Cont’d)

Project schedule

Milestone Title & Description	**Planned Completion Date**	**Status**
M1 - Update Project Management Plan	10/31/2019	Completed
M2 - Determine Bakken reservoir rock wettability	06/30/2020	Completed
M3 - Identify optimum chemical formulation for cycle 1 of pilot test	09/01/2020	Completed
M4 - Develop a pad-scale model for foam EOR	10/01/2020	Completed
M5 - Implement first cycle of the field pilot test	11/30/2021	
M6 - Re-assess optimum chemical formulation and foam properties for cycle 2 of the field pilot test	10/01/2021	
M7 - Validate the pad-scale model for foam EOR against data from cycle 1 of the field pilot test	01/01/2022	
M8 - Implement second cycle of the field pilot test	03/31/2023	
M9 - Validate the pad-scale model for foam EOR against data from cycle 2 of the field pilot test	06/01/2023	
M10 - Evaluate the field pilot test success	09/30/2023	

Technical Approach (Cont'd)

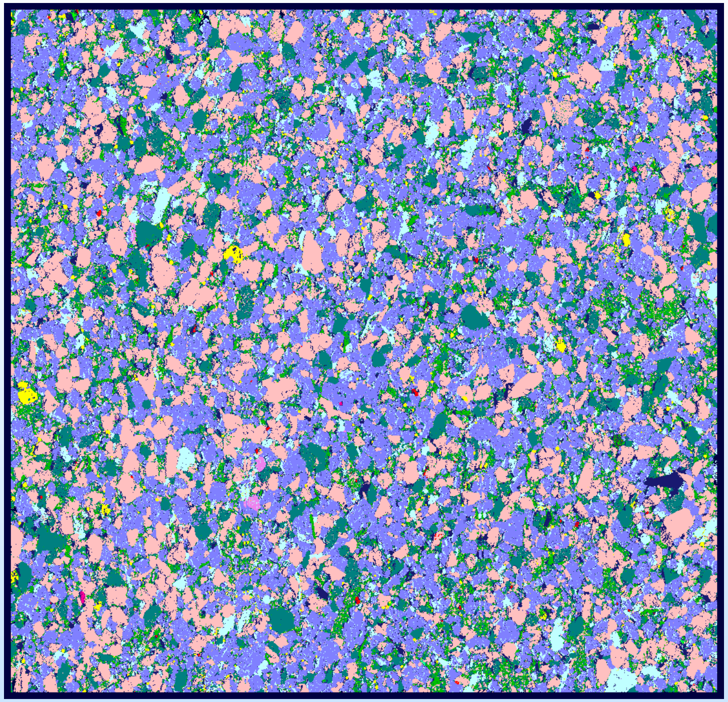
Risk Assessment and Mitigation

- Potential injectivity challenges due to foam injection that may result in possible lower gas injection rates.
  - ➢ Mitigation measures: Increase injection duration to meet required injection volumes.
- Challenges to forming foam of needed quality (developing stable foam, maintain reasonable ΔP across fractures).
  - ➢ Mitigation measures: Vary surfactant concentration and gas-to-water ratio to regain required foam quality.
- Early gas breakthrough in neighboring wells in spite of foam injection for gas performance.
  - ➢ Mitigation measures: Shut-in wells as needed to divert gas flow into rock matrix.

Pilot success to be measured using the following criteria:

- Meeting target injection rates and volumes
- Ability of foam to control gas mobility and reduce/eliminate gas breakthrough
- Incremental production due to EOR process
- Gas utilization factor
- Surface equipment reliability

Reservoir Rock Mineralogy

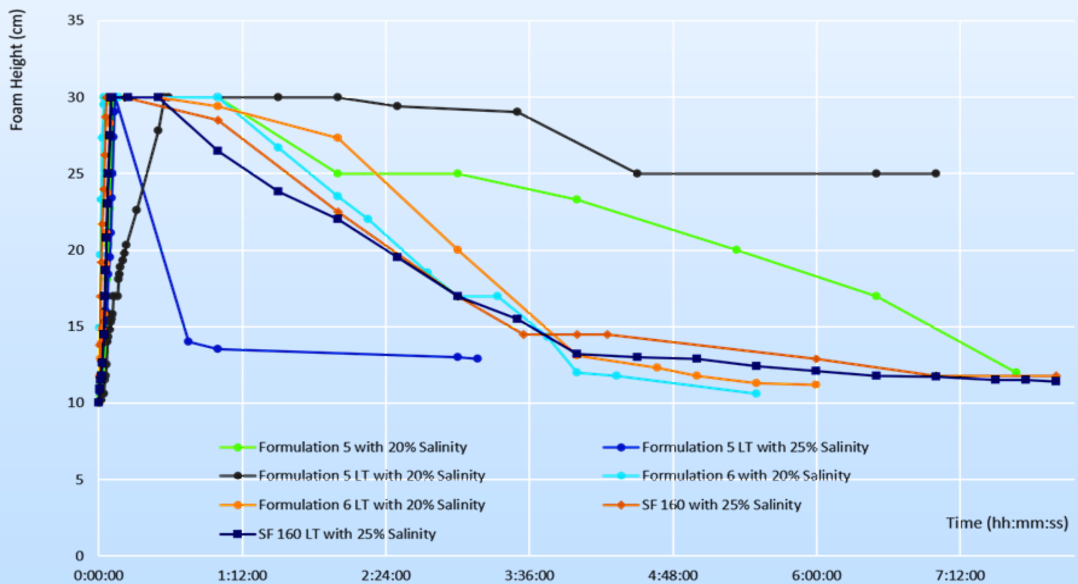


	Mineral	Area Percent
	Dolomite	32.59
	Quartz	27.72
	Feldspars	13.61
	Pores	9.81
	Calcite	8.41
	Mica Minerals	6.35
	Pyrite	1
	Rutile	0.12
	Apatite	0.11
	Trace Minerals	0.07
	Gypsym/Anhydrite	0.07
	Chamosite	0.06
	Clinochlore	0.04
	Zircon	0.02
	Expansible Clays	0.01
	Kaolinite	0.01

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

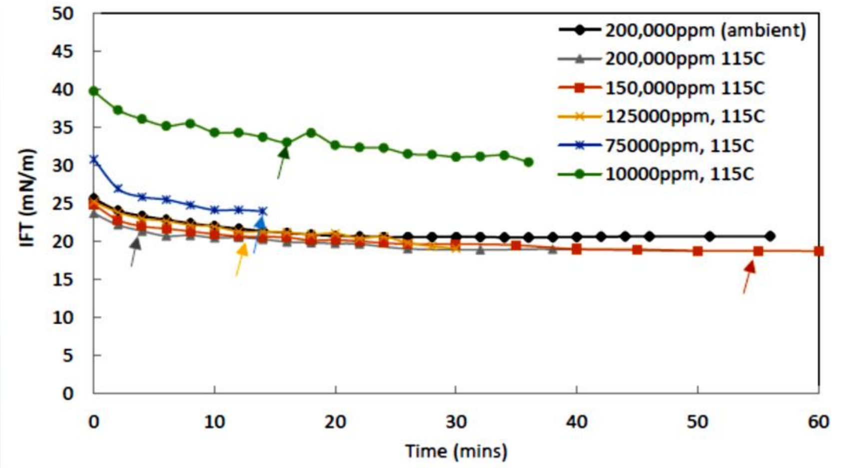
Surfactant Screening

- More than forty (40) foaming formulations were investigated for their aqueous stability at high temperature (115 °C) and the top five (5) chemicals were identified initially for additional studies.
- Bulk foam tests, static adsorption test, and emulsion tendency tests were conducted on the selected surfactants, and their winterized (LT) versions to identify the best performing surfactant(s) for further studies.

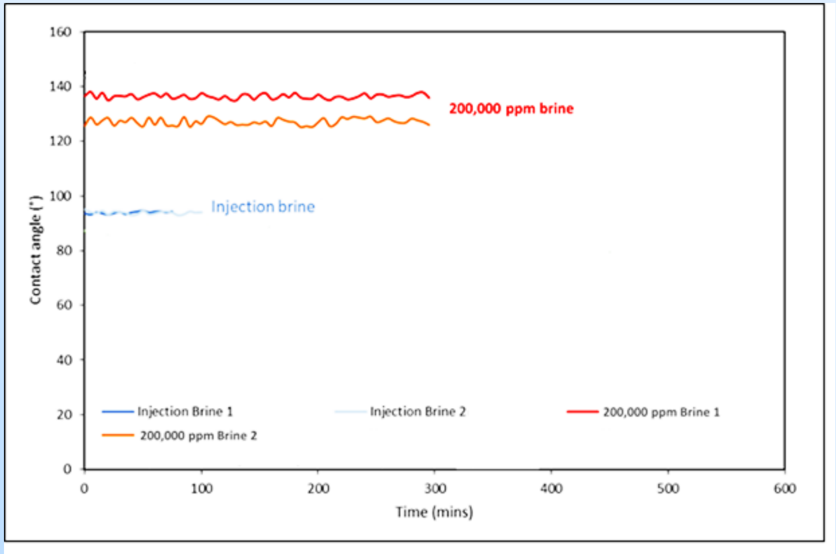


Bulk foam test: foam height vs time comparison for the selected surfactants; LT versions perform better compared to the normal versions.

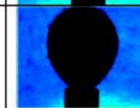
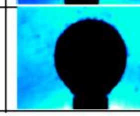
Interfacial Tension and Wettability



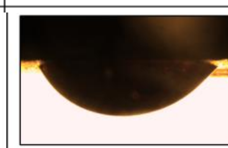
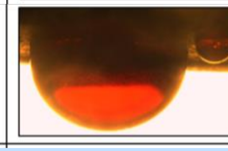
Dynamic oil-brine IFT with Bakken crude oil and various brine salinities at 3,500 psi and 115 ºC temperature.



Contact angle variation with time on aged Bakken rock chips for various brine and surfactants.

Salt concentration	Before heating	After heating
200,000 ppm		
150,000 ppm		
125,000 ppm		
75,000 ppm		
10,000ppm		

Salt precipitation when Bakken oil and brine solutions are brought in contact at high-pressure and high temperature conditions.

	Average Contact angle (°)	Contact angle Measurement
200,000ppm brine	132	
Injection brine (Method 2)	94	

Images of average contact angles on aged Bakken rock chips. Injection brine salinity: 500 ppm.

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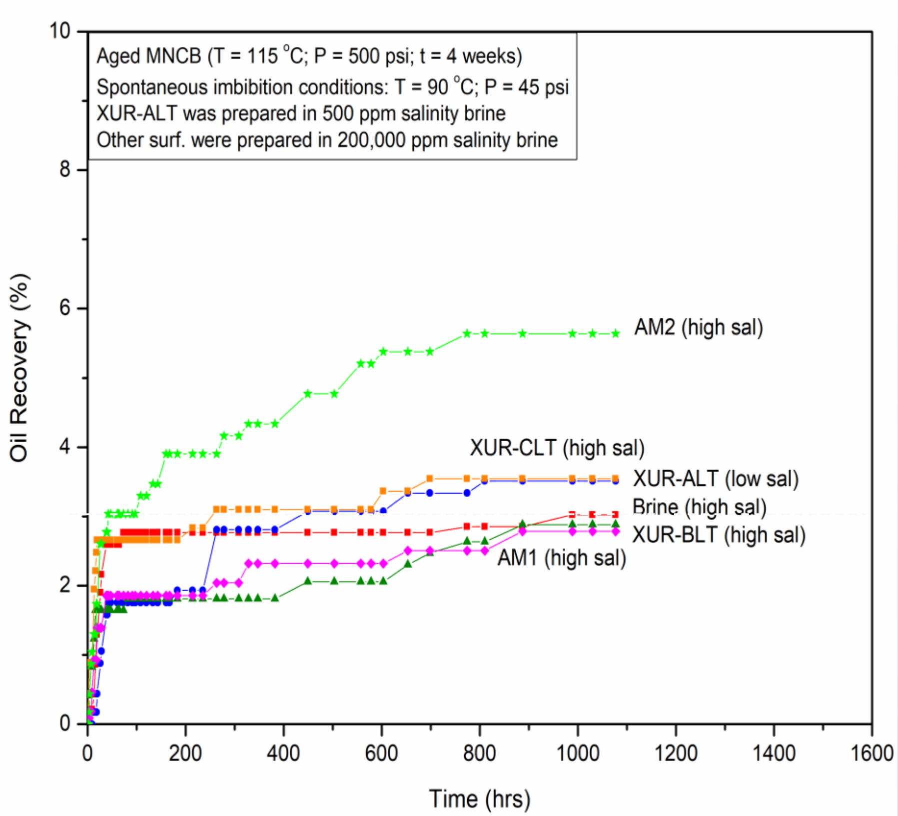
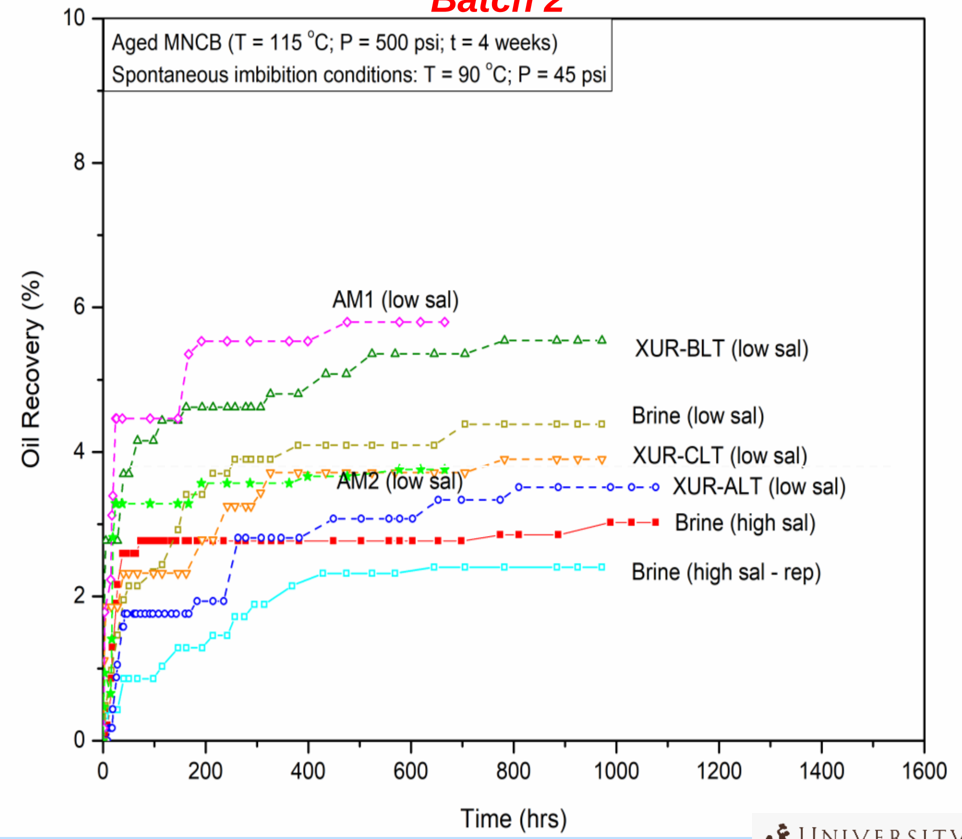
Spontaneous Imbibition Tests

- High temperature spontaneous imbibition tests were conducted on the aged Minnesota Northern Cream Buff (MNCB) rock samples at high-temperature conditions. In total, five (5) surfactant solutions were prepared with high and low salinity brine solutions, respectively. The rock samples had been aged with Bakken crude oil at HTHP conditions for a period of four weeks.

Batch 1



Batch 2



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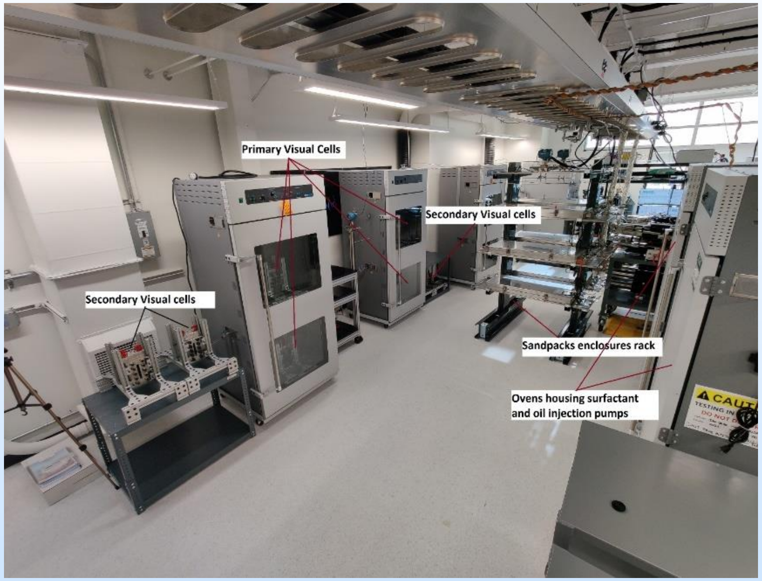
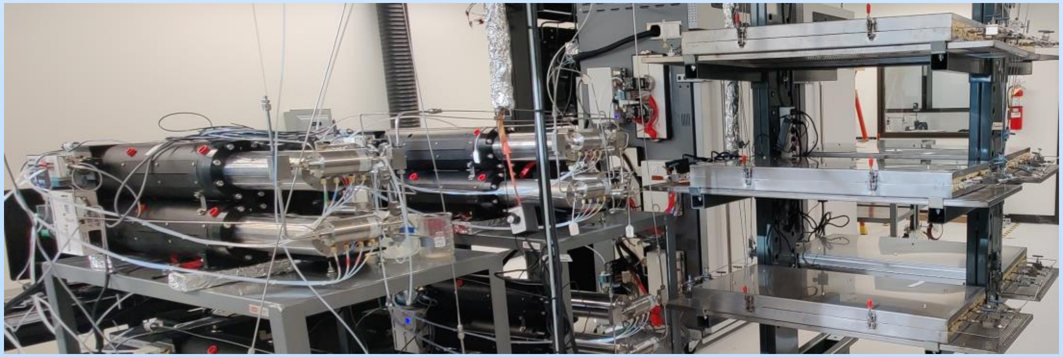
Foam Evaluation Facility

- A state-of-the-art HPHT foam generation and evaluation system was fabricated from scratch. A total of **Eighteen (18)** foam generation mixed-wet proppant packs have been incorporated into the platform (Hastelloy components, Quizix precision pumping systems, Visual cells, Methane detection sensors, etc.).





- Efficient and simultaneous HC gas foam generation and evaluation for different surfactants at high-pressure and high-temperature conditions.
- Study 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.
- We generate the foam at high-pressure (3,500 psi) and temperature (115 °C) conditions.

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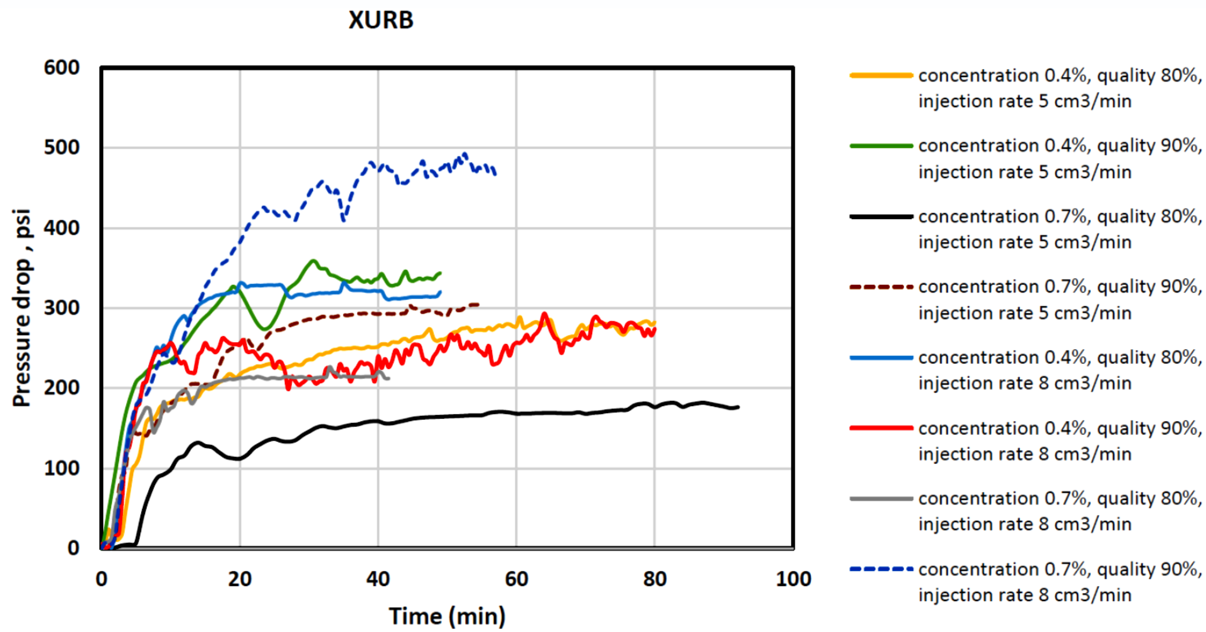
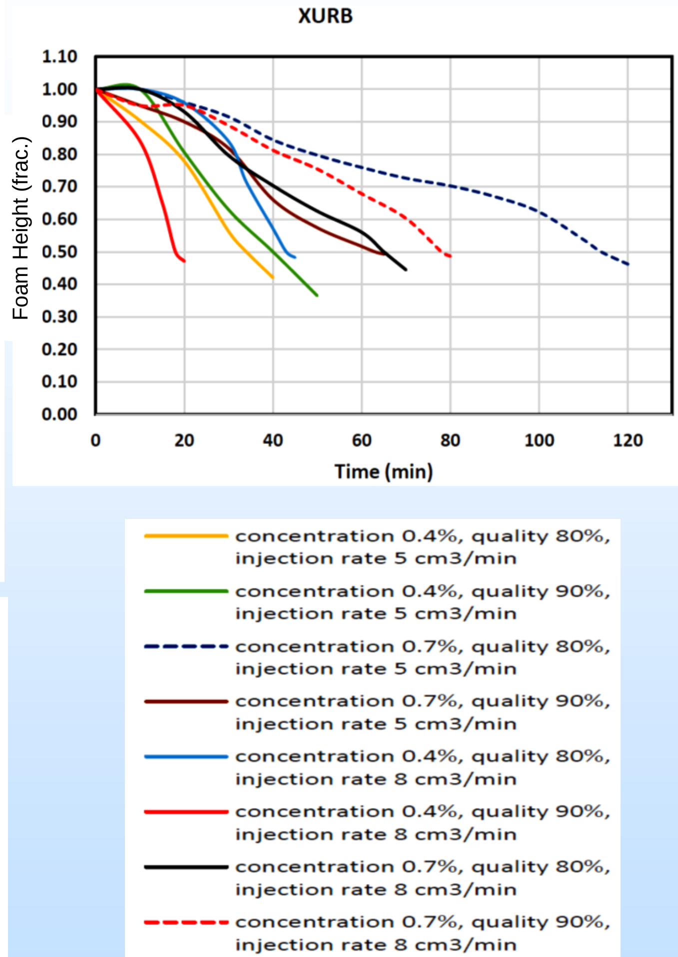
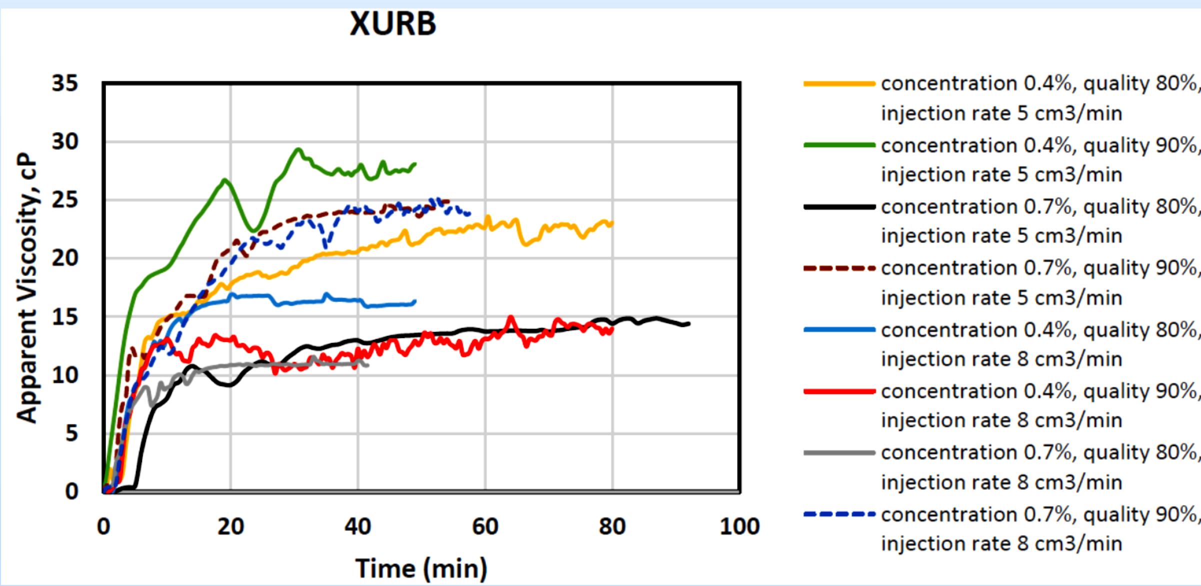
Foam Evaluation Experiments





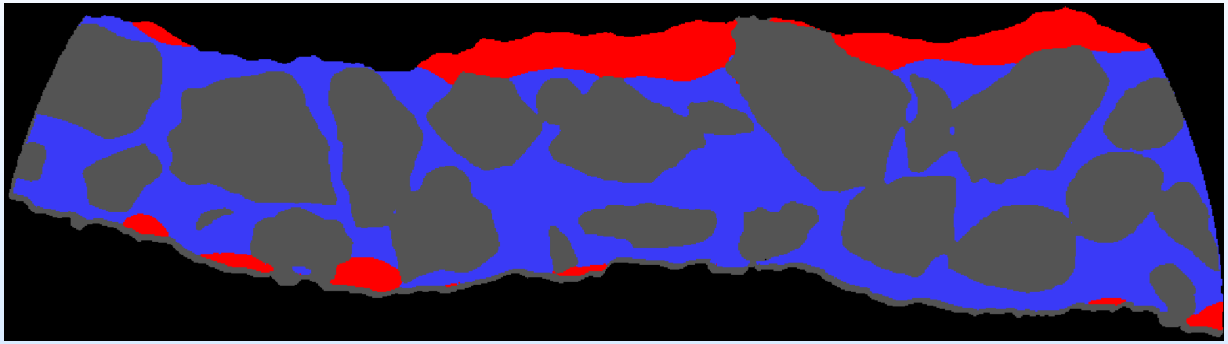
Half-life for XUR-BLT



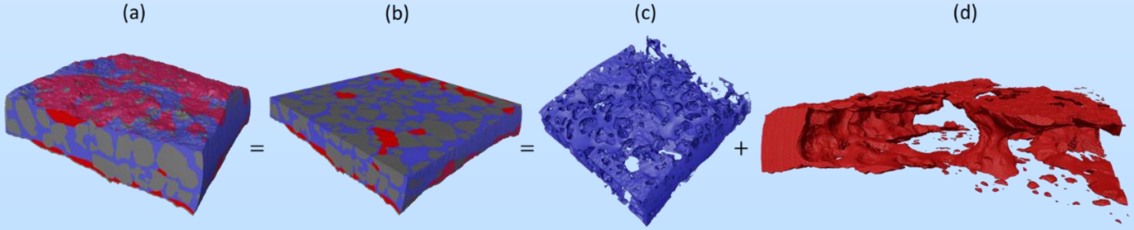
Pressure drop (top) and apparent viscosity (bottom) for surfactant XUR-BLT

Multiscale Core Flooding

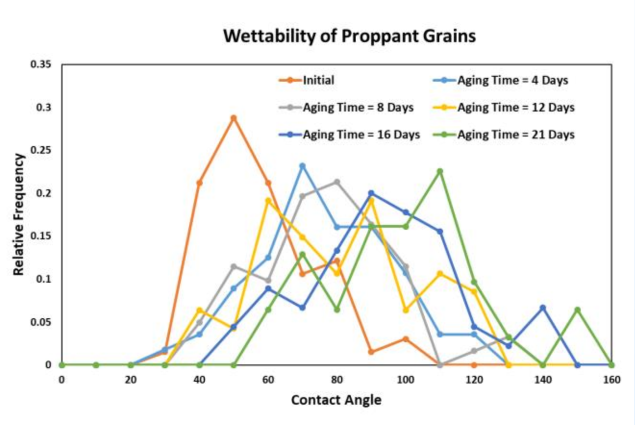
- A HPHT three-phase miniature core-flooding system integrated with a high-resolution x-ray micro-CT scanner was used to perform core-flooding tests on a miniature fractured reservoir rock sample for the purpose of proppant and fracture wall in-situ wettability characterization.

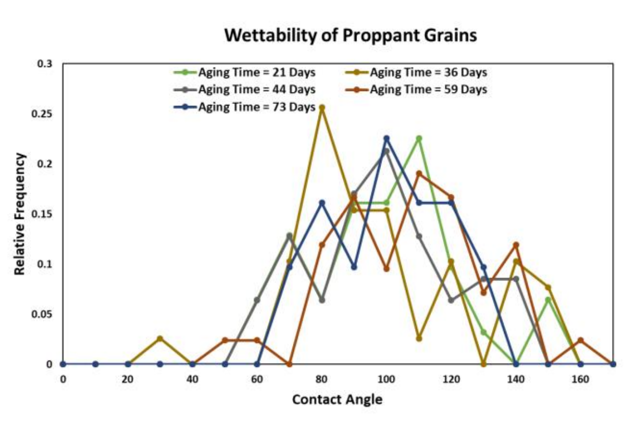


A segmented image of a slice obtained after introducing the doped oil into the proppant pack (red, blue, and gray represent oil, brine, and and proppant grains, respectively.



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





Fluid Properties; EOS Models

- Several EOS models were developed to describe EN Ortloff reservoir fluids.
- Challenges such as high computational cost, optimizations related specific simulations, and large CPU time were addressed by lumping the 15 components model to reduced component fluid models, as low as 5 components.

	EOS Model Component Slate							
EOS Models	15-C	10-C	9-C	8-C	7-C	6-C	5-C	Black Oil
	N_2	N_2	C_1N_2	C_1N_2	C_1N_2	$N_2CO_2C_1$	$N_2CO_2C_1$	Oil
	CO_2	CO_2	CO_2	C_2	$C_2C_3CO_2$	C_2C_3	$C_2C_3C_4C_5$	Gas
	C_1	C_1	C_2	C_3CO_2	C_4-C_5	C_4C_5	C_6-C_{19}	
	C_2	C_2	C_3	C_4-C_5	C_6-C_{14}	C_6-C_{19}	C_{20}-C_{29}	
	C_3	C_3	C_4-C_5	C_6-C_{14}	C_{15}-C_{19}	C_{20}-C_{29}	C_{30+}	
	iC_4	C_4C_5	C_6-C_{14}	C_{15}-C_{19}	C_{20}-C_{29}	C_{30+}		
	nC_4	C_6-C_{14}	C_{15}-C_{19}	C_{20}-C_{29}	C_{30+}			
	iC_5	C_{15}-C_{19}	C_{20}-C_{29}	C_{30+}				
	nC_5	C_{20}-C_{29}	C_{30+}					
	C_6	C_{30+}						
	C_7-C_{10}							
	C_{11}-C_{14}							
	C_{15}-C_{19}							
	C_{20}-C_{29}							
	C_{30+}							
Applications	Reservoir/ Facilities/Wellbore Simulation	Hydrocarbon Gas Injection Simulations	CO_2 Injection Simulations	Ethane Injection Simulations	Large Scale Resevoir Simulations	Large Scale Resevoir Simulations	Large Scale Resevoir Simulations	PTA/RTA & Surveillance Data Interpretation
General Comments	Large EOS Models Required for Accurate EOR Processes Simulation	Large Scale Reservoir Simulations Require Moderate # of EOS Components	CO_2 Injection Simulations ==> Special Handling of CO_2	Etahne Injection in Unconventional Promising	Lesser # of Components ==> Faster Computations	Lesser # of Components ==> Faster Computations	Lesser # of Components ==> Faster Computations	Key to EOR Project Monitoring

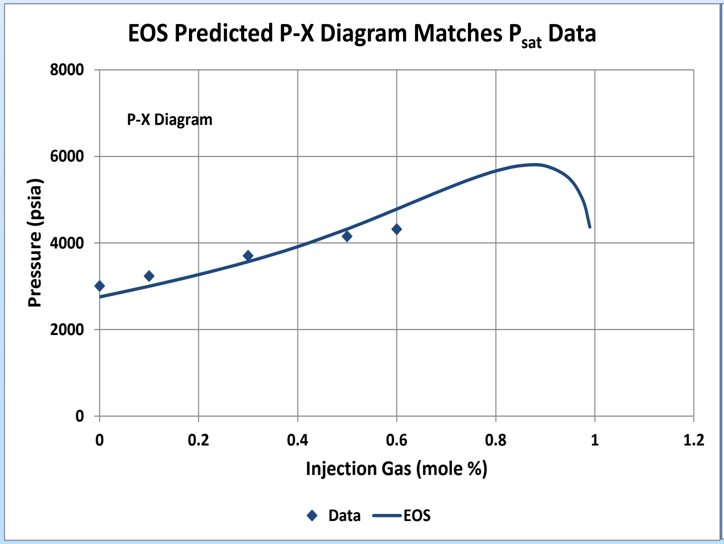
EOS models' component slate and applications

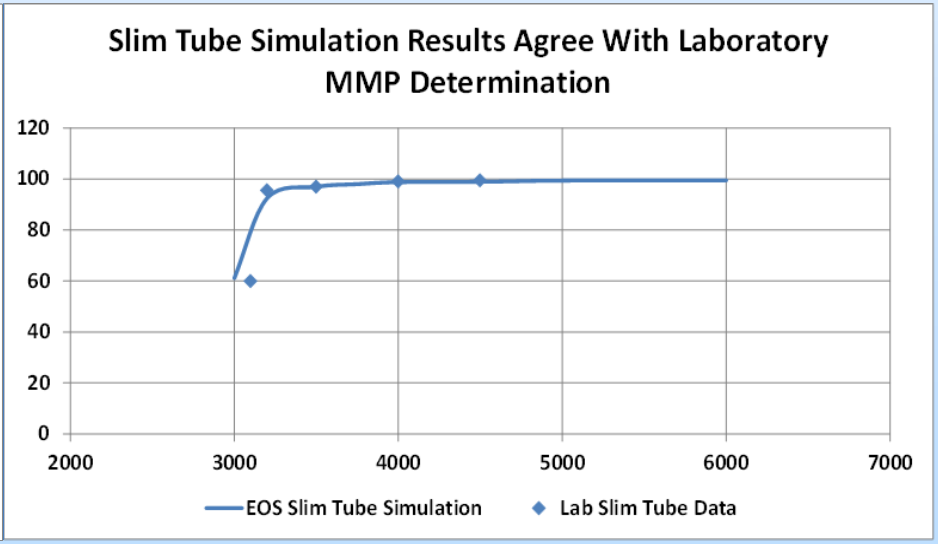
Fluid Properties; EOS Models (Cont'd)

Property	EOS Models						
	15-C	10-C	9-C	8-C	7-C	6-C	5-C
Bubble Point Pressure (psia)	2870	2868					
Separator Flash GOR (SCF/STB)	1112	1175	1147	1154	1178	1216	1225
Stock Oil Density (lb/ft3)	50.5092	50.5511	50.4874	51.7435	51.7679	52.7785	52.2654
Stock Oil Density (°API)	43	43	43	39	39	39	39
Oil FVF @ Bubble Point P(RBBL/STBBL)	1.734	1.817	1.778	1.789	1.784	1.965	1.795
Oil Density @ Bubble Point P (lb/ft3)	37.5856	36.2356	36.8948	37.6525	37.6588	35.9005	36.3745
Oil Viscosity @ Bubble Point P (cP)	0.152	0.150	0.146	0.166	0.152	0.130	0.168

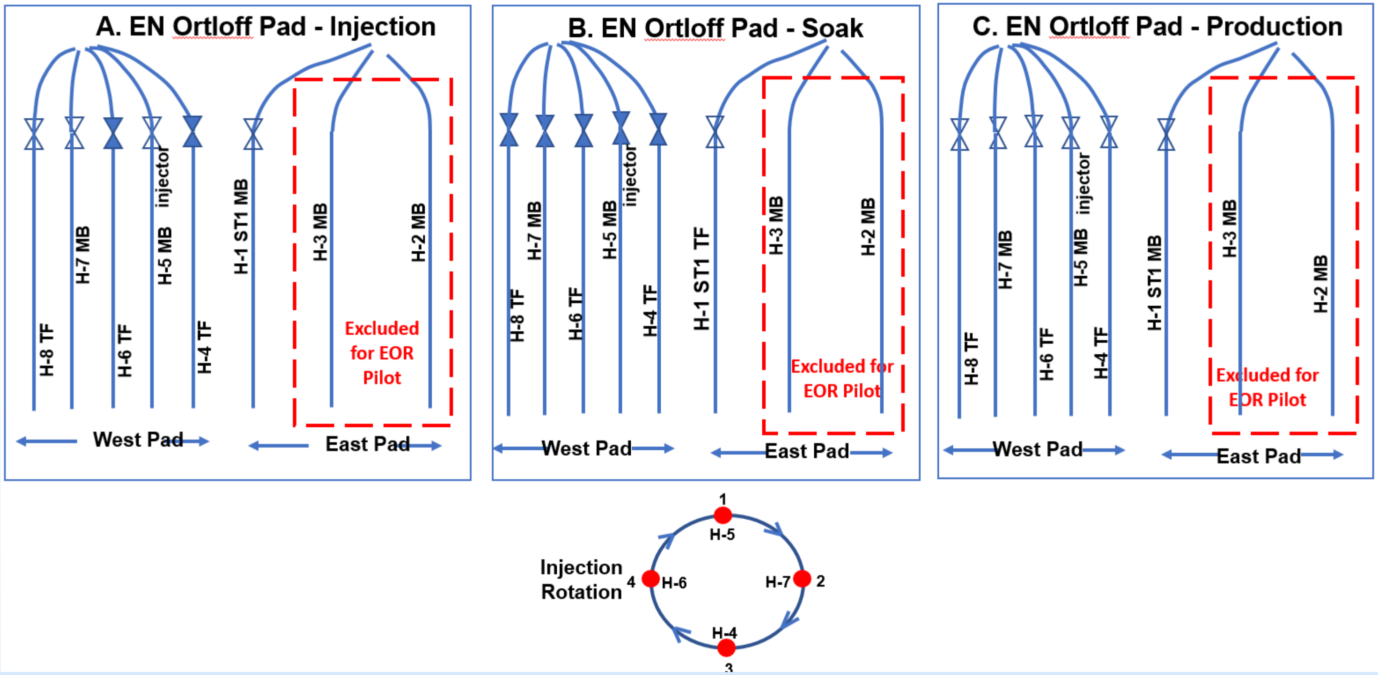
Comparison of predicted PVT properties of Bakken fluid by several EOS models.

- Predictions of various PVT properties of EN Ortloff Bakken fluid as function of reservoir pressure and temperature from different EOS models were consistent and showed strong agreements.





Field Pilot Test Plan



Rot #	Process	Duration	Injection Strategy
1	Inject	45 days	Inject in H-5, SI H-4 and H-6 at GBT
	Soak	7 days	Shut in all wells
	Produce	45 days	Produce all wells
2	Inject	45 days	Inject in H-7, SI H-6 and H-8 at GBT
	Soak	7 days	Shut in all wells
	Produce	45 days	Produce all wells
3	Inject	45 days	Inject in H-4, SI H-5 and H-1 at GBT
	Soak	7 days	Shut in all wells
	Produce	45 days	Produce all wells
4	Inject	45 days	Inject in H-6, SI H-5 and H-7 at GBT
	Soak	7 days	Shut in all wells
	Produce	45 days	Produce all wells

- Test plan will rotate injection between 4 wells; schematic shown is for the initial injection well and will be repeated as shown in the table
- Initial rotation will not include foam and serve as a baseline for gas only injection

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Simulation and Optimization

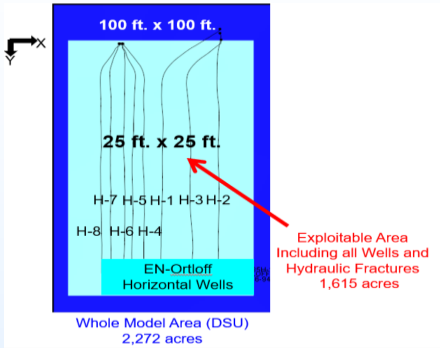
DSU Scale Reservoir Simulation Model Development and Results

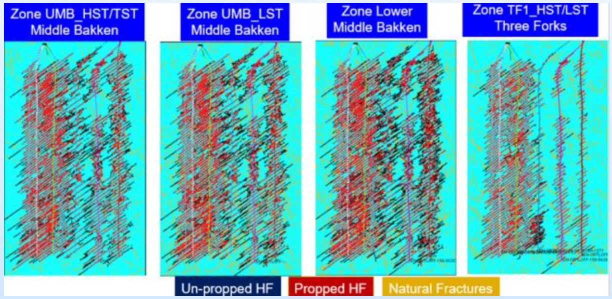
Geological and Simulation Model

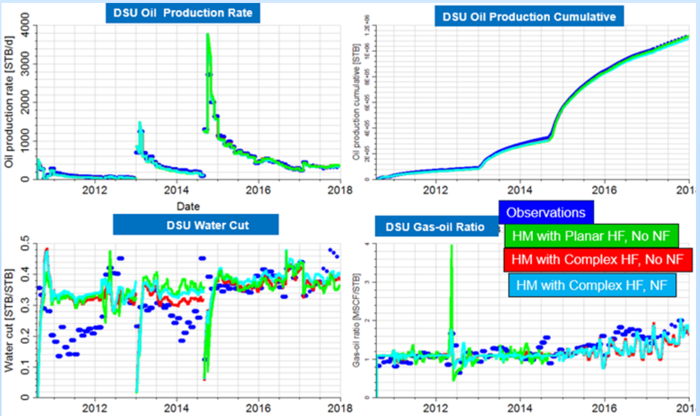
- 52 Layers in the EN Ortloff geological model with input from Well logs and core data from 8 appraisal wells (including 3 cored wells).
- Built an upscaled 12-layer simulation model with upscaling of petrophysical properties for gas and gas foam EOR evaluations.
- Hydraulic and natural fracture network model was generated and superimposed on simulation model. Structured grid with a horizontal grid block size of 25’x25’ and a dual porosity/dual perm model was built.

History Matching

- Three-stage history matching runs were conducted to follow the sequence of production starting from H1 through H8. Various reservoir and flow parameters (transmissibility factors, compaction, etc.) were adjusted in the HM.
- Good history matches were achieved for oil, water, and gas rates along with the bottom hole pressure matches. And reasonable matches were obtained for ‘difficult-to-match’ water cut and GOR trends.







Model validation for evaluations of gas-only and gas-foam injection EOR; HM- History Matching.

Future Plans

- Continue according to the project management plan, and prepare quarterly progress reports, financial updates, and milestone reports.
- Collect surface oil and gas samples from EN Ortloff wells and recombine them to the original GOR of the in-situ fluid for validation of the fluid properties specific to EN Ortloff.
- Develop a pilot monitoring and surveillance plan that allows for proper data acquisition and analysis.
- Optimize the injection strategy towards the desired production enhancement during the foam pilot.
- Develop and improve calibrated empirical foam model that would enable conducting more realistic reservoir simulations toward designing the pilot implementation strategy. Additionally, determining optimum foam parameters using the state-of-the-art foam generation setup at UW for the rigorous evaluation of foaming agents.
- Produce large quantities of the foaming formulation required for the field trial
- 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.
- 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.

Summary

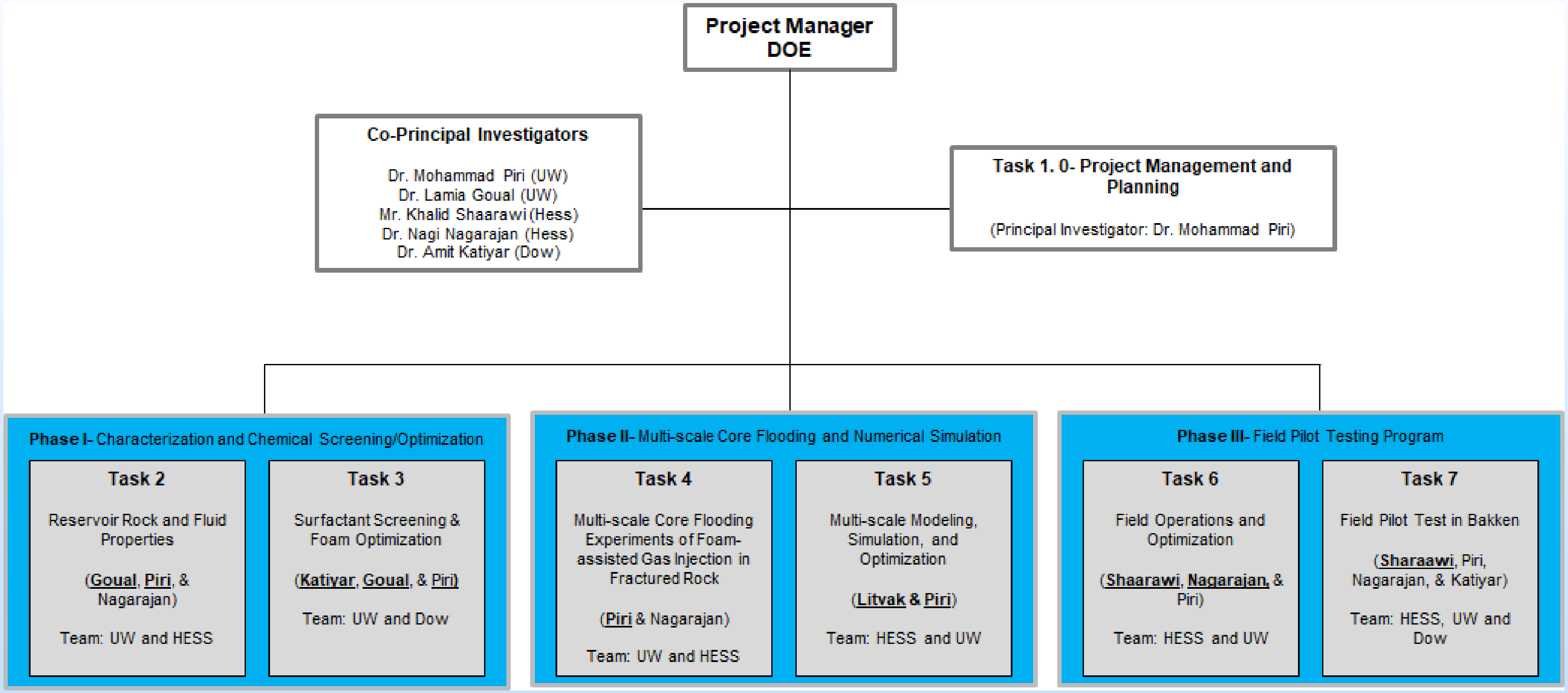
- An efficient and adaptable project management plan was developed to ensure continuous progress.
- Followed guidelines from CDC and UW to ensure the safety of the staff during the pandemic, while maintaining progress under different laboratory and modeling tasks.
- Developed various fluid models with varying number of components with high consistency in predicting PVT properties for EN Ortloff.
- Developed three phase-stable, freeze-protected, low-adsorbing, low-viscosity, and non-emulsifying foaming formulations for the harsh Bakken field conditions.
- 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.
- Completed the fabrication of a state-of-the-art HPHT Hastelloy foam generation and evaluation platform. system.
- 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.
- Made significant progress in DSU-scale simulations. Updated the DSU-scale simulation model to simulate surfactant transport, calculate foam adsorption and desorption in the solid phase, account for varying surfactant concentration in grid cells, simulate foam decay, and mimic reduction in gas mobility.
- Obtained the authorization from the North Dakota Industrial Commission to inject the fluid for Enhanced Recovery. The authorization was granted to Hess Corporation after the Hess team made the case for the project in a public hearing.
- Obtained regulatory authorization and land rights for the project.

Appendix

The following items are included in the Appendix

I. Additional foam evaluation results
II. Schematic of the state-of-the-art foam generation platform
III. Schematic of the miniature core-flooding apparatus
IV. The Injection/Soak/Production Strategy for FAGI operation
V. Interfacial Tension and Wettability Characterization Apparatus

Organization Chart



Gantt Chart

Task #	Description	Year 1				Year 2				Year 3				Year 4				No-cost extension		
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19
1	Project Management and Planning	6%	12%	18%	25%															
2	Reservoir Rock and Fluid Properties	27%	50%	75%	95%															
3	Surfactant Screening and Foam Optimization	8%	14%	21%	28%															
4	Multi-scale Core-flooding Experiments of Foam-assisted Gas Injection in Fractured Rock	6%	11%	17%	25%															
5	Multi-scale Modeling, Simulation, and Optimization	6%	12%	18%	25%															
6	Field Operations and Optimization	25%	50%																	
7	Field Pilot Test in Bakken																			

No-cost extension

Delays due to COVID-19 pandemic

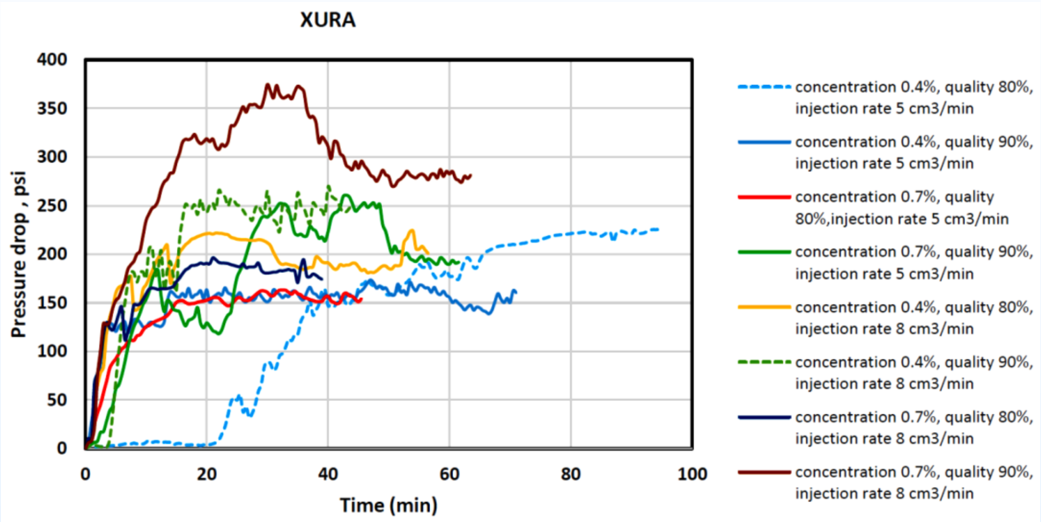
Adjusted schedule due to COVID-19 pandemic

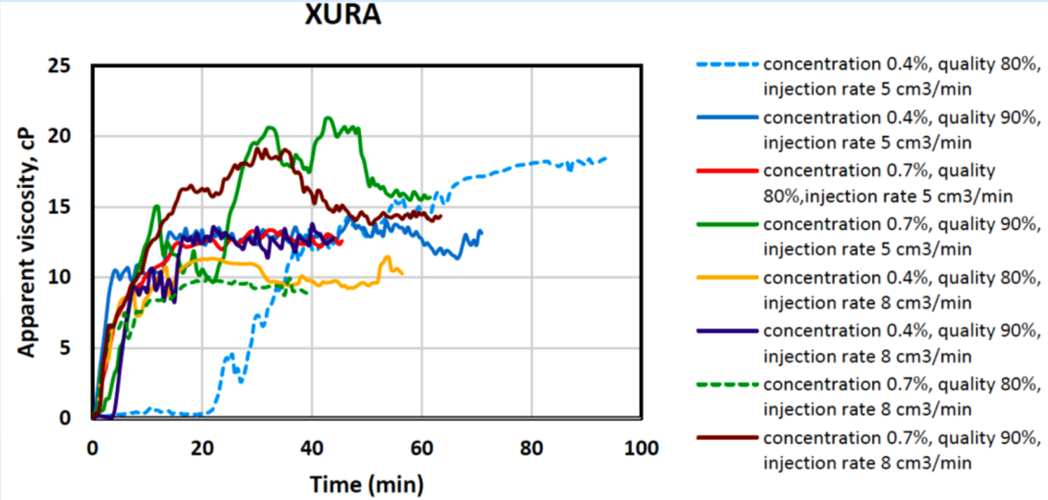
Planned progress for various tasks and includes the cumulative percentages of the actual progress made in the first four quarters.

Thank you!

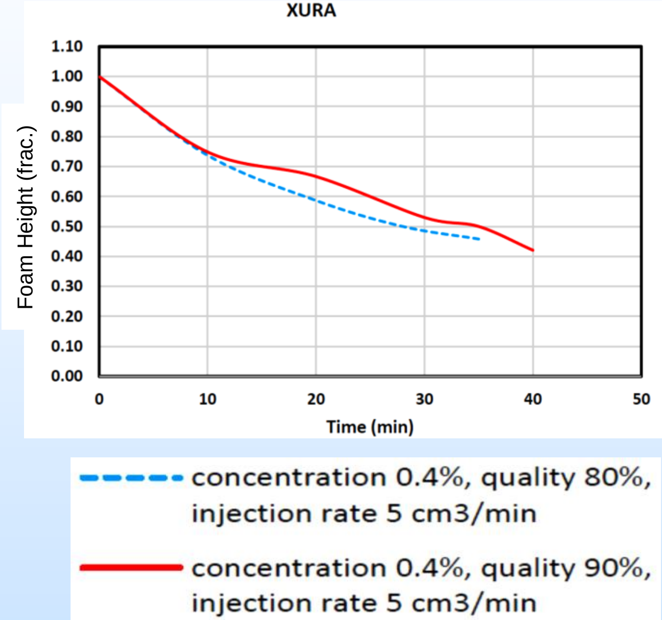
Appendix-I

Foam evaluation for the surfactant XUR-ALT





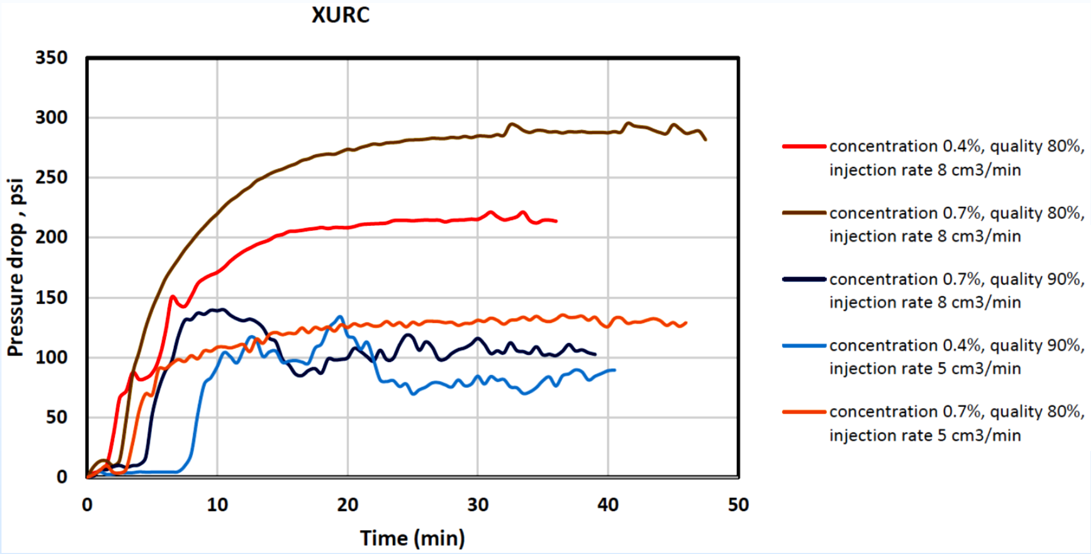
Pressure drop (top) and apparent viscosity (bottom) for the surfactant XUR-ALT

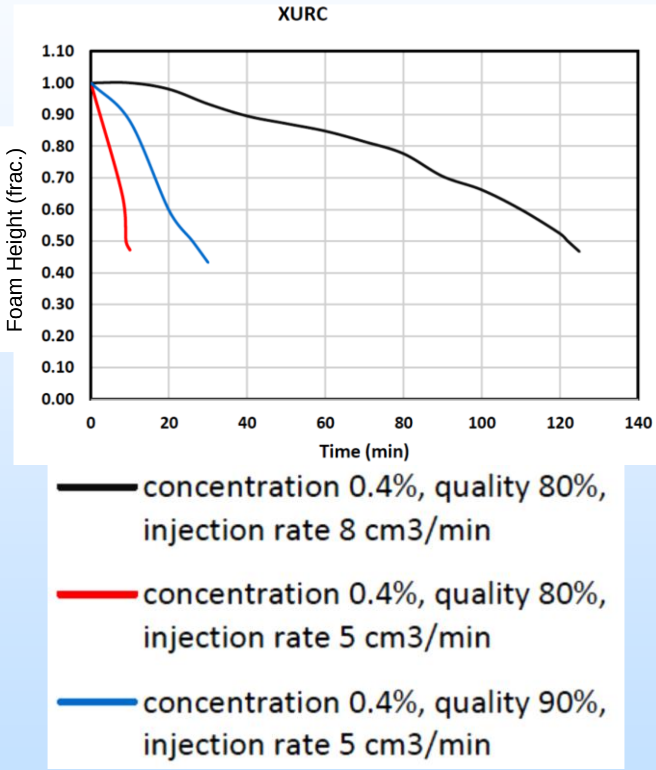


Half-life for XUR-ALT

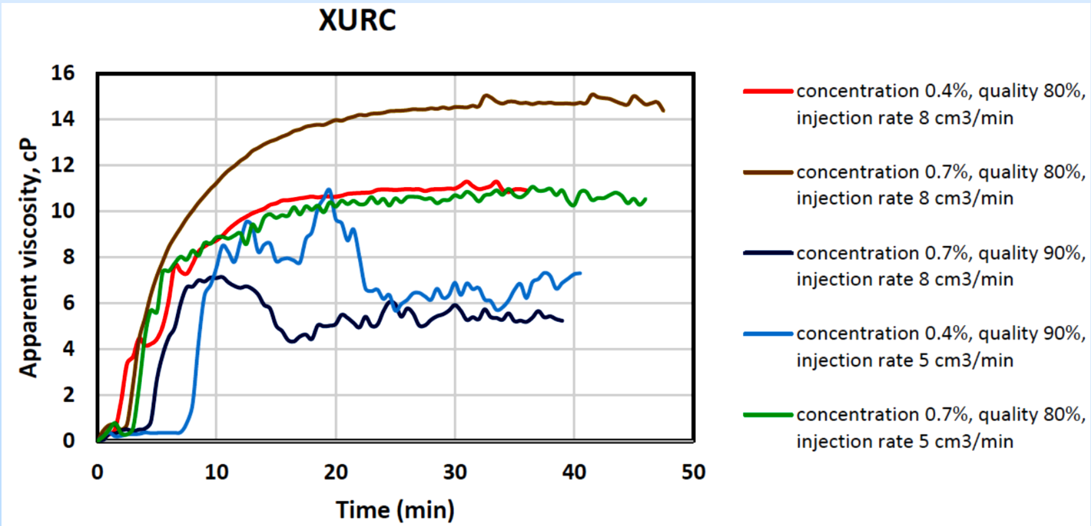
Appendix-I (Cont'd)

Foam evaluation for the surfactant XUR-CLT





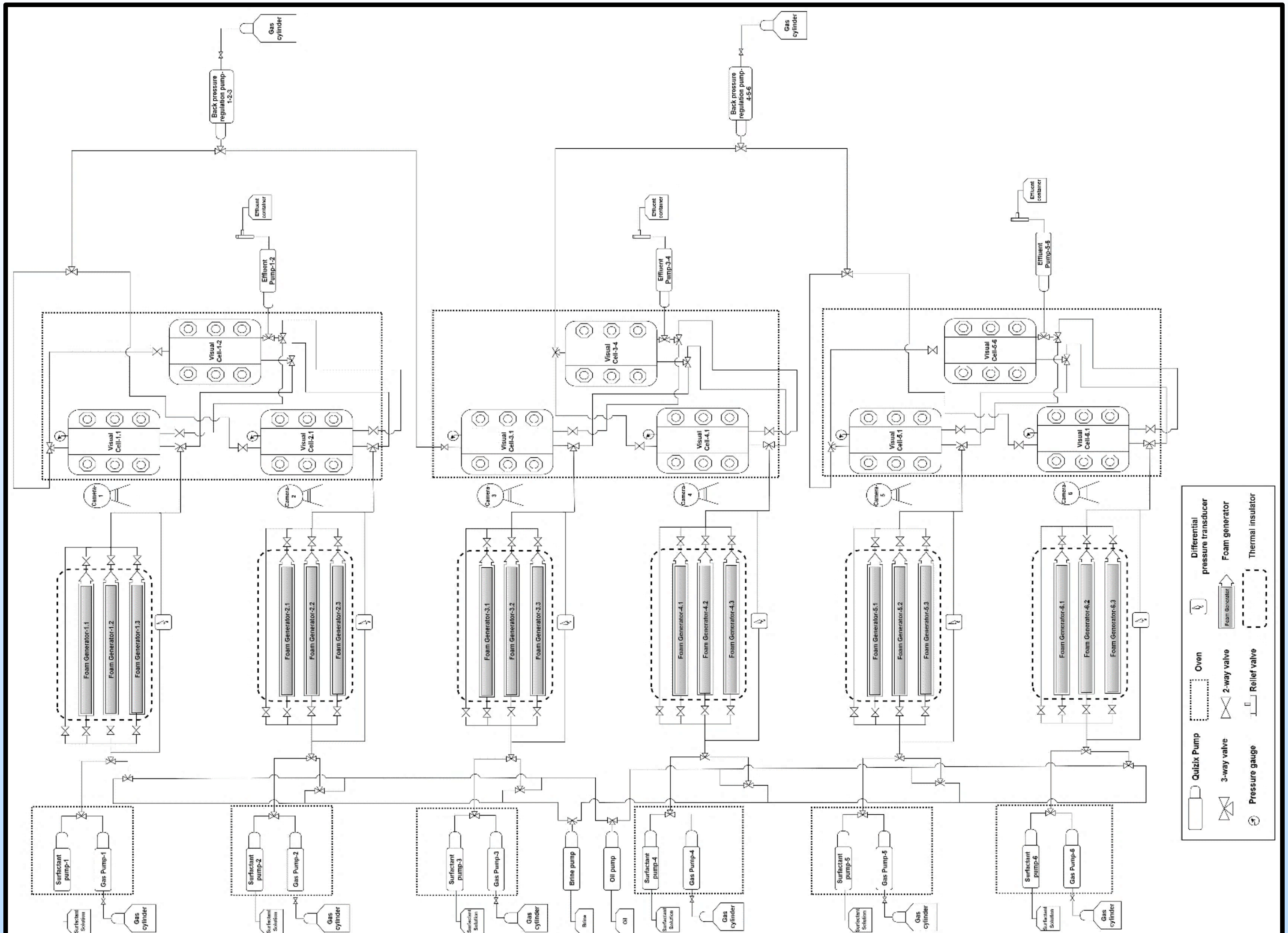
Half-life for XUR-CLT.



Pressure drop (top) and apparent viscosity (bottom) for the surfactant XUR-CLT.

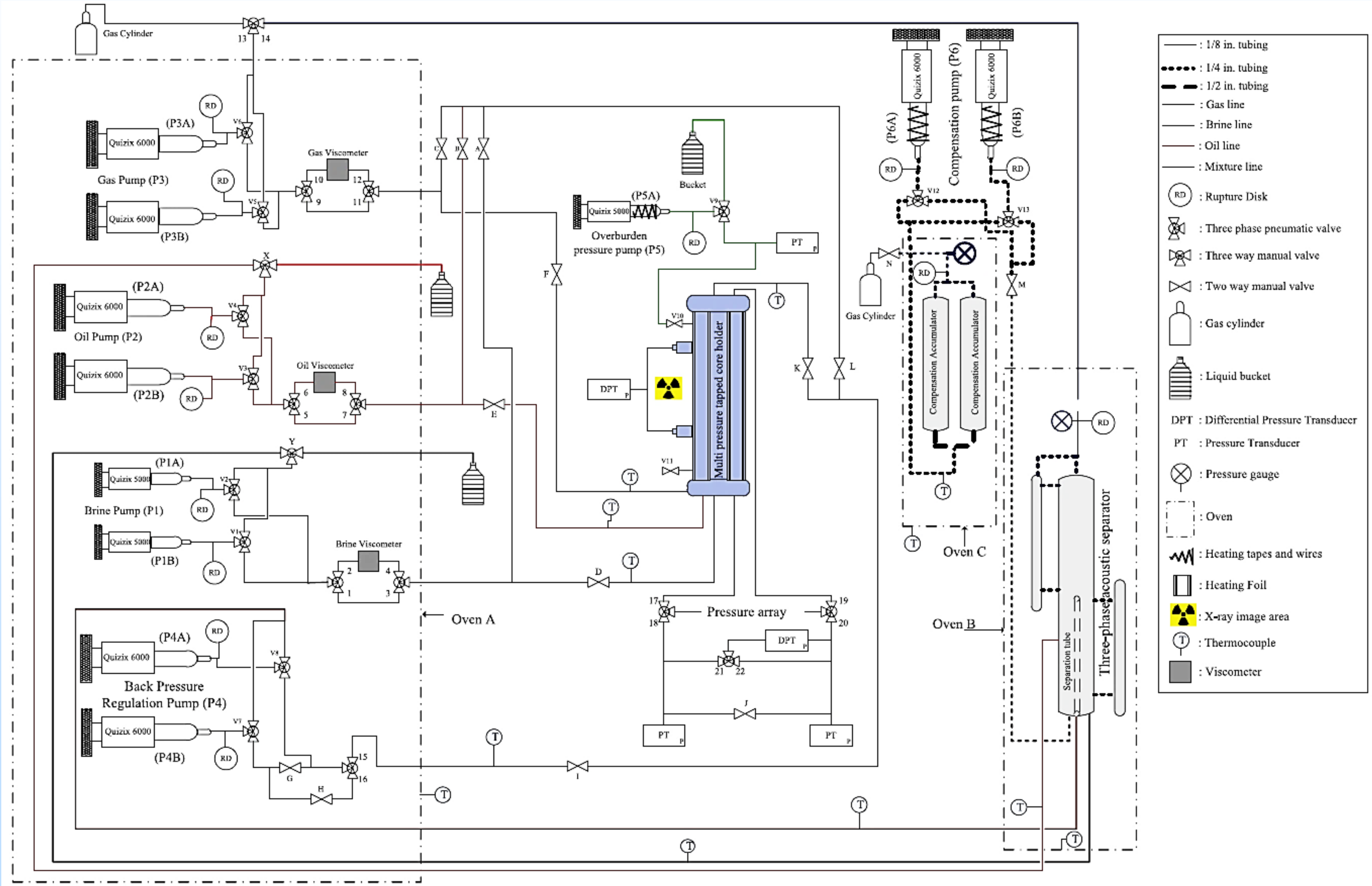
Appendix-II

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



Appendix-III

- Miniature core-flooding apparatus used in this project:



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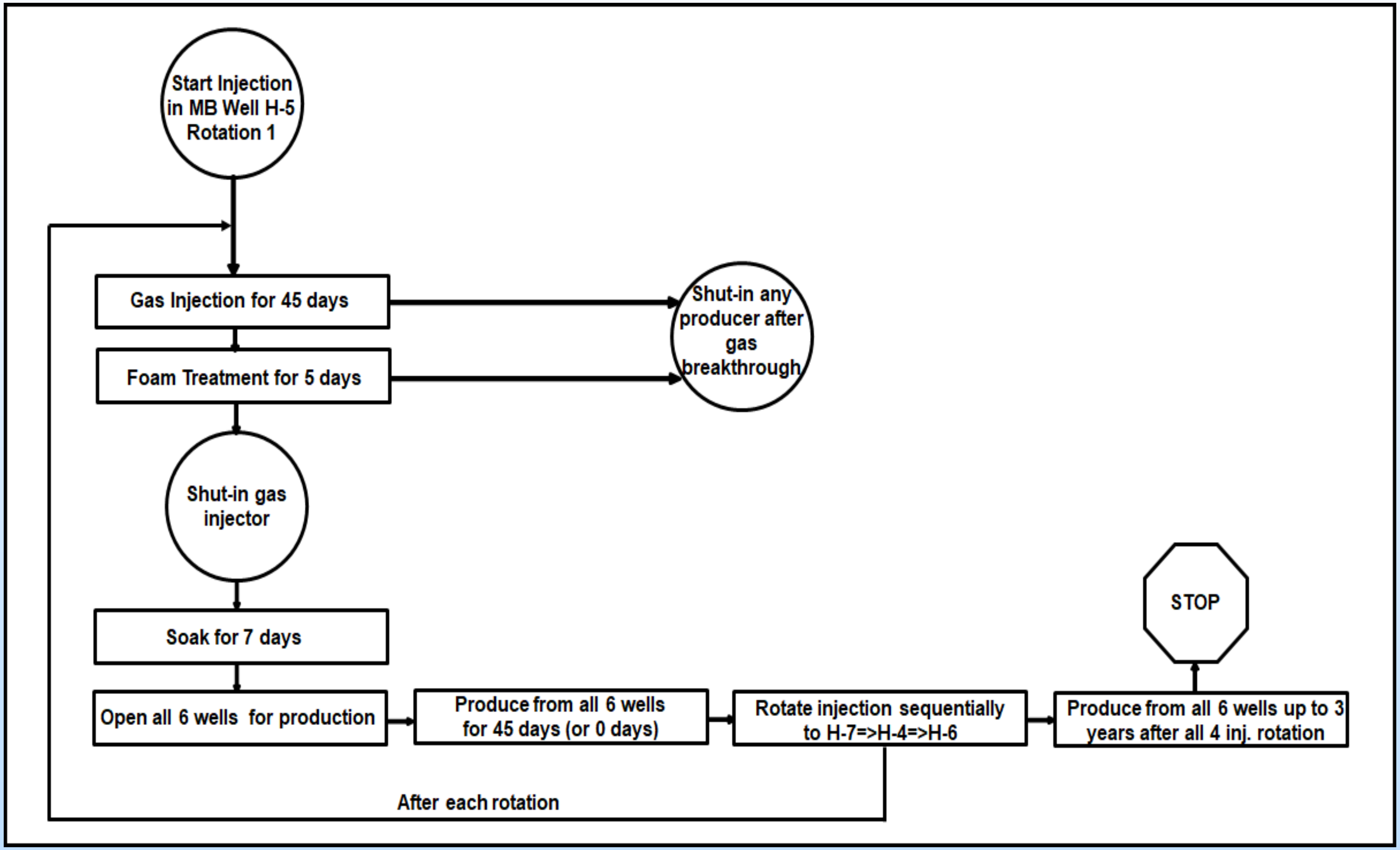
Appendix-IV

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



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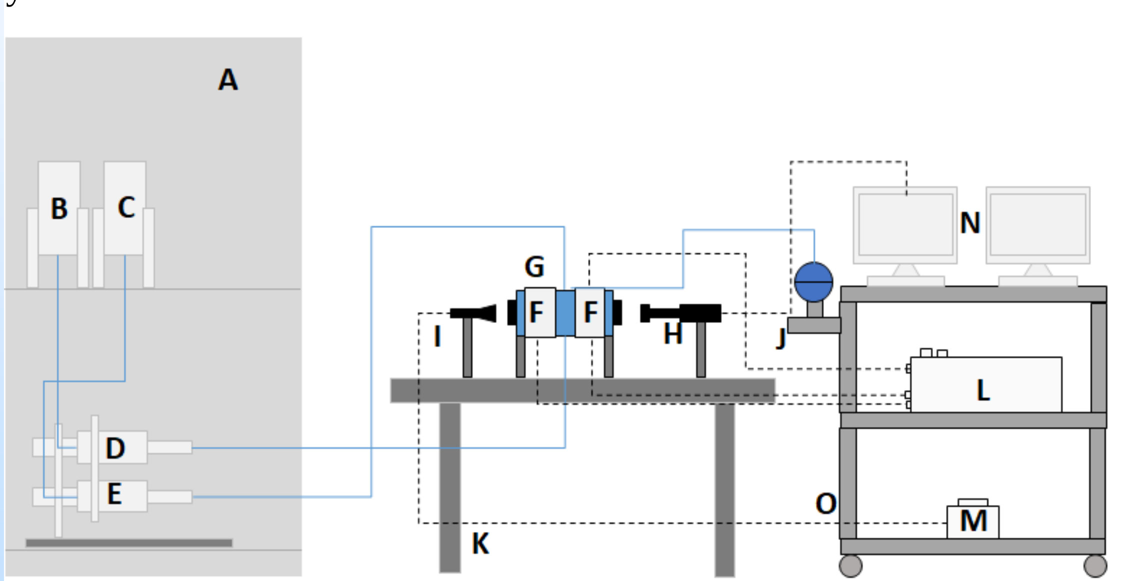
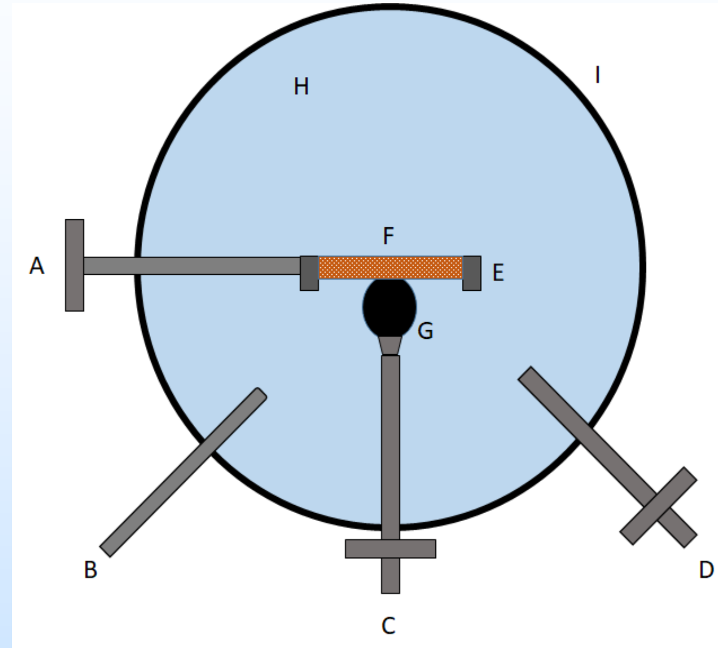
Appendix-V

Interfacial Tension and Wettability Characterization Apparatus

A high-pressure, high-temperature (HPHT) interfacial tension and contact angle (IFT/CA) measurement system



Schematic of the IFT/CA system. A. Oven; B. Brine cell; C. Oil Cell; D. Brine Pump; E. Oil Pump; F. Heating Jackets; G. IFT Cell; H. Camera; I. Light Source; J. Pressure Sensor; K. Anti-vibrational table; L. Temperature control system; M. Control for the light source; N. Controlling computers.



Cross-section of the IFT/CA cell. A. Horizontal Drive Shaft; B. RTD assembly; C. Needle; D. Inlet for brine; E. Holder for chip; F. Rock chip; G. Oil drop; H. Brine; I. Cross-section of IFT cell.