Development and Field Testing Novel Natural Gas Surface Process Equipment for Replacement of Water as Primary Hydraulic Fracturing Fluid

Project # DE-FE0024314

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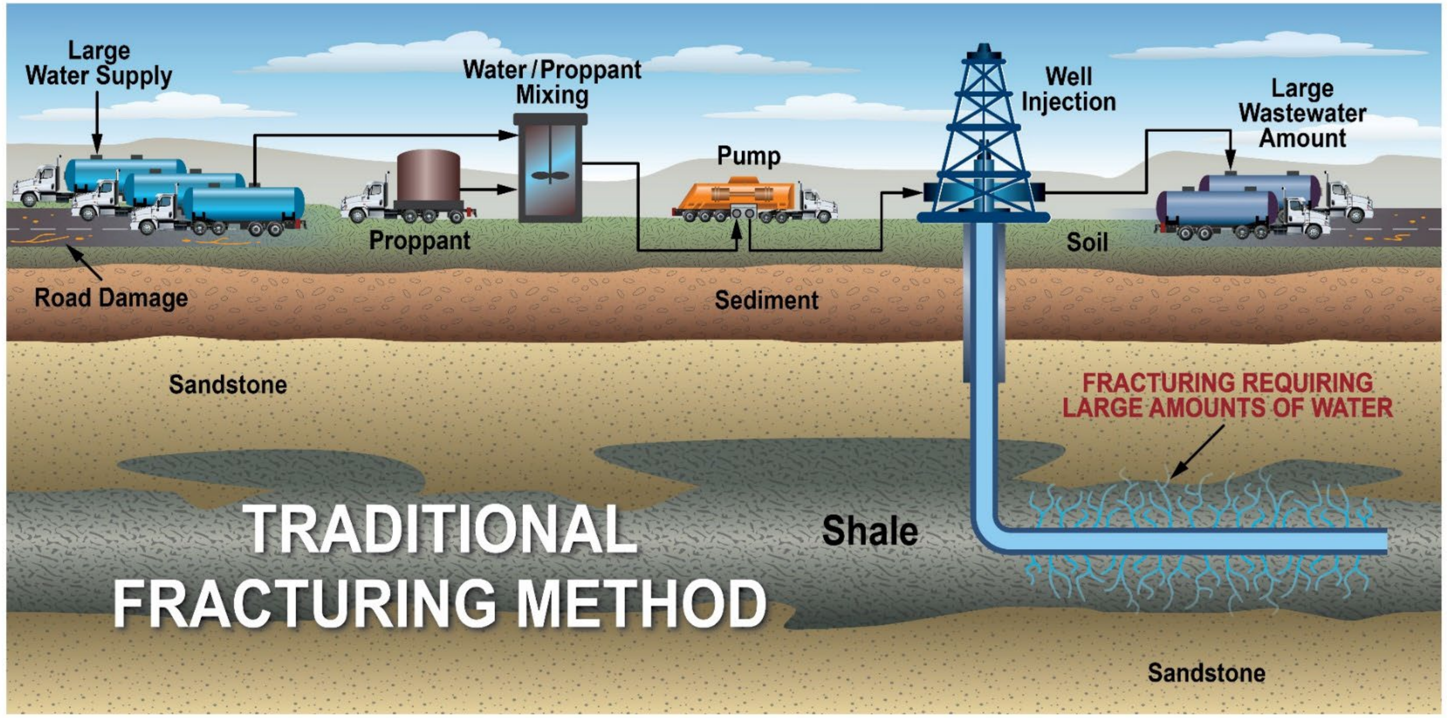
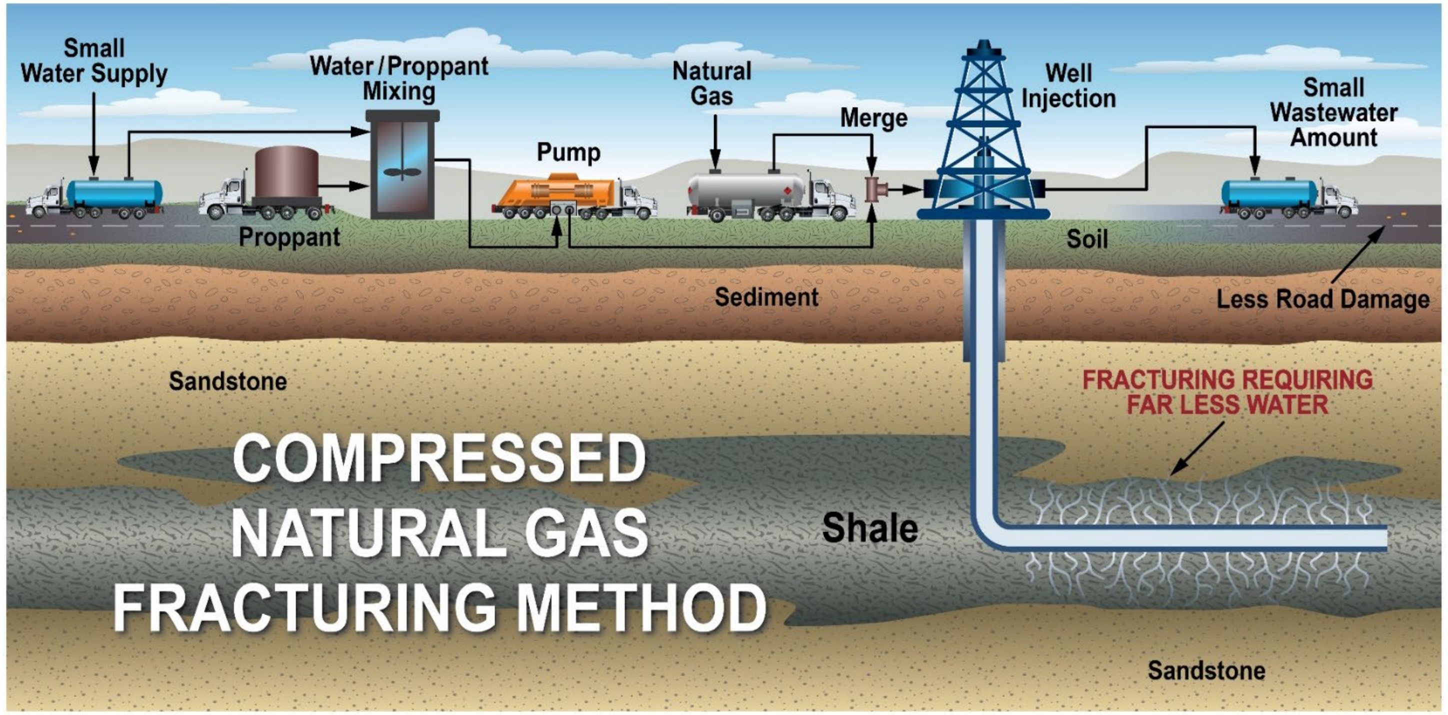
A novel process is being developed that uses natural gas as the primary fracturing fluid

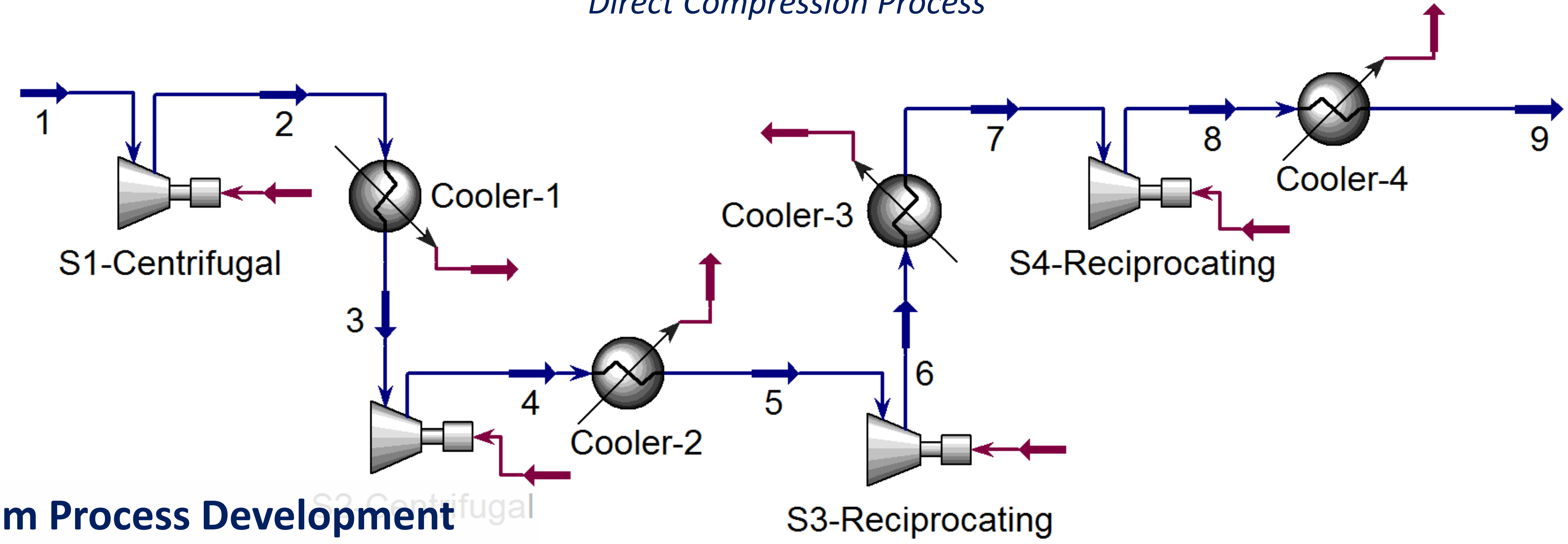




- The proposed process uses NG foam for hydraulic fracture treatment.
- Reduce water consumption by as much as 80%.
- Reduce swelling in water sensitive reservoirs
- Reduce polymer residue within fracture and maintain higher conductivity
- Natural gas is readily available at well site/processing plants.
- The recovered natural gas would be processed.

Work in BP 1 identified an appropriate surface process to compress natural gas at pipeline conditions to pressures needed for injection

Direct Compression Process

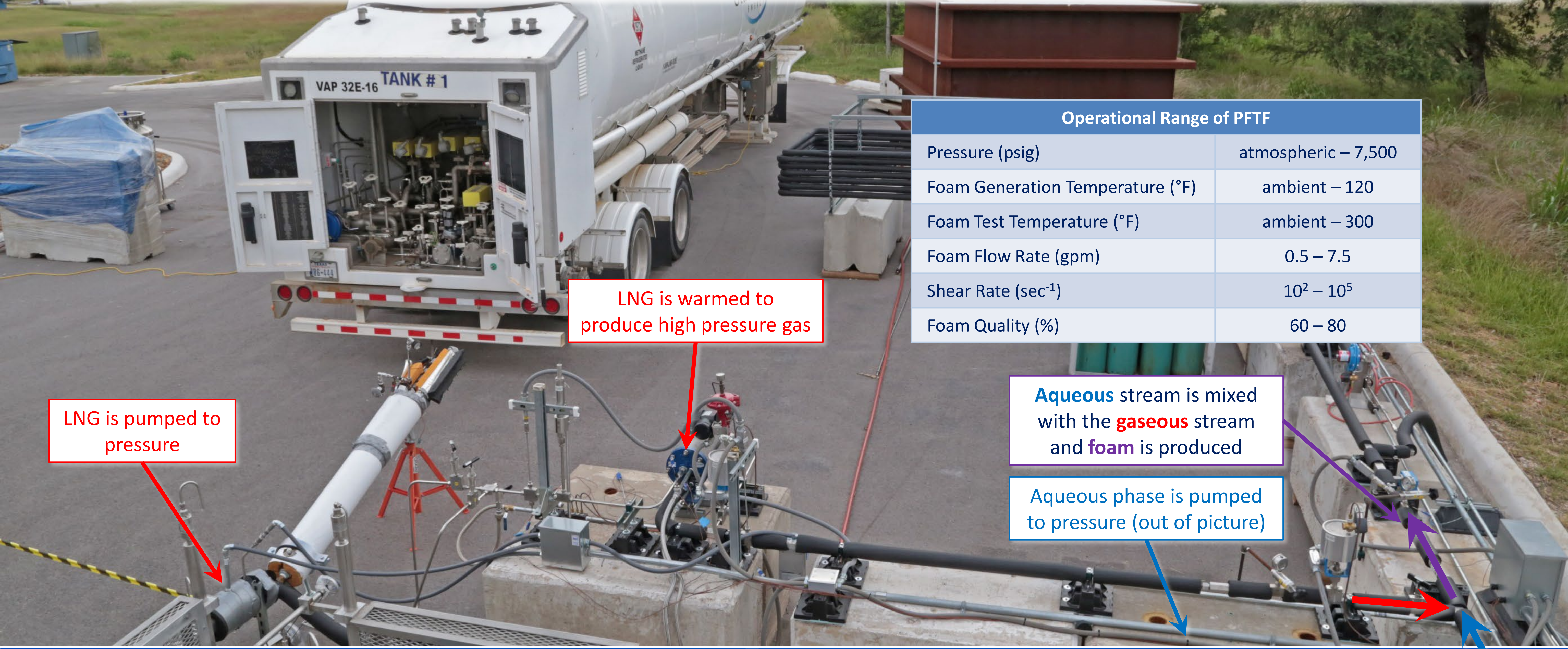


Key Findings from Process Development

- Six processes (including compression and liquefaction cycles) were analyzed.
- The optimal process to produce high pressure NG is through direct compression.
- Equipment needed to compress gas is commercially available.
- A *mobile* compression fleet is feasible but requires more development.

At close of BP1, TRL = 3

A pilot-scale foam test facility (PFTF) was constructed to explore the feasibility of using natural gas-based foam as a fracturing fluid

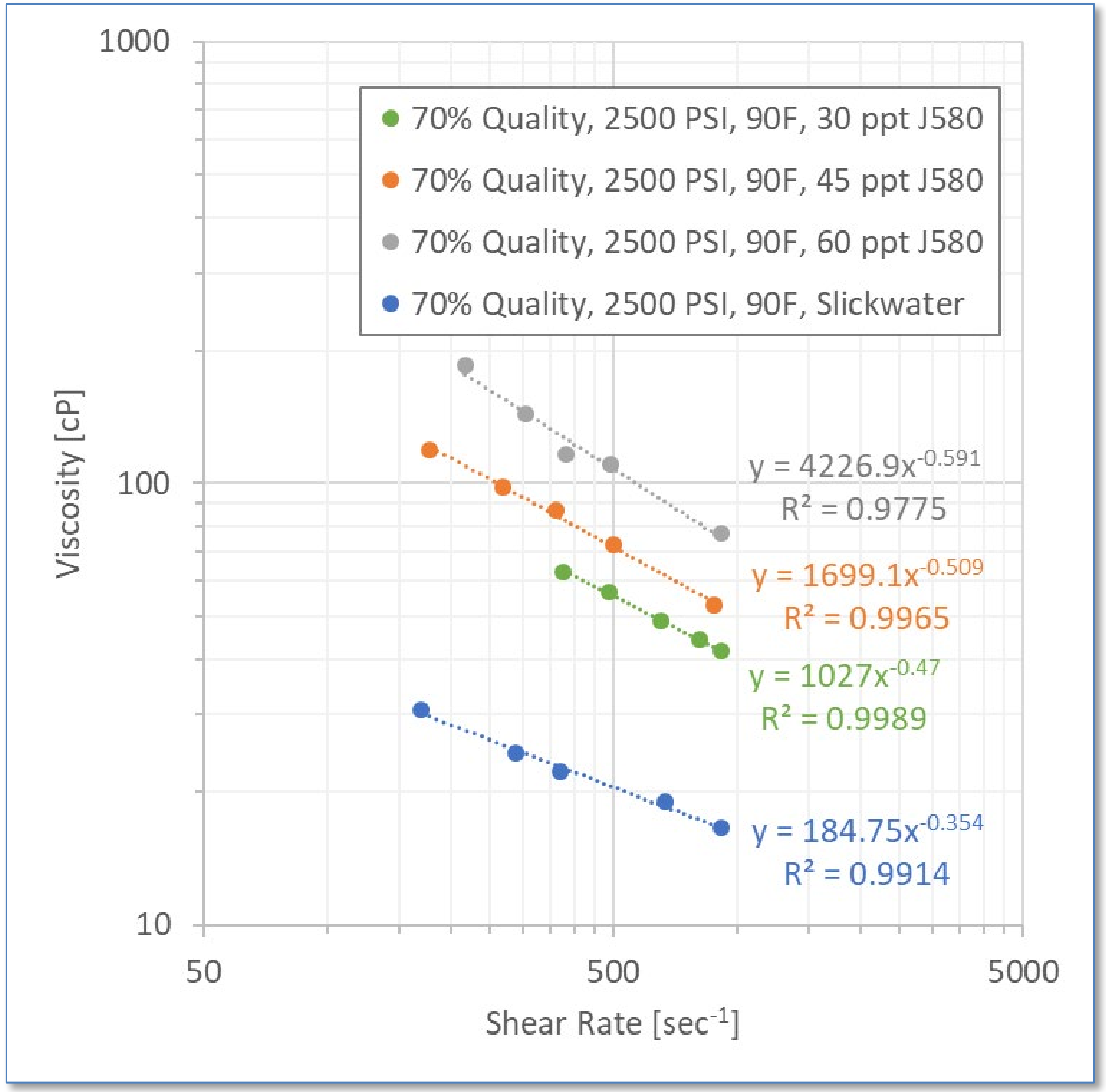


Operational Range of PFTF	
Pressure (psig)	atmospheric – 7,500
Foam Generation Temperature (°F)	ambient – 120
Foam Test Temperature (°F)	ambient – 300
Foam Flow Rate (gpm)	0.5 – 7.5
Shear Rate (sec^{-1})	$10^2 – 10^5$
Foam Quality (%)	60 – 80

Stable natural gas-based foam was generated using the pilot-scale test facility

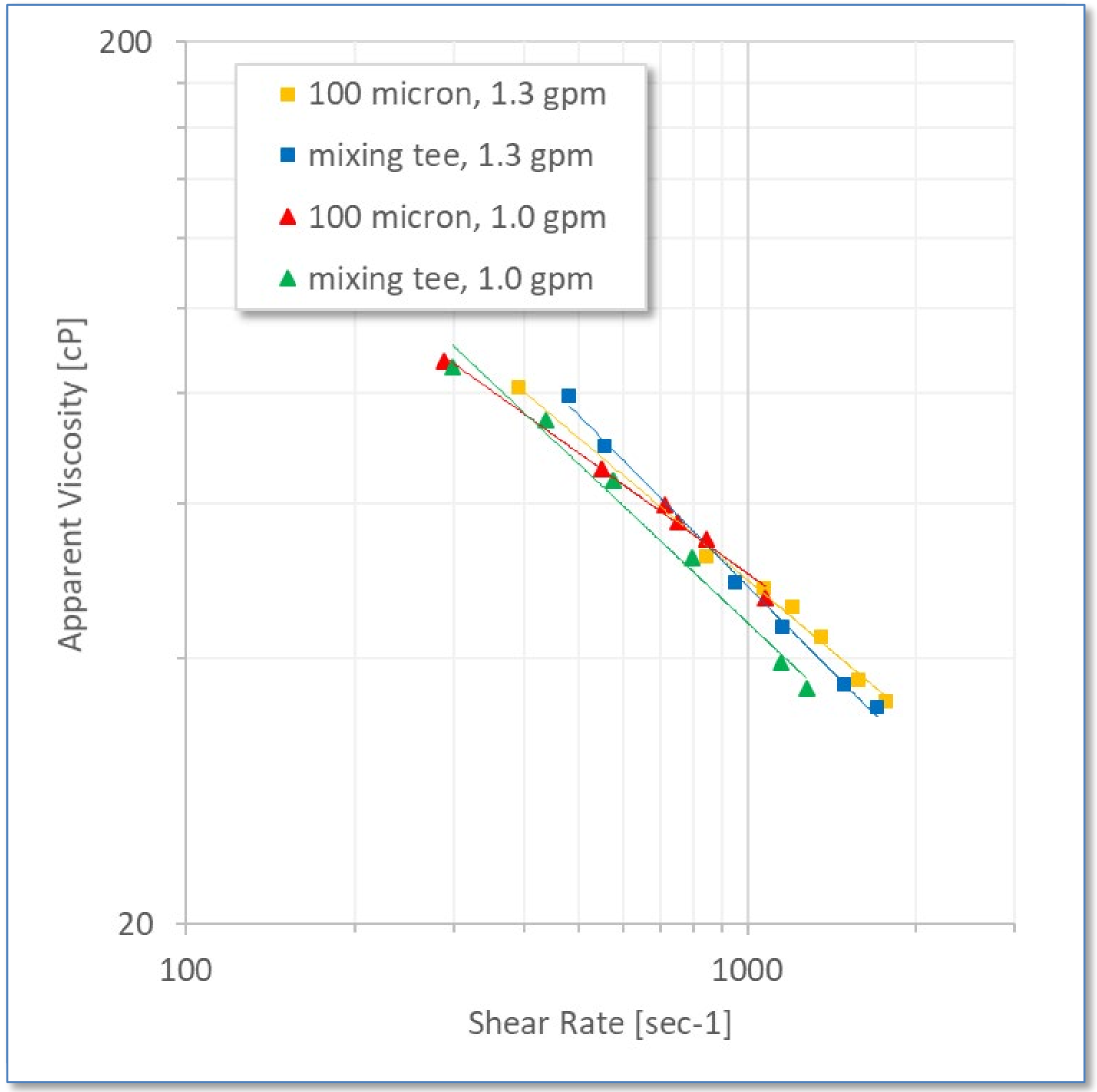
Key Findings from Pilot-Scale Tests

- Stable NG foam was generated at 6000 psi using commercially available viscosifiers and surfactants.
- Four base fluid mixtures were used to generate NG foam
- NG foam is qualitatively similar to other foams observed in literature:
  - Shear thinning, power law fluid
  - Increased viscosity with foam quality

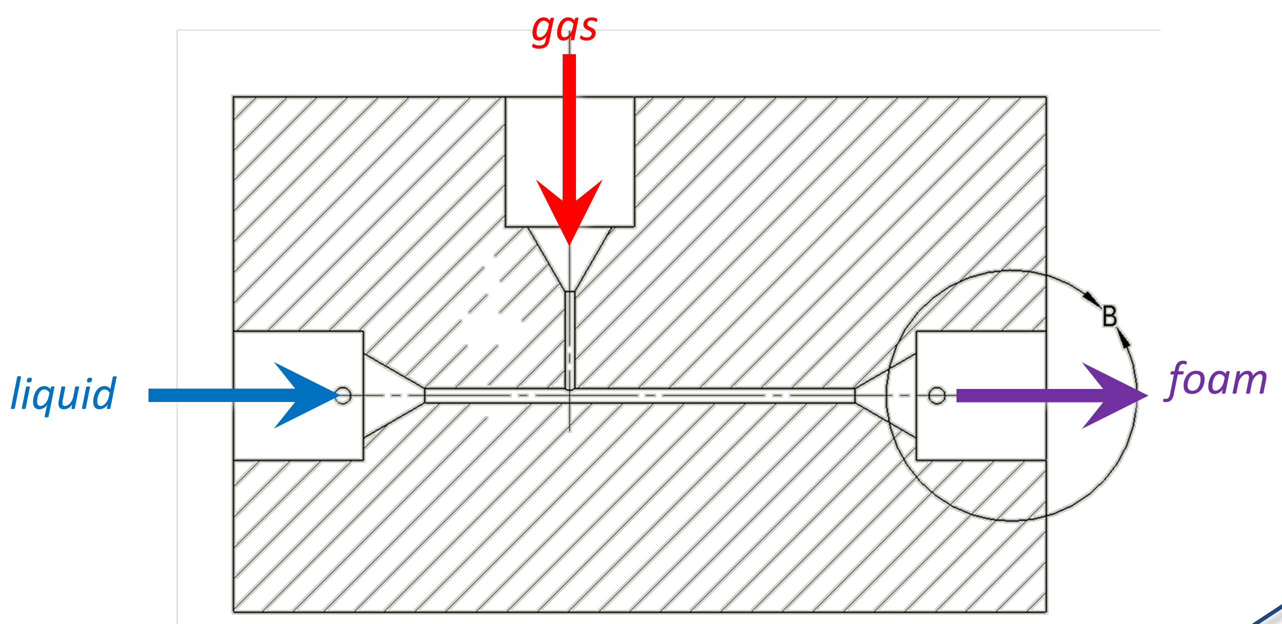


Four different base fluids were tested: slickwater and guar at three different concentrations

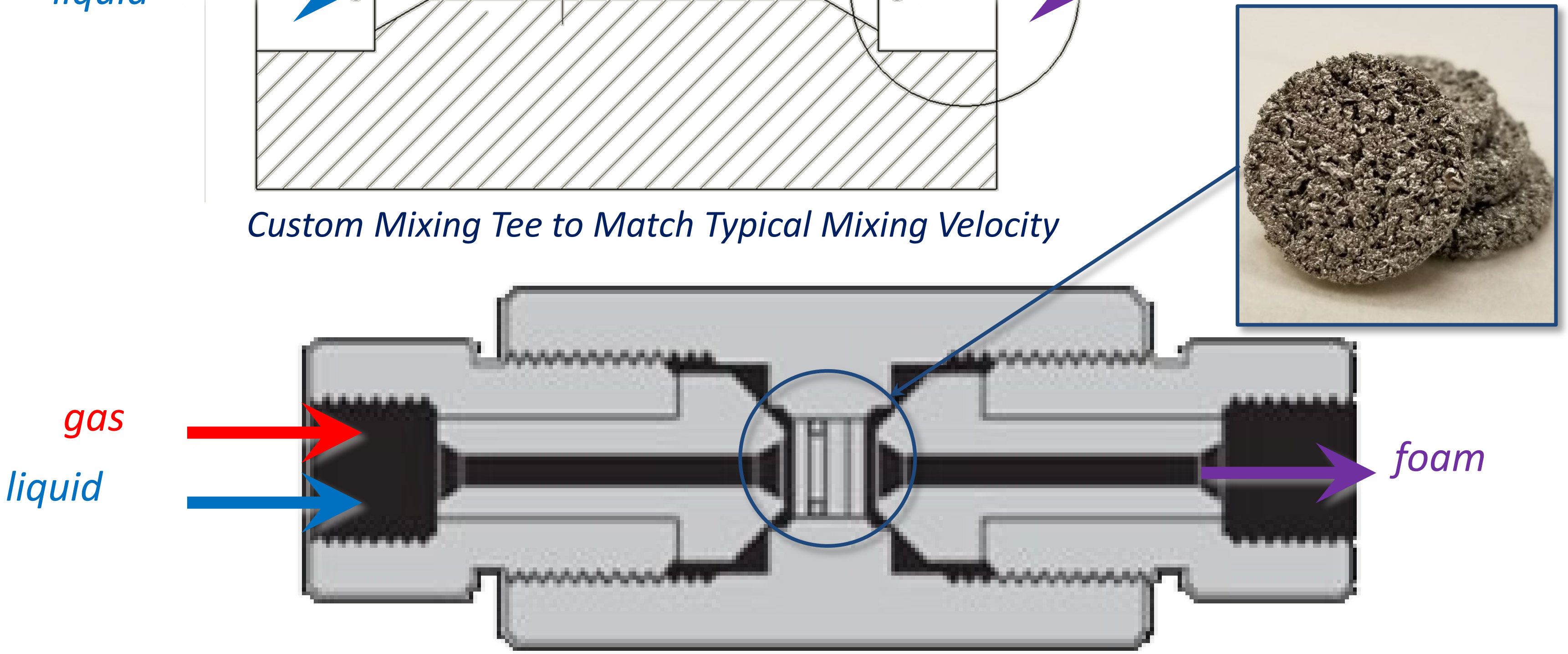
Two mixing methods were explored and results indicate that field mixing methods are sufficient to generate stable foam



Foam mixed in a 100 µm filter and in a custom mixing tee had nearly identical viscosity



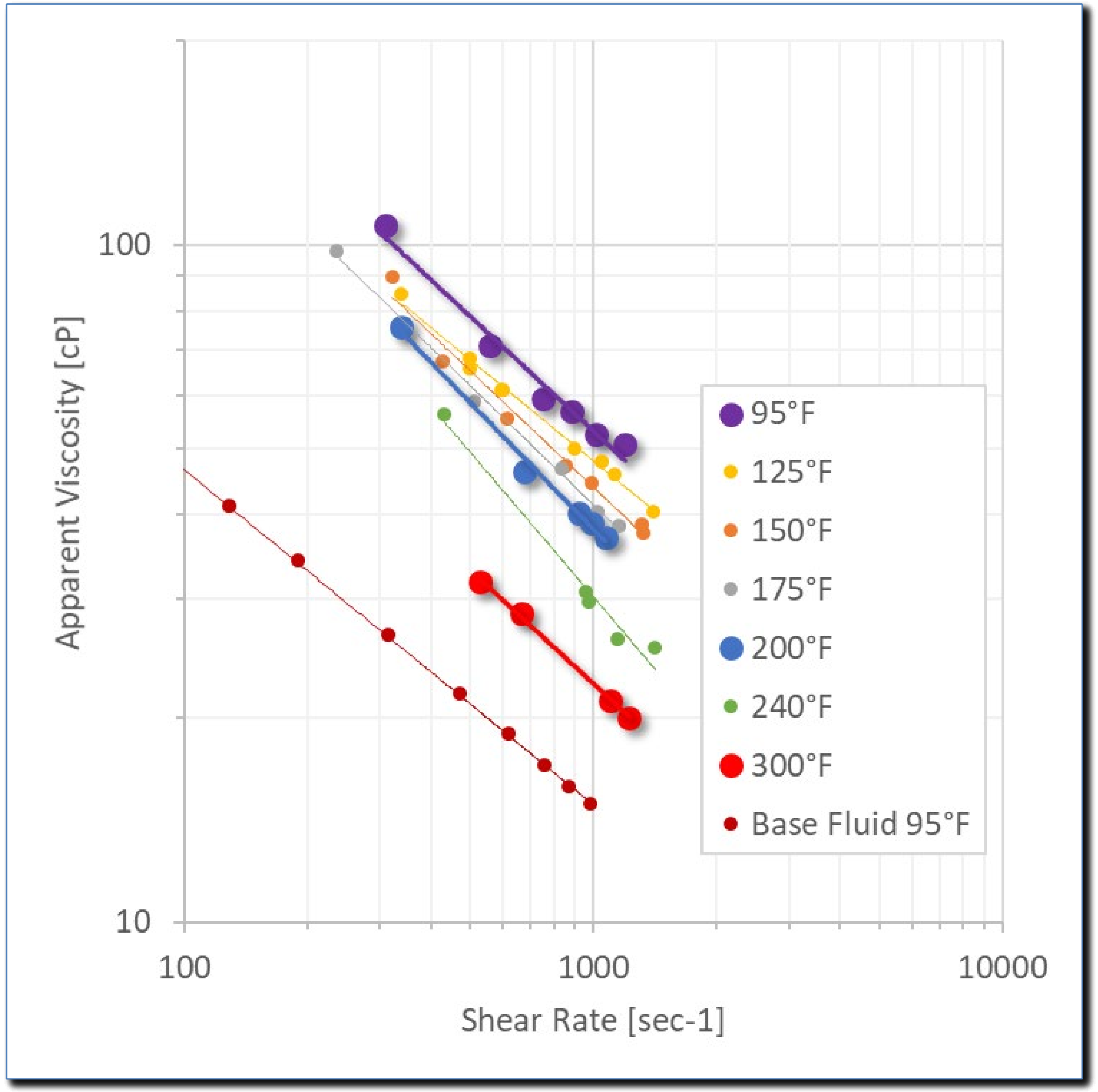
Custom Mixing Tee to Match Typical Mixing Velocity



100 µm Filter (20-51LF9 High Pressure Equipment Co.)

NG foam was tested at elevated temperature conditions to mimic elevated reservoir temperature

- Enhanced foam heating capability on PFTF
  - Capable of foam temperatures in excess of 300°F
- Tests conducted by mixing aqueous and gaseous streams at given quality and then heating foam to test temperature
- 70% quality foam mixed with 30 ppt guar:
  - Foam @ 95°F, 3-4x base fluid viscosity @ 95°F
- Foam viscosity reduces w/ temperature increase:
  - Foam @ 200°F, 20-30% reduction in viscosity
  - Foam @ 300°F, 55-60% reduction in viscosity

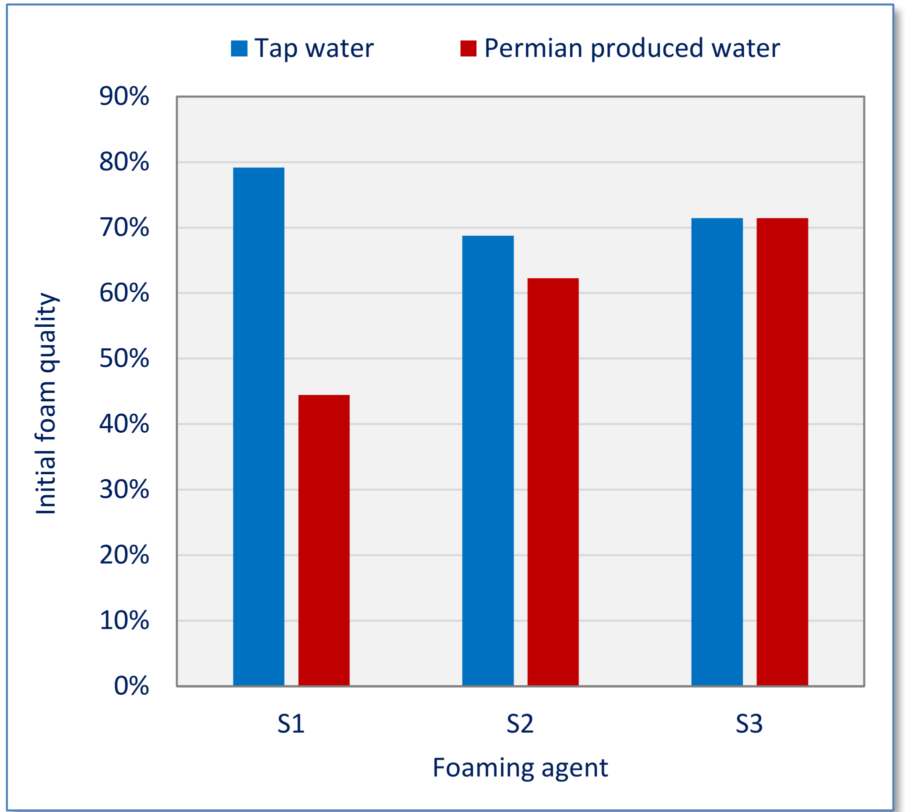


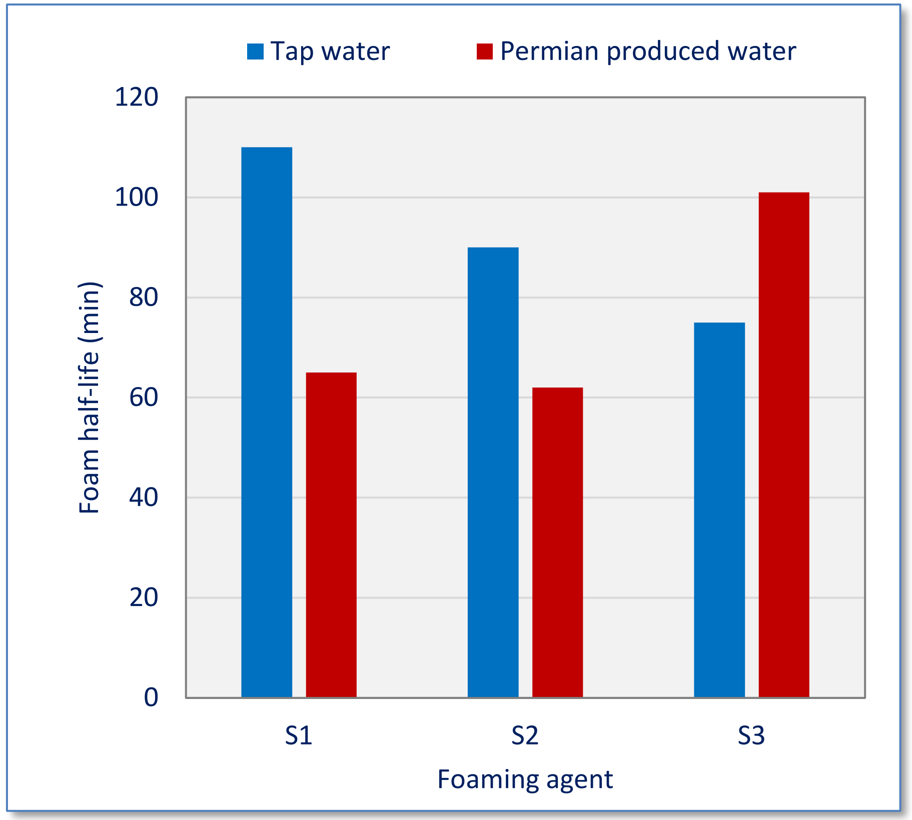
70% quality at mixing conditions, 30 ppt guar, 4500 psi (except base fluid data), heated after mixing to various temperatures

A laboratory test was performed to compare the stability of foam created from produced water to one created with clean tap water

Compositional analysis of Permian Basin produced water sample

Analyte	Concentration [mg/L]
Sodium (Na)	57,330
Potassium (K)	1,068
Silicon (Si)	3.5
Iron (Fe)	0
Calcium (Ca)	6,275
Magnesium (Mg)	1078
Strontium (Sr)	843
Barium (Ba)	0
Boron (B)	62
Chlorides (Cl)	96,241
Carbonates (CO3)	0
Bicarbonates (HCO3)	58
Sulfates	200
Total Dissolved Solids (TDS)	173,456
Specific Gravity (SG, unit-less)	1.1055





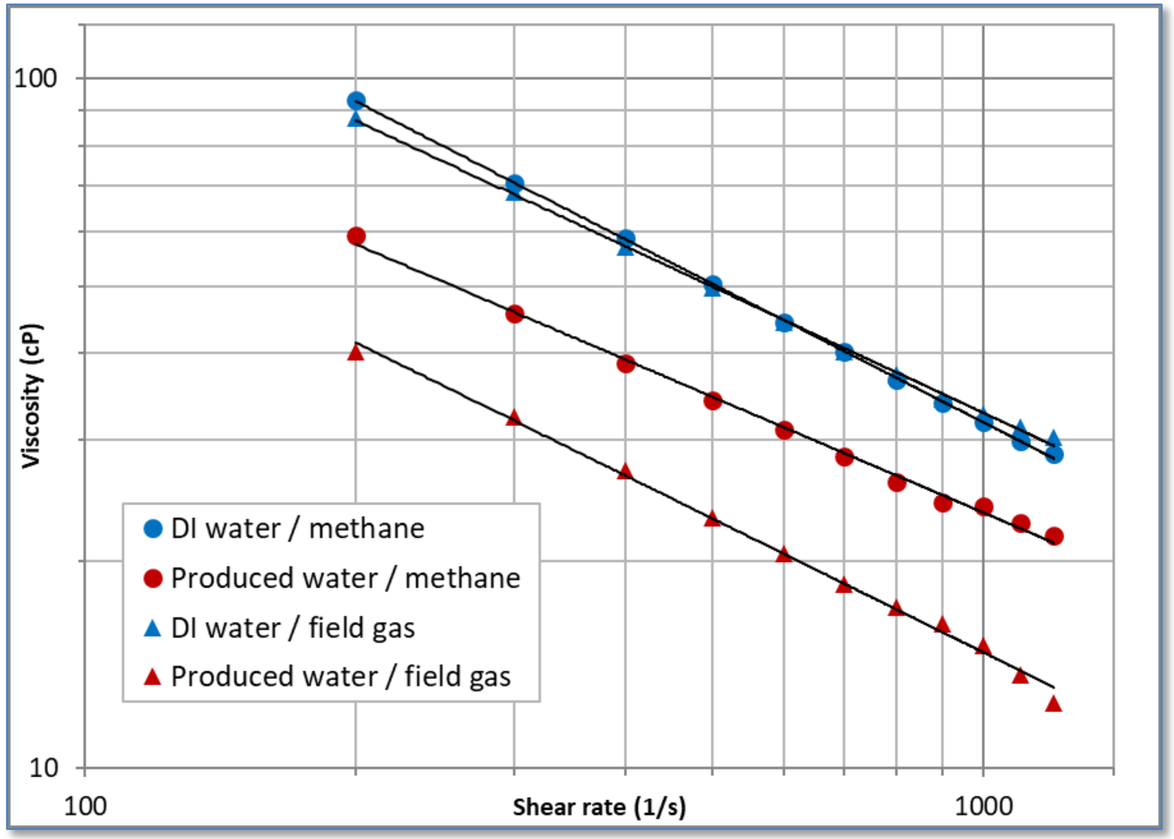
- Three foaming surfactants: anionic (S1), nonionic (S2), & zwitterionic (S3)
- S1 yielded the highest initial quality and longest half-life with tap water
- S3 yielded the highest initial quality and longest half-life with the produced water analog

Laboratory tests also investigated the rheology of foam created from produced water and field gas compositions

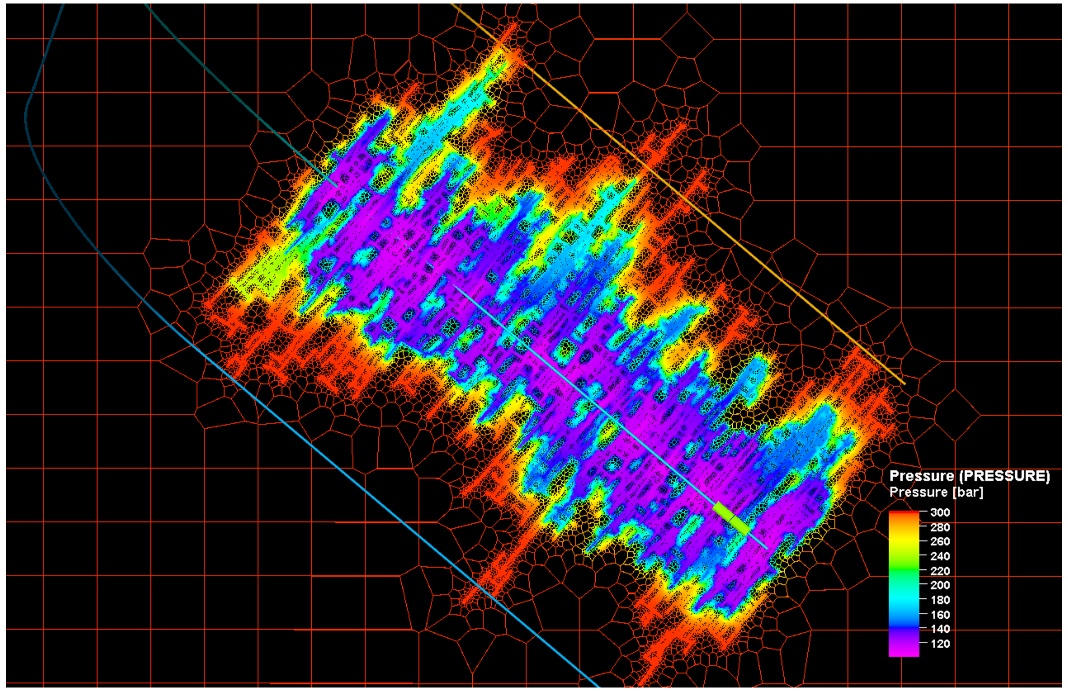
- Tests conducted at 4500 psi and 100°F
- Replacement of methane by field gas does not change the rheological profile of the foam
- Replacement of DI water w/ produced water yields a 20% to 30% decrease in rheology
- A foam of produced water and field gas yields even further decrease
- Surfactant selection will be critical for field implementation

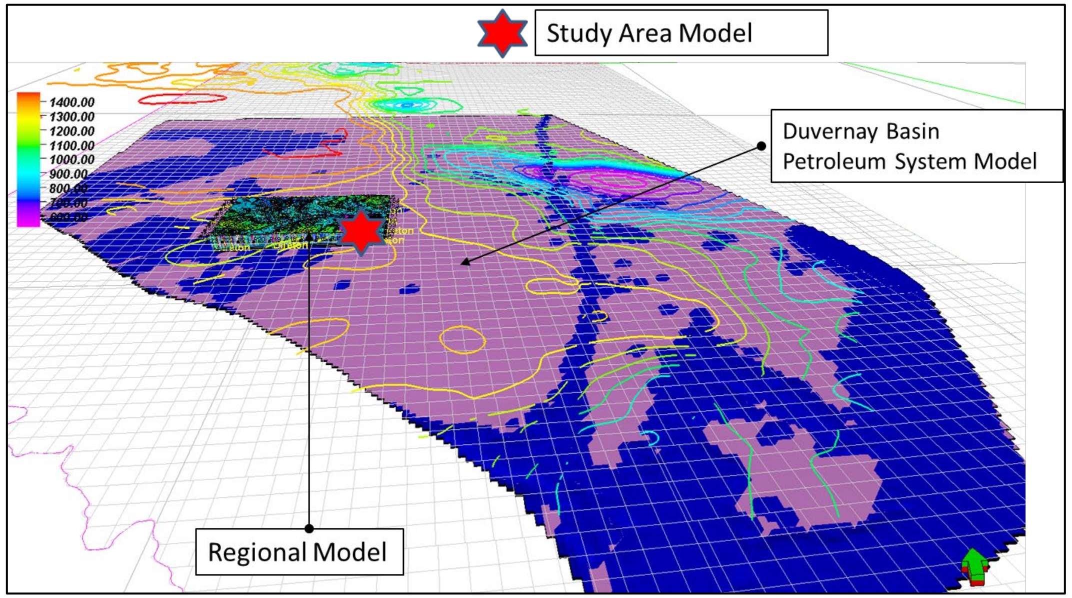
Laboratory Gas Mixture

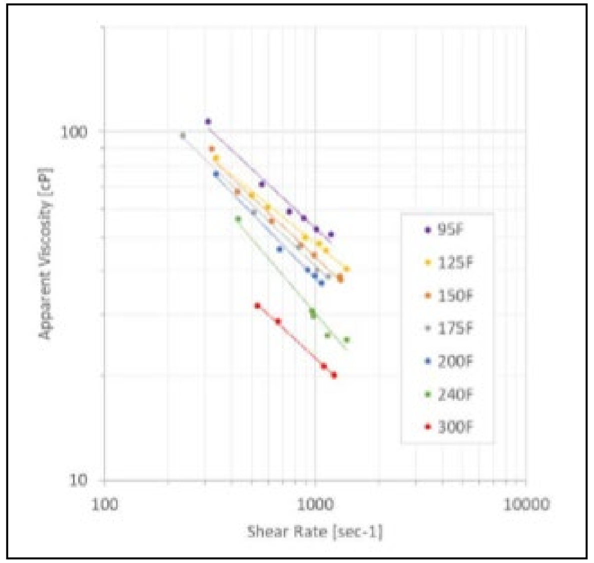
Component	Mole %
N2	1.144
CO2	0.641
C1	80.327
C2	12.217
C3	4.147
i-C4	0.369
n-C4	0.647
i-C5	0.123
n-C5	0.144
C6	0.131
C7	0.107



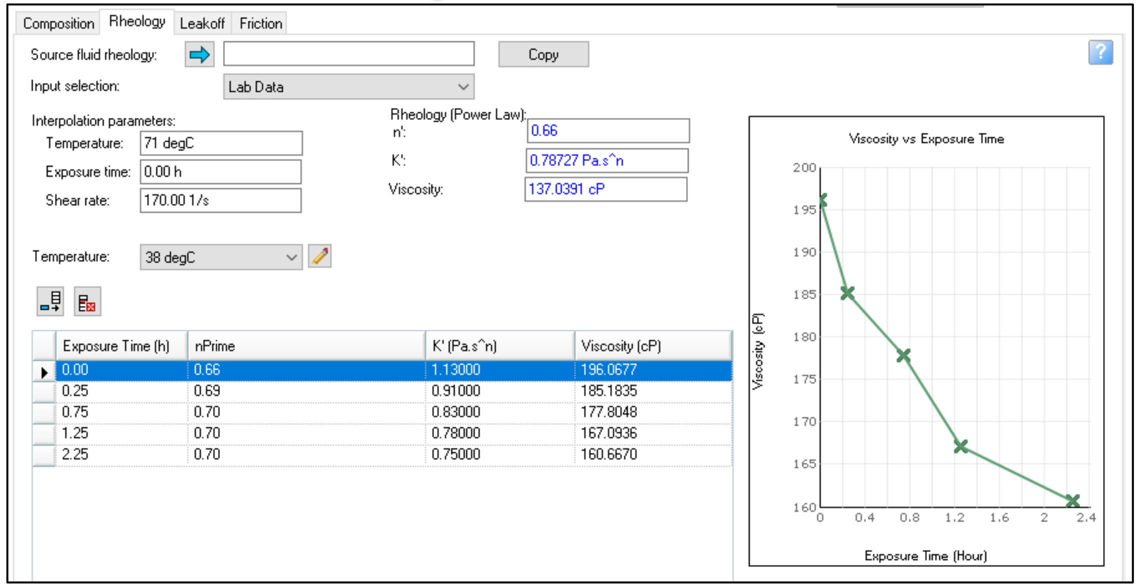
In BP4, a numerical model was created for NG foam stimulation of the Duvernay formation







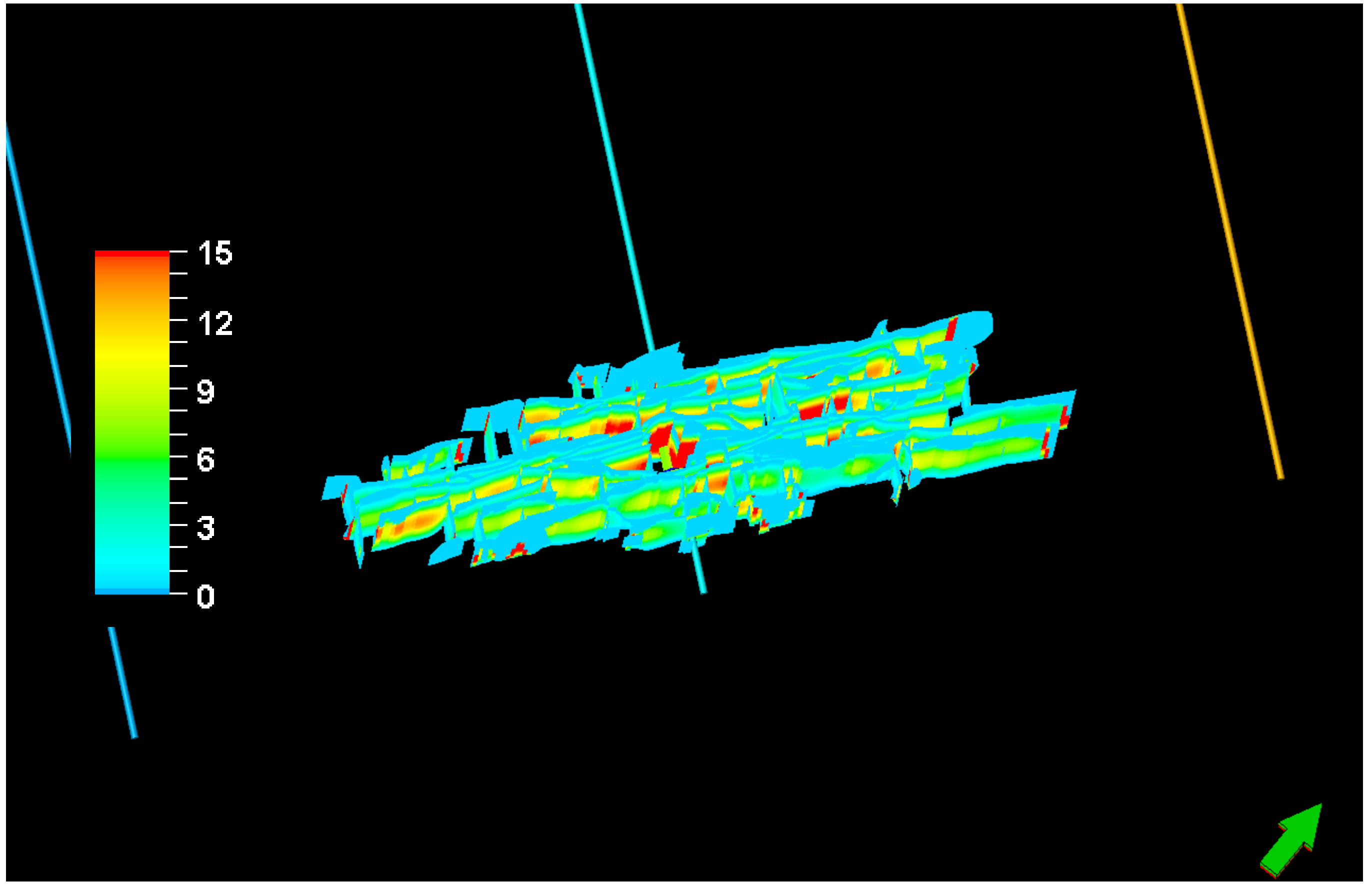
Gas	Foaming Agent	Time (min)	n'	Geometry-independent K'
CH4	F109	0:16:01	0.6636	1.131927394
CH4	F109	0:46:02	0.693208	0.911921691
CH4	F109	1:16:04	0.701291	0.835752744
CH4	F109	1:46:06	0.704287	0.781146167
CH4	F109	2:16:[illegible]	[illegible].704939	0.750181531



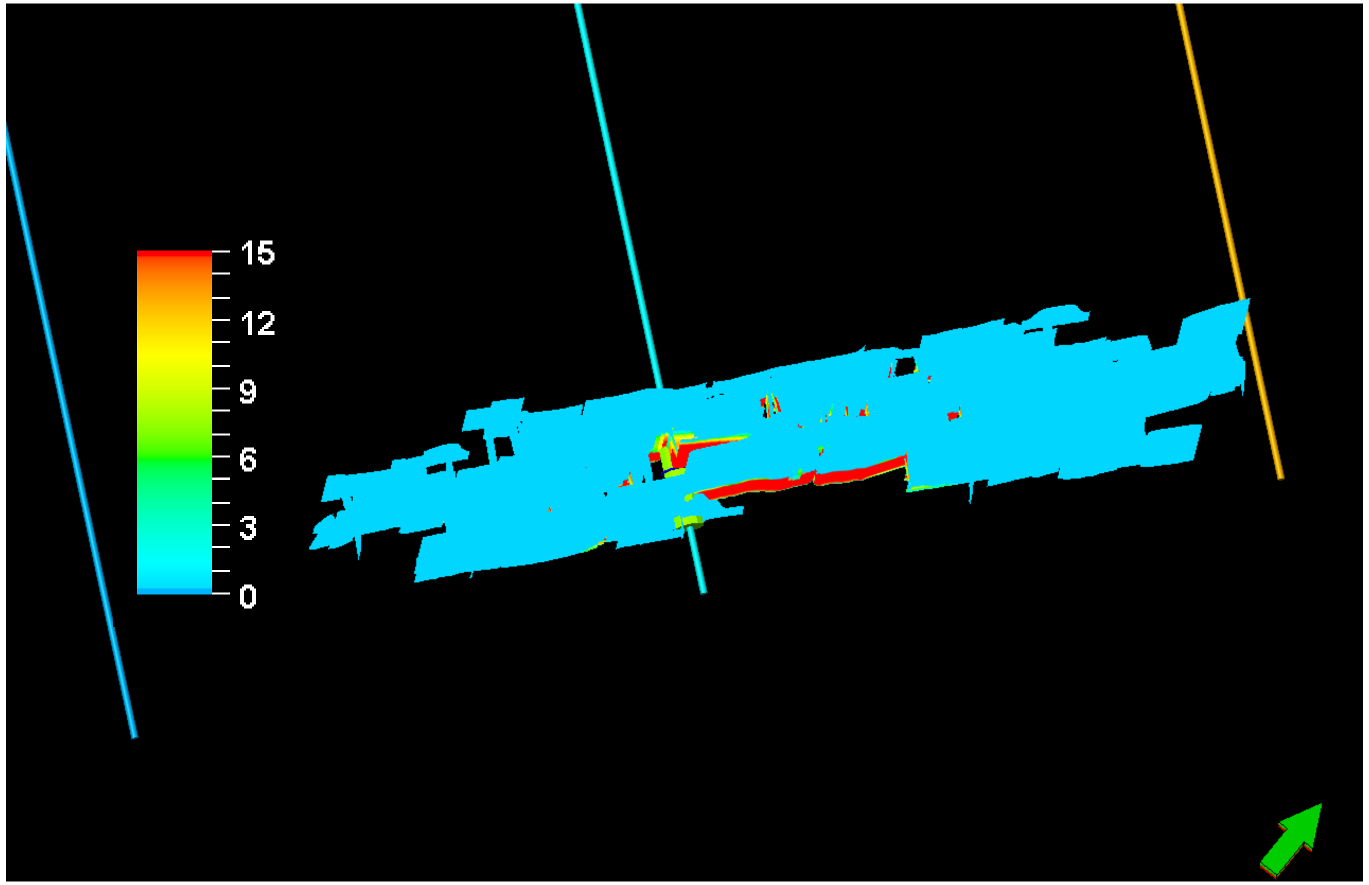
- Time- and temperature-dependent rheology data generated in the BP2 – BP4 laboratory work was incorporated into the simulation rheology models

Reservoir simulations predict improved fracture conductivity compared to slickwater treatments.

Conductivity with 60% Quality NG Foam Treatment

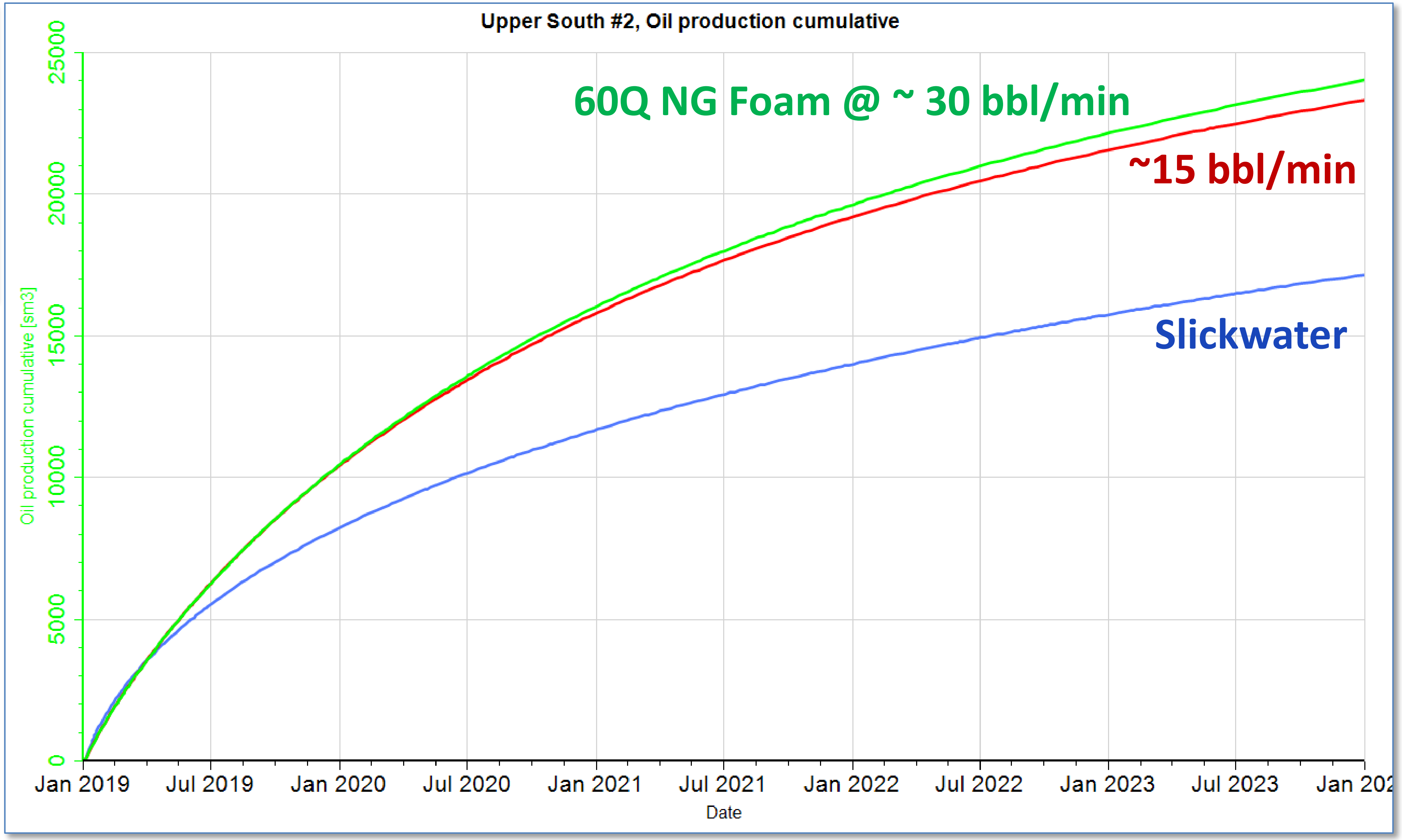


Conductivity with Slickwater Treatment



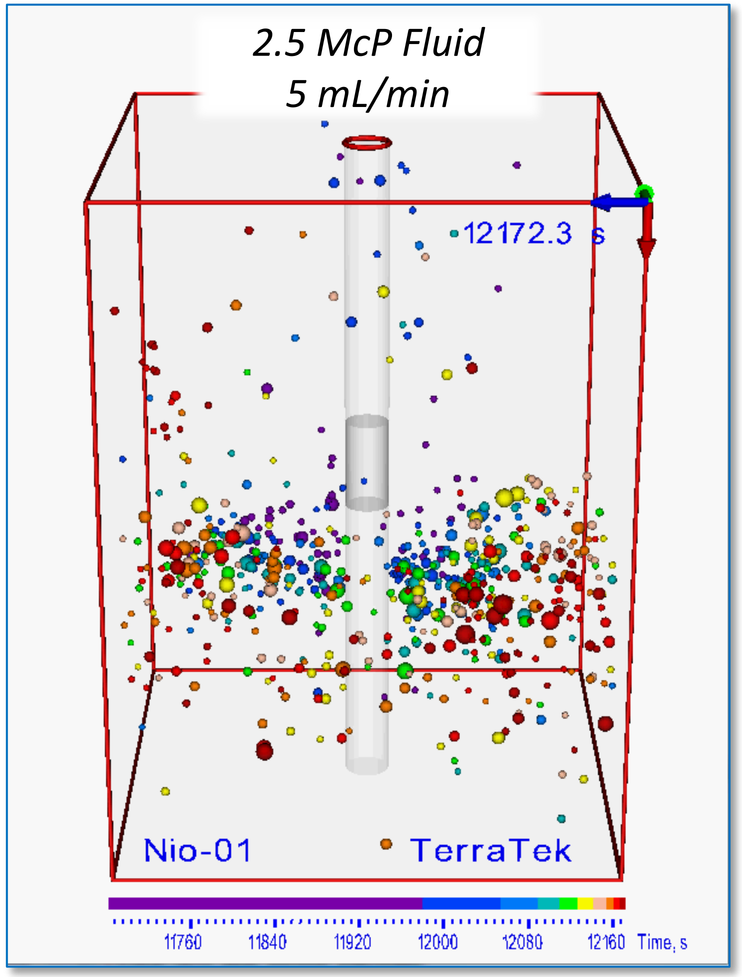
Initial results show an improvement in cumulative oil production using NG foam compared to traditional slickwater treatments

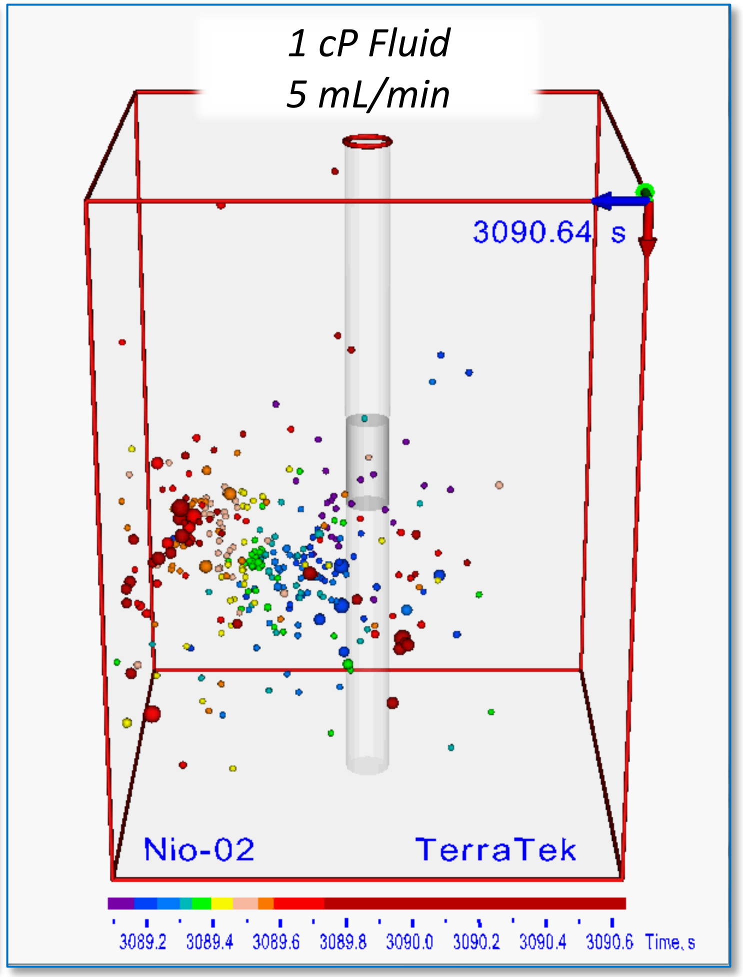
- NG foam system outperforms slickwater treatment by 25%
- NG foam system at 30 bpm and 15 bpm shows equivalent production performance



Current work is focused on characterizing the fracture network generated by a foamed fracturing fluid

- Increased fracture density leads to improved hydrocarbon recovery
- The fracture network density in a given shale is a function of fluid properties
- Fracture network/propagation has not yet been characterized for compressible fracturing fluids such as NG foam but is being explored in BP5





Acoustic Emissions Monitoring of Rock Fractured with Fluids of Different Viscosities

There are several opportunities for collaboration between the natural gas foam hydraulic fracturing project and other projects

Foam/Fracture Fluid Test Stand

- Pilot-scale foam test facility can be used to investigate a variety of foams and other fracturing fluids at relevant operating conditions
- Such tests can bridge the gap between bench-top and field demonstrations

Enhanced Oil Recovery (EOR)

- Use of natural gas as a fracturing fluid could enhance recovery
- Present and future research of EOR using natural gas can be leveraged to improve the NG foam fracturing methods

Foam Fluid Data

- Limited NG foam rheology data published
- Foam rheology results from current work can be used in multiple simulation codes

Current results indicate that natural gas foam is a viable hydraulic fracturing fluid and future work will explore production benefits

Results of Completed Project Work

- Compression cycle is the most efficient means of generating high pressure natural gas stream
- Equipment is commercially available but requires more development to mobilize
- Single-pass, pilot scale facility was designed, built, and operated.
- Stable NG foam was generated at 6000 psi using a commercially available viscosifier and surfactant.
- NG foam can be generated from produced water and multicomponent gas mixtures
- Relevant mixing methods were explored
- NG foam is qualitatively similar to other foams.
  - Shear thinning, power law fluid
  - Increased viscosity with foam quality
  - Laminar and turbulent regimes
- Reservoir model shows improved production compared to slickwater treatment

Current and Future Work

- Work in current budget period will determine if compressible foams generate improved fracture networks

Acknowledgement

This work was funded by the Department of Energy under award DE-FE0024314, ‘‘Development and Field Testing Novel Natural Gas Surface Process Equipment for Replacement of Water as Primary Hydraulic Fracturing Fluid”. Co-funding for this work was provided by Schlumberger Technology Corporation and Chevron Energy Technology Company.

Questions?

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The work accomplished during this project supports the Department of Energy program goals

The work to develop an alternative hydraulic fracturing process that uses natural gas-based foam supports a "critical component of the DOE portfolio to advance the environmentally-sound development of unconventional domestic natural gas and oil reserves" (as stated in DE-FOA-0001076). The process being developed will help to "ensure these resources are developed safely and with minimal environmental impact" by minimizing the usage of fresh water in the hydraulic fracturing process. The process being developed could decrease water usage by 70% or more compared to typical, water-based hydraulic fracturing techniques.

The overall goals and objectives of this project are…

Project Objective

The objective of this project is to develop a rugged, mobile, and economic system that can take natural gas and prepare it for use in fracturing of gas shale to significantly reduce water usage from traditional fracturing methods

Project Goals by Budget Period (BP)

- **BP1** - Identify optimal process for bringing the wellhead gas to injection pressure (10,000 psia) and temperature (ambient ±20 °F)
- **BP2** - Complete a laboratory scale test to validate fracturing concept
- **BP3** - Determine if typical hydraulic fracturing fluids (i.e., base fluids) can be used to generate stable NG foam
- **BP4** - Quantify NG foam stability with multi-component natural gas mixtures and at elevated operating temperatures
- **BP5** - Investigate production benefits of using compressible foam fracturing fluids

The current project team includes members from SwRI, Schlumberger, and Chevron

Griffin Beck	*Principal Investigator, Project Manager*
Carolyn Day	*Pilot-Scale Test System Lead*
Swanand Bhagwat, Ph.D.	*Visualization Lead, Testing Support*
James Donnelly	*Technical and Testing Support*
Nathan Poerner	*Data Acquisition Lead*
Brandon Ridens	*Process Model Lead, Testing Support*
Liz Garcia	*Contracts*
John Stubbs	*Technical and Testing Support*

Sandeep Verma, Ph.D.	*Principal Investigator*
Chris Daeffler, Ph.D.	*Foam Rheometer Lead*
Raj Malpani	*Reservoir Simulation Lead*
Ashwani Zutshi	*Fracture Network Test Advisor*

Joseph Renk	*Federal Project Manager*

Leo Chaves	*Principal Investigator*
Sarvesh Naik, Ph.D.	*Technical Advisor*

Results and key findings have been presented to scientific and industry communities through the following publications and presentations

1. **Beck, G. and Verma, S.,** "Development and Field Testing Novel Natural Gas (NG) Surface Process Equipment for Replacement of Water as Primary Hydraulic Fracturing Fluid," presented at the 2016 Carbon Storage and Oil and Natural Gas Technologies Review Meeting, Pittsburgh, PA (August 16-18, 2016).
2. **Verma, S., et al.,** "Novel Fracturing Process Utilizing Natural Gas," presented at the AIChE Annual Meeting, San Francisco, CA (November 13-18, 2016).
3. **Beck, G., et. al.,** "Laboratory Evaluation of a Natural Gas-Based Foamed Fracturing Fluid," presented at the 2017 AIChE Spring Meeting, San Antonio, TX (March 26-30, 2017)
4. **Beck, G., et. al.,** "Development and Evaluation of a Mobile Plant to Prepare Natural Gas for Use in Foam Fracturing Treatments," presented at the 2017 ASME Turbo Expo, Charlotte, NC (June 26-30, 2017).
5. **Verma, S., Pankaj, P., and Phatak, A.,** "Application of Natural Gas for Foamed Fracturing Fluid in Unconventional Reservoirs", AAPG International Conference and Exhibition, Cape Town, South Africa, November 4-11, 2018.
6. **Pankaj, P., Phatak, A., & Verma, S.** (2018, October 19). Evaluating Natural Gas-Based Foamed Fracturing Fluid Application in Unconventional Reservoirs. Society of Petroleum Engineers. doi:10.2118/192042-MS. https://www.onepetro.org/conference-paper/SPE-192042-MS
7. **Pankaj, P., Phatak, A., & Verma, S.** (2018, August 13). Application of Natural Gas for Foamed Fracturing Fluid in Unconventional Reservoirs. SPE Argentina Exploration and Production of Unconventional Resources Symposium, 14-16 August, Neuquén, Argentina. doi:10.2118/191863-MS.
8. **Malpani, R., et al.,** "Reducing the Volume of Water Needed for Hydraulic Fracturing by Employing Natural Gas Foamed Stimulation Fluid", presented at the 2020 SPE Annual Technical Conference and Exhibition, Virtual (October 26-29, 2020)
9. **Beck, G., et al.,** "A Pilot Scale Evaluation of Natural Gas Based Foam at Elevated Pressure and Temperature Conditions", presented at the 2020 SPE Annual Technical Conference and Exhibition, Virtual (October 26-29, 2020)