Application of Natural Gas-Based Foamed Fracturing Fluid in Unconventional Reservoirs*

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Abstract

Foamed fracturing fluids have been used in unconventional reservoirs to reduce the water usage and minimize deleterious impact on water-sensitive formations. As part of a Department of Energy (DOE) sponsored program, we have previously identified an optimal thermodynamic pathway to transform wellhead natural gas (NG) into pressurized NG suitable for use as the internal phase in a foamed fracturing fluid. This study now extends that work to determine the impact of using NG Foam fracturing fluid on hydraulic fracture geometry and the productivity from the unconventional reservoirs. The current study is focused on investigating the impact of the natural gas-based foam of various foam qualities in hydraulic fracture geometries and their production through simulation models.

Field data and lab-based measurements for NG foam fluid properties are incorporated in the study. In addition, the transient response of the fluid flowback from foam-based fluid is studied using numerical simulation. Comparative analysis is done with typical Slickwater, linear gel and full crosslinked fluid application for hydraulic fracturing using 3D-complex hydraulic fracture models. 1D and 2D particle transport models have been used to verify the differences in proppant distribution in the hydraulic fractures. Rapid wellbore clean-up, low clay damage, and effect of the relative permeability difference between the NG foam and rock matrix is an added advantage, apart from reducing the water requirements for hydraulic fracturing. In addition to logistical benefit of using wellsite liberated low pressure gas utilization, NG foamed fracturing fluid has a dynamic fluid leak-off behavior and increase effective viscosity over the base fluid that allows pump and transport sand at least 10% farther in the hydraulic fractures than linear gel. Slickwater displays poor proppant transport and hence poses inability to pump higher concentrations of sand. NG foam fracturing fluid, on the other hand, displays improved proppant transport and has shown to create more complexity than Slickwater (Hall et al.). Use of NG foamed fracturing fluid is a concept that has not been practiced widely over wellsites due to safety concerns. However, the applications to under-pressured reservoirs, logistical benefits, and improved production performance are found lucrative in this study. Hence, operators can invest in creating safer handling environment for wellsite application of NG foam to reap the benefits.

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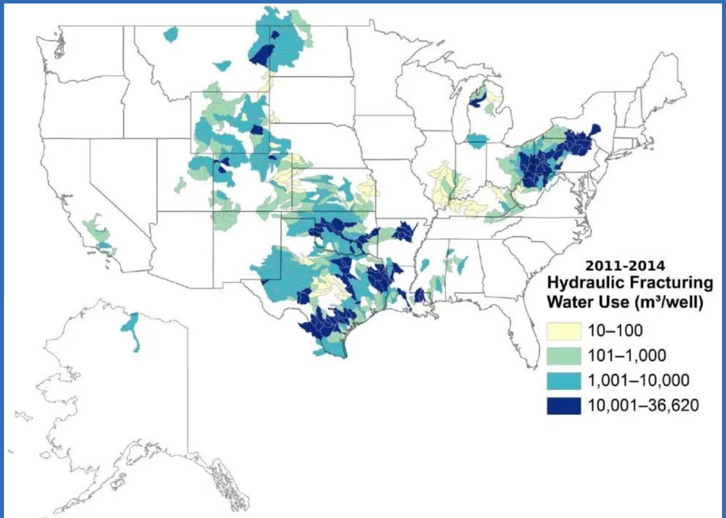
Water as a fracturing fluid

Hydraulic fracturing revolution has increased water use and wastewater production in the United States. From 2000 to 2014, water consumption increased by >2600% from 0.17M gallons per oil and gas well to more than 15000 m^3 per oil well and 19000 m^3 per gas well.



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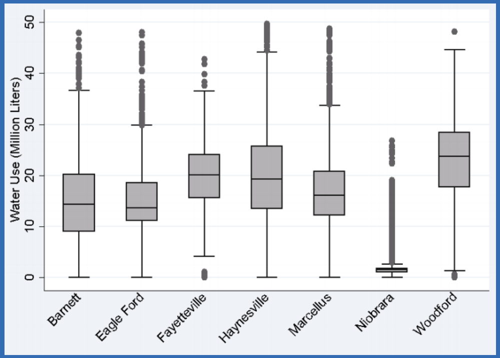
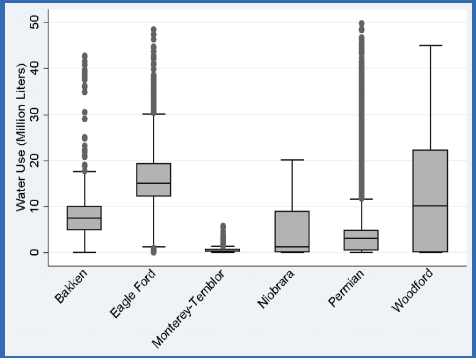


Water consumption in major unconventional shale gas formations



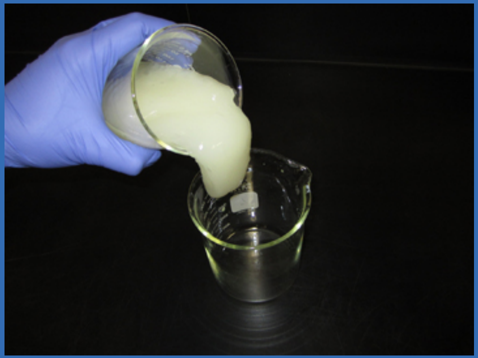
Water consumption in major unconventional shale oil formations

Downside of using water in massive volumes

- Significant transportation required
- Wellsite infrastructure needed
- Recovered water must be either cleaned or disposed

Fracturing with wellsite natural gas: Concept

- Fracturing fluid prepared in real-time using natural gas delivered from a pipeline, or nearby wells.
- Benefits
  - May reduce water usage by >70%.
    - Composition of injected fluid 70% natural gas/30% water.
    - Reduction in water transportation costs.
  - Reduced flowback volumes
    - Smaller water pit.
    - Cost savings in treatment of produced water.
    - Surface water separation costs reduced.
  - Potential production enhancement
    - Mobility of natural gas/water mixture higher than water.
    - Effective proppant placement.
    - Reduced clay swelling and improved conductivity of fracture network..
- Challenges
  - Pipeline infrastructure/gas volumes.
  - Use of central gas processing facility.
  - HSE concerns.

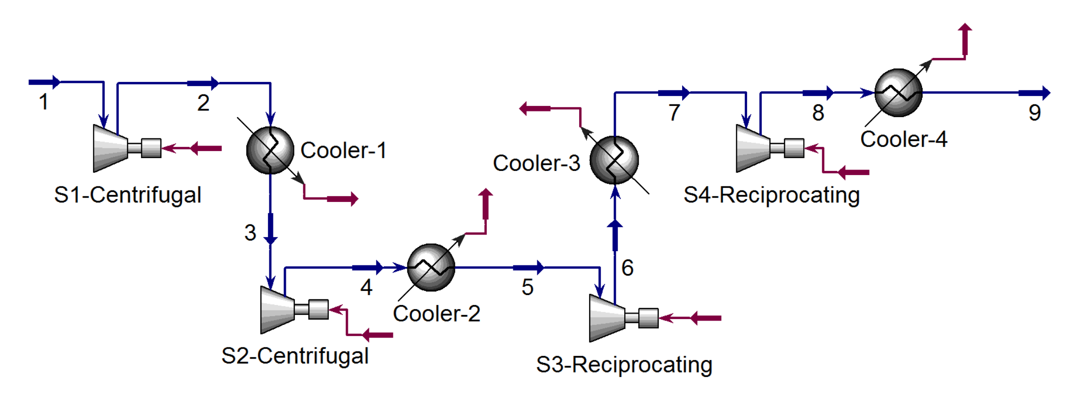


Key questions

- Source – natural gas is often available at well site and nearby processing plants.
- Surface Equipment – detailed engineering calculations conducted.
- Rheology – pilot plant designed and built. Key data generated.
- Applicability – wellbore fluid flow calculations simulated for foamed flow.
- Efficacy – fracture network creation simulated.
- Production – numerical modeling using a history matched reservoir.

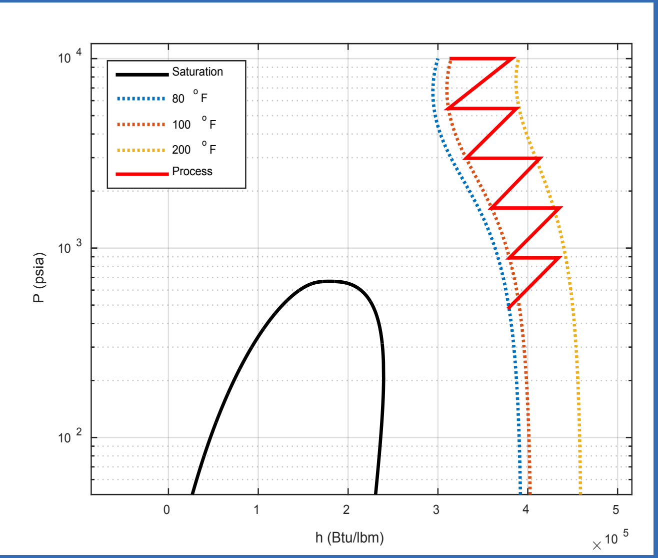
Concept modeling and selection

- Compress natural gas from 500 psig → 10,000 psig.
- Concepts selected/evaluated
  - Direct compression
  - Natural gas liquefier cycle
    - Provides temporary storage for peak shaving
  - Mixed refrigerant liquefier cycle
    - Provides better efficiency
- All concepts modeled in Aspentech HYSYS®

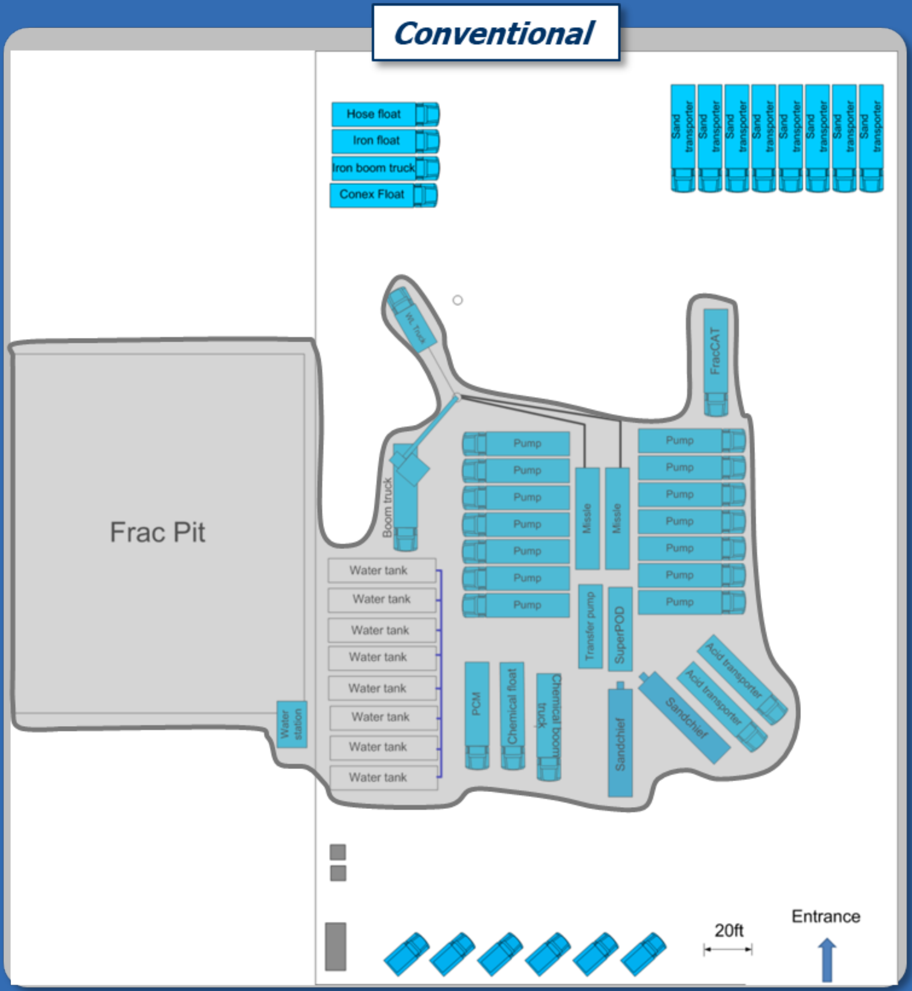


Key Metrics for Direct Compression

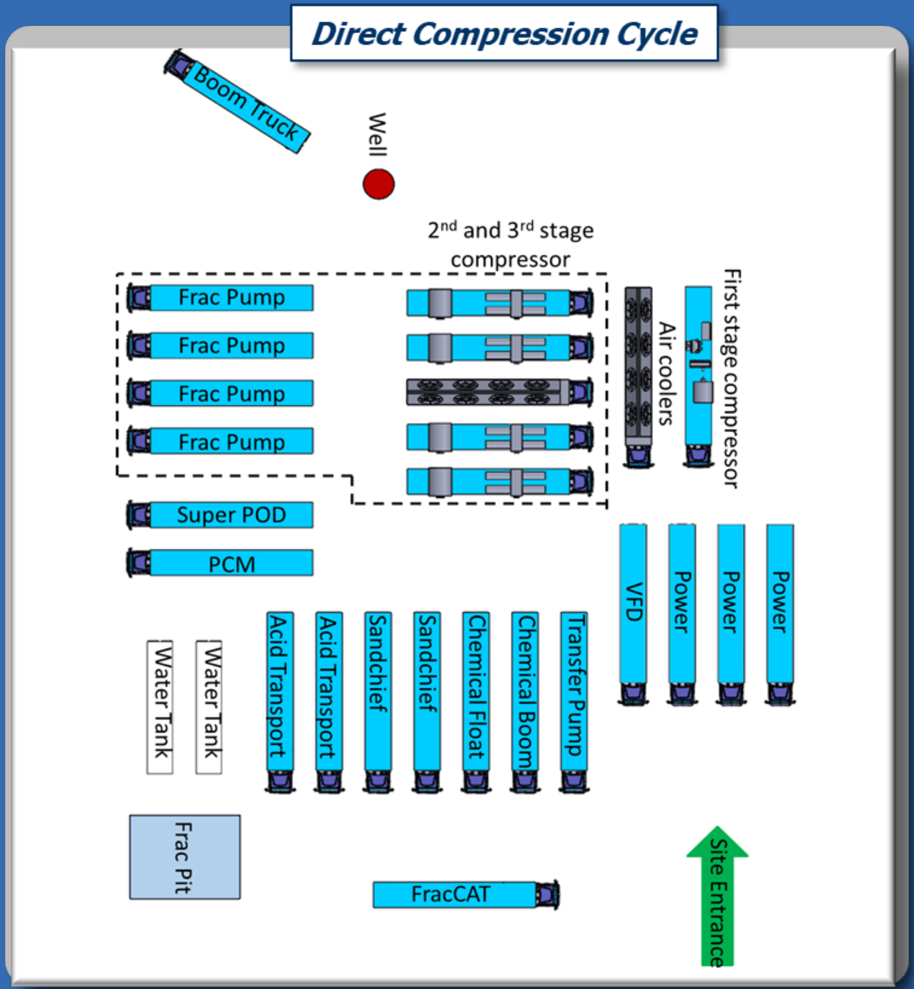
Parameter	Value
Total Power Required	20 MW
Compressor Power	20 MW
Pump Power	0
Expander Power	0
Specific Power	305 Btu/lbm
Heat Rejected	24 MW



Footprint

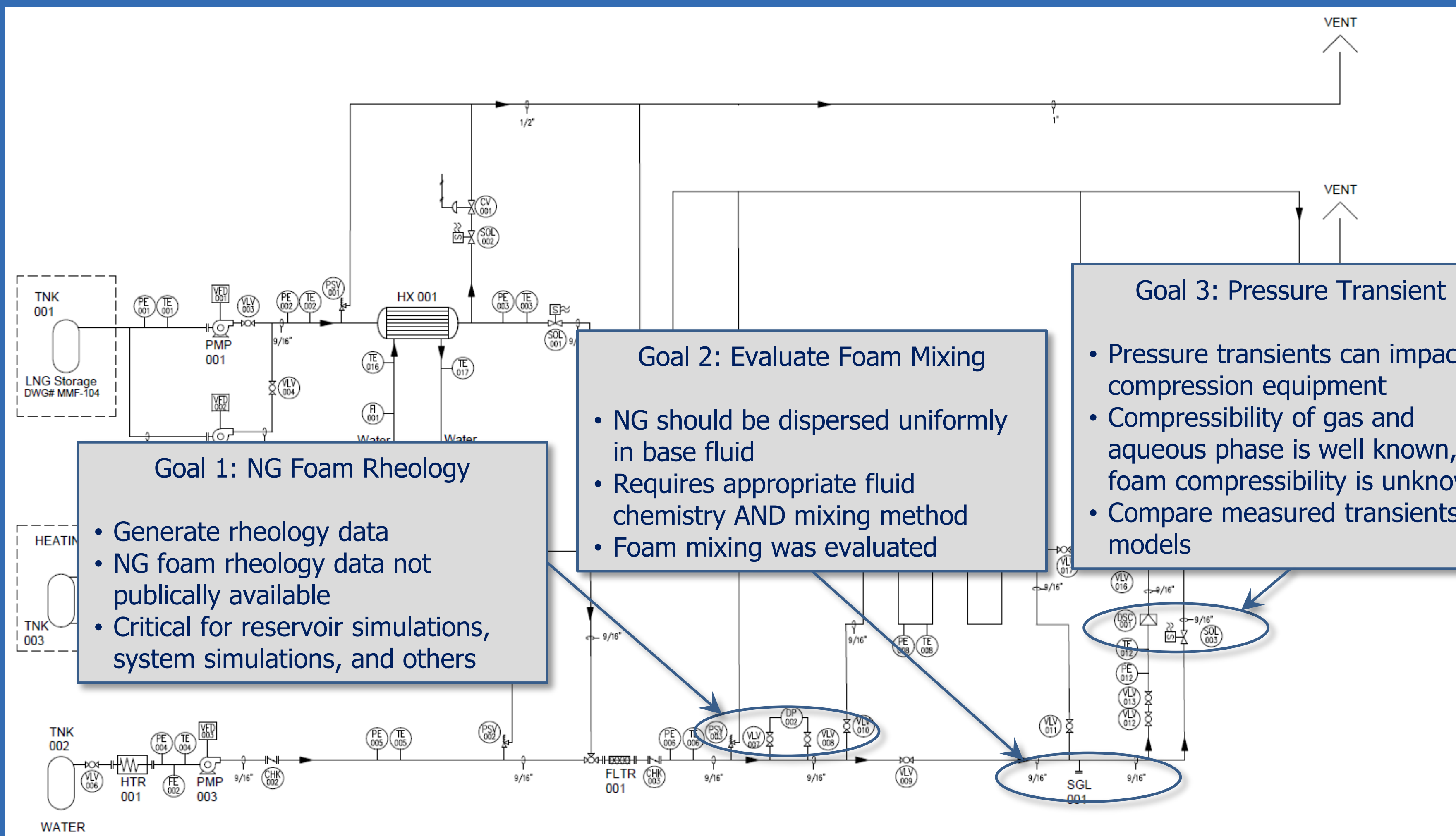


Conventional
Hose float
Iron float
Iron boom truck
Conex Float
Sand transporter
Frac Pit
Boom truck
FracCAT
Pump
Missile
Transfer pump
SuperPOD
Water tank
Water station
PCM
Chemical float
Chemical boom truck
Sandchief
Acid transporter
20ft
Entrance



Direct Compression Cycle
Boom Truck
Well
2nd and 3rd stage compressor
Frac Pump
Frac Pump
Frac Pump
Frac Pump
Air coolers
First stage compressor
Super POD
PCM
VFD
Power
Power
Power
Water Tank
Water Tank
Acid Transport
Acid Transport
Sandchief
Sandchief
Chemical Float
Chemical Boom
Transfer Pump
Frac Pit
FracCAT
Site Entrance

Pilot facility to generate NG foam rheology



Goal 1: NG Foam Rheology

- Generate rheology data
- NG foam rheology data not publically available
- Critical for reservoir simulations, system simulations, and others

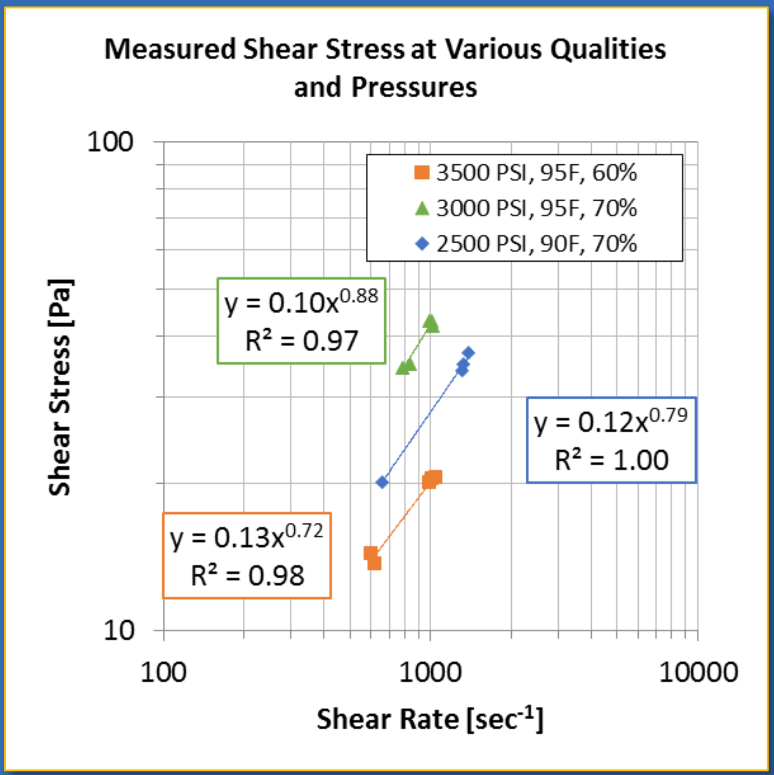
Goal 2: Evaluate Foam Mixing

- NG should be dispersed uniformly in base fluid
- Requires appropriate fluid chemistry AND mixing method
- Foam mixing was evaluated

Goal 3: Pressure Transient

- Pressure transients can impact compression equipment
- Compressibility of gas and aqueous phase is well known, foam compressibility is unknown
- Compare measured transients to models

NG foams behave similar to other gas foams



Herschel-Bulkley

$$\tau = \tau_0 + K\dot{\gamma}^n$$

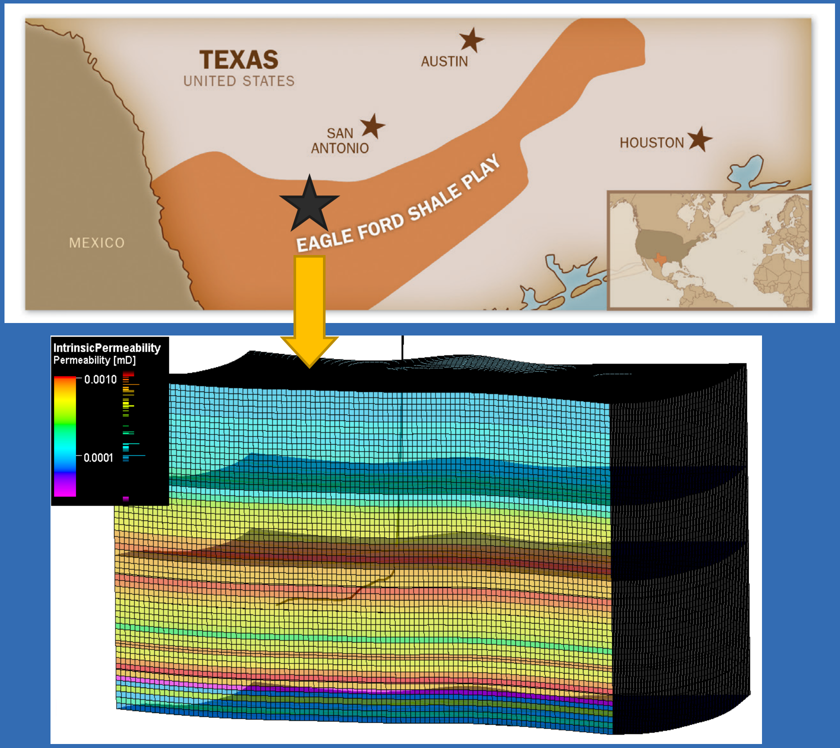
Power Law

$$\tau = K\dot{\gamma}^n$$

- Foam rheology in laminar regime often described as either a *Herschel-Bulkley* or a *power law* fluid.
- Experiments indicate that, for a given tube size, the data all collapse to a single curve regardless of quality in the turbulent regime.
- Foam rheology is a strong function of quality :
  - Apparent viscosity increases with foam quality
  - Newtonian at qualities up to 50 to 55%
  - Non-Newtonian at qualities greater than 50 to 55% (shear thinning)
  - Foam inversion at ~95%
- Apparent viscosity decreases with temperature
- Pressure has a limited effect on apparent viscosity

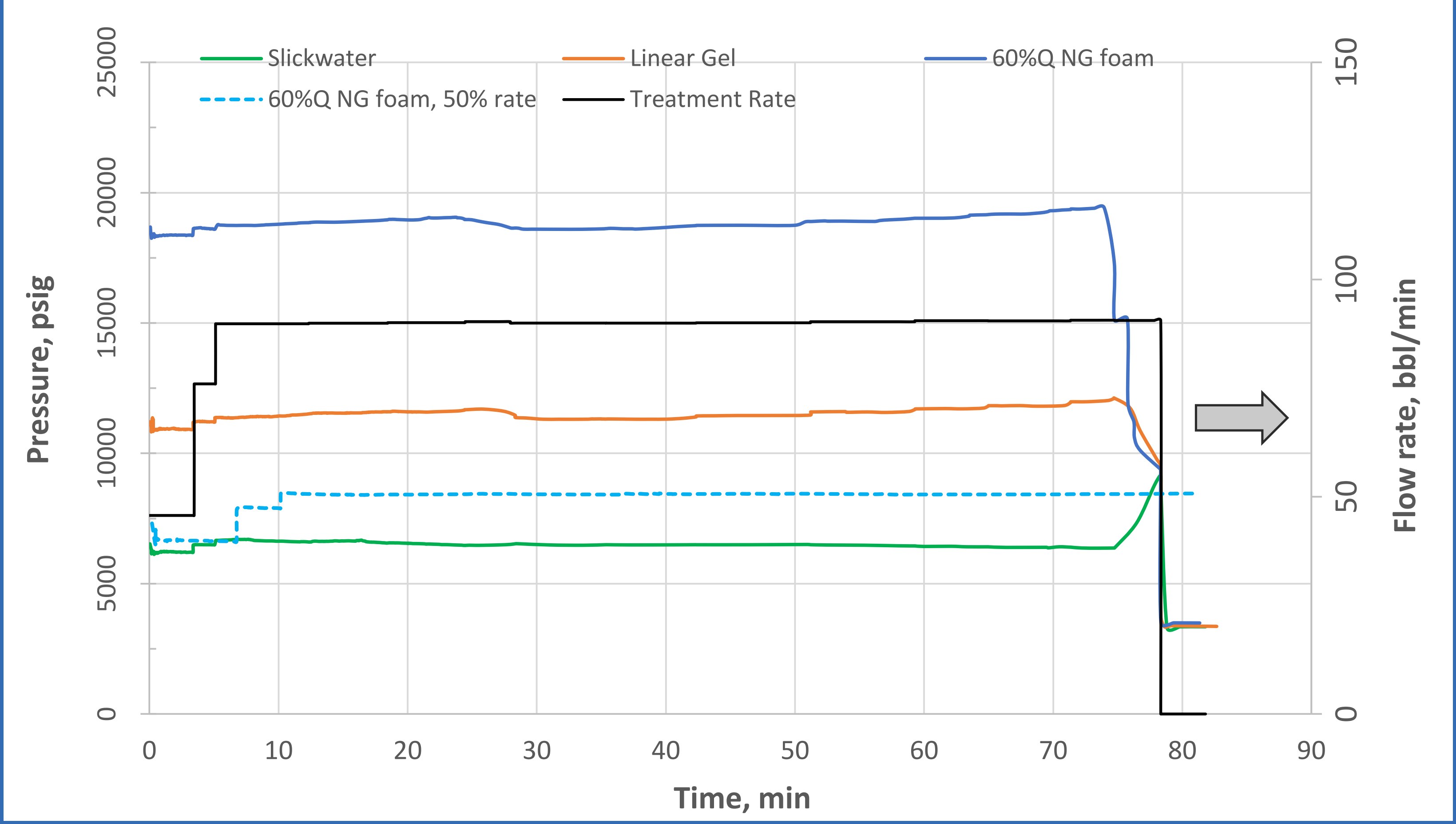
Numerical modeling stimulation with NG foams

- Geological and geomechanical model for well located in the Eagle Ford formation was used for this study.
- Following characteristics of hydraulic fracture geometry were analyzed and compared:
  - **Surface Pressure**
  - **Proppant transport** and its effect on productivity
  - Improved **fracture initiation** and cluster breakdown
  - Lower **proppant embedment** in a clay-rich formation



Surface pressure calculation

Eagle ford formation, 8200 ft TVD
Identical treatment rate, and fracture initiation pressure



Proppant Transport Animation

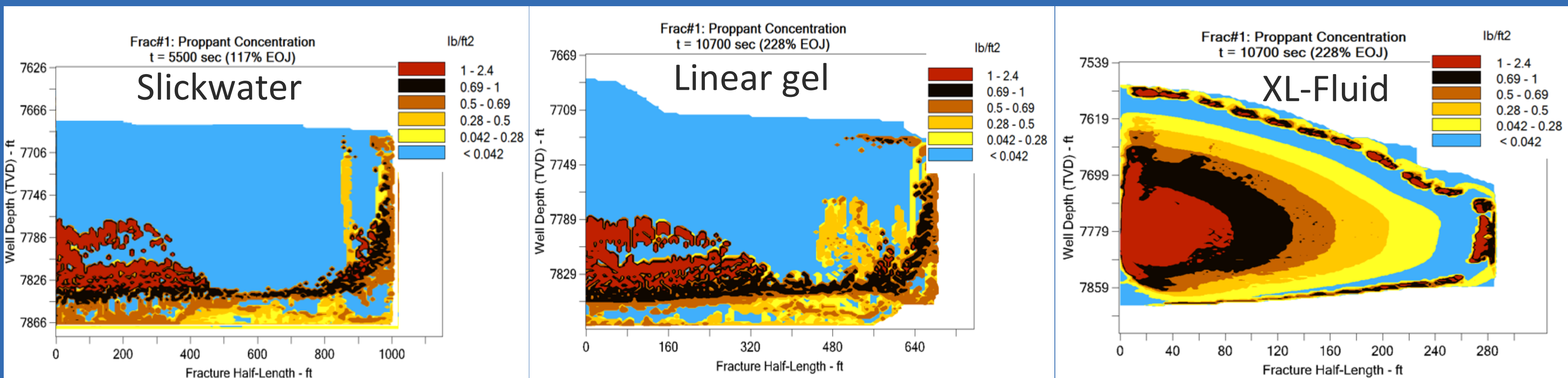
Click to Activate

Transport of proppant evaluated using advanced 2D transport model incorporating particle-in-cell (proppant transport) method.

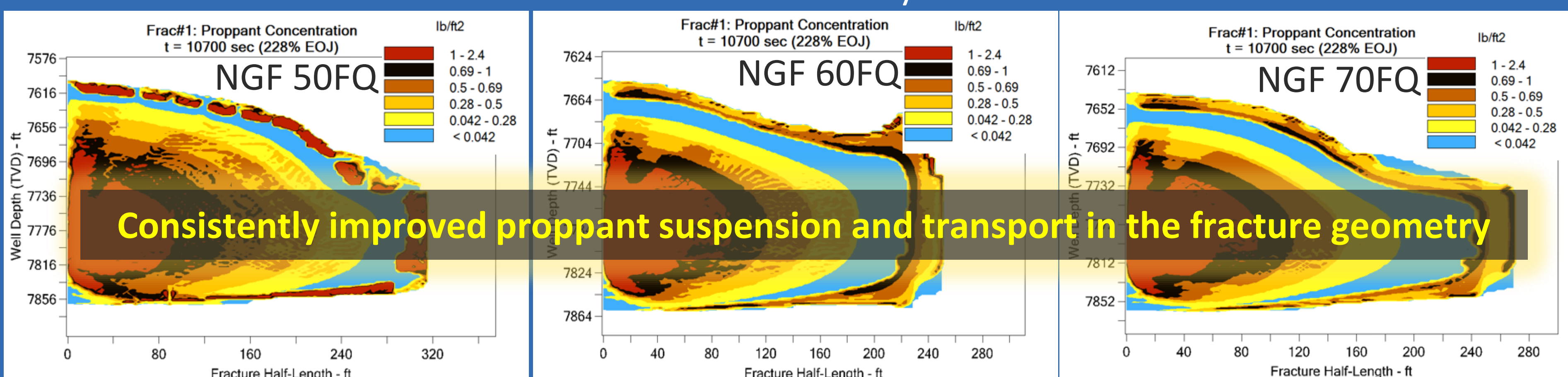
Wider, shorter and taller effective fracture geometry with NG foam as compared to linear gel fracturing fluid.

Improved proppant transport

Conventional fluid Systems

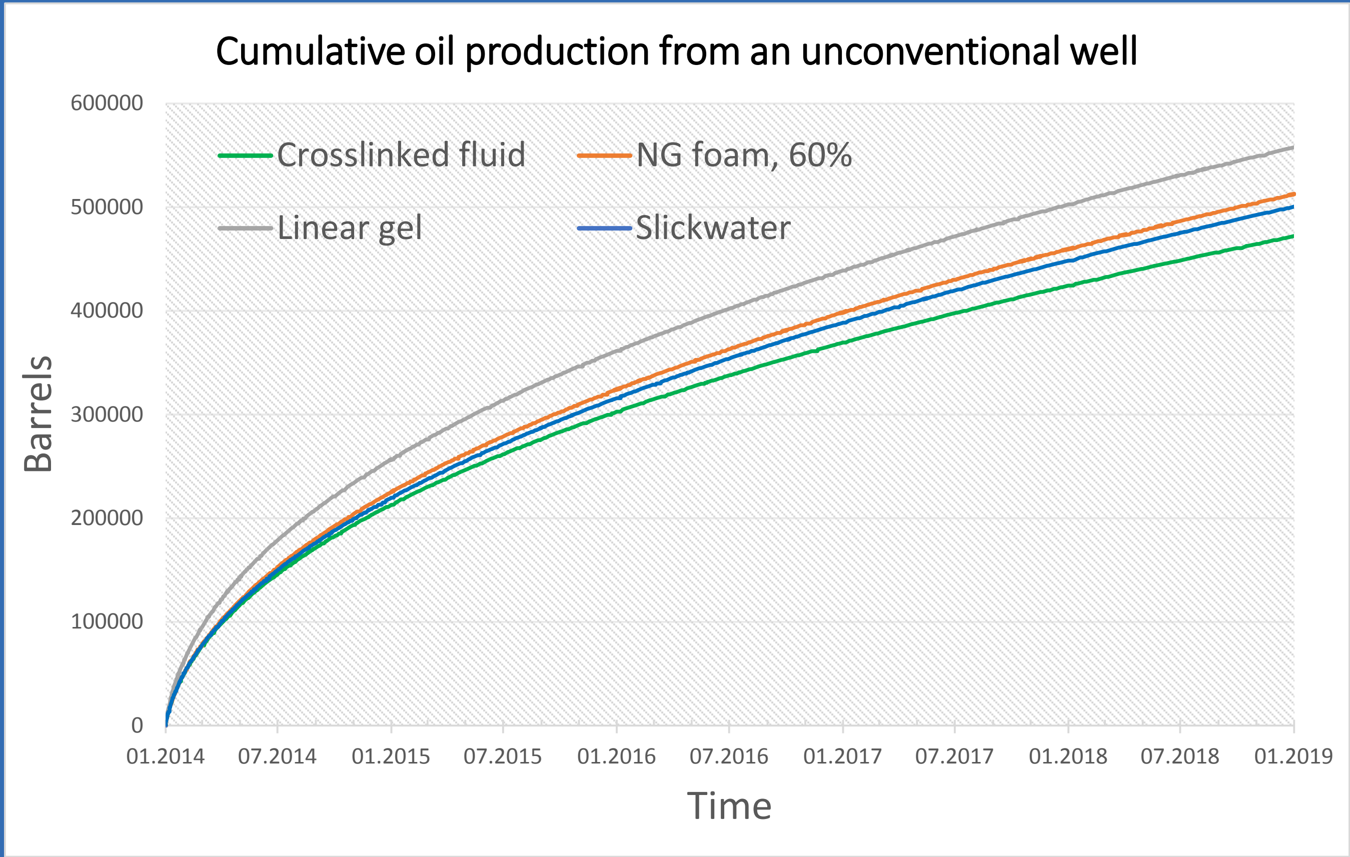


NG Foamed fluid Systems



Consistently improved proppant suspension and transport in the fracture geometry

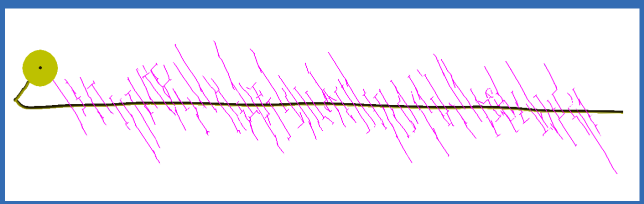
Impact on production



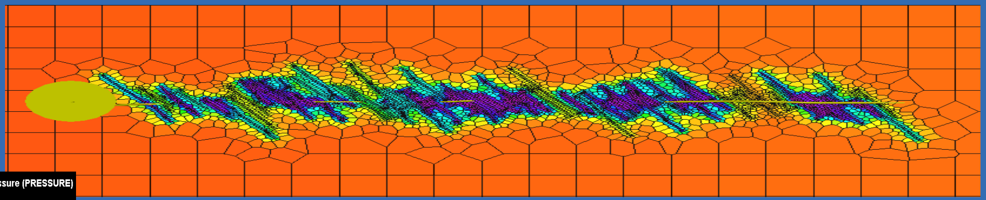
- Linear gel has the best cumulative production as it creates greater surface area with longer fractures.
- NG foam based fracturing fluid has the second highest production performance.

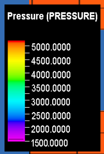
Fracture initiation, and oil production

Gomaa et al. (2014) : Nitrogen foam initiated a fracture at almost half the injection pressure when compared to brine or slickwater formulation.

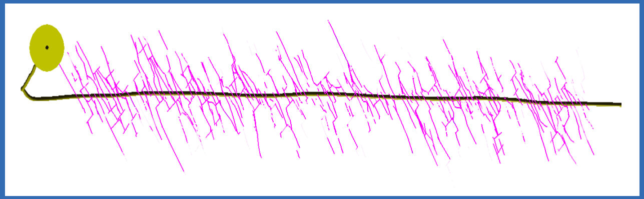


Fracture geometry with 50% cluster breakdown using slickwater

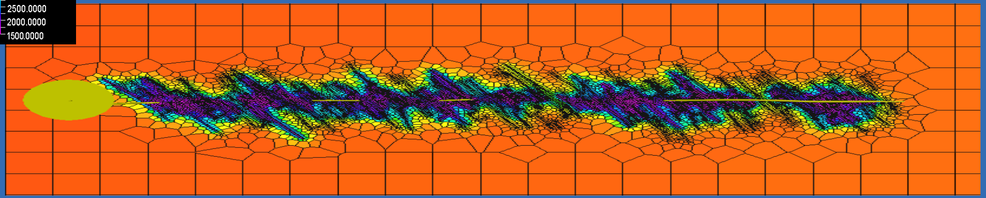




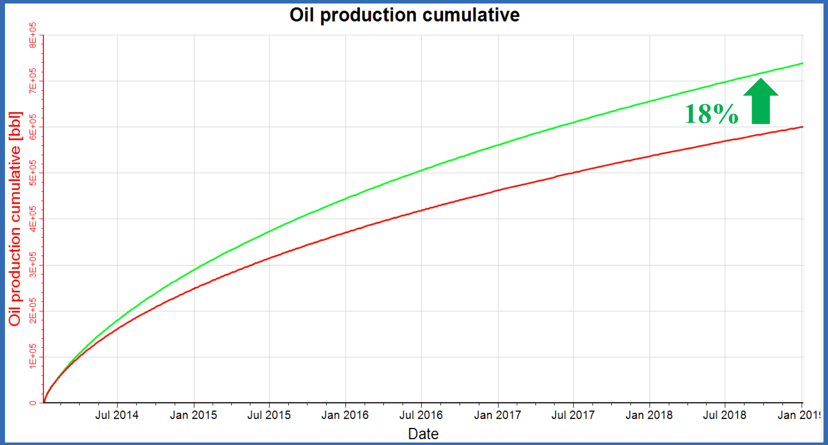
Pressure depletion in the NWB region using slickwater



Fracture geometry with all clusters breakdown using NG foam fluid



Pressure depletion in the NWB region using NG foam fluid



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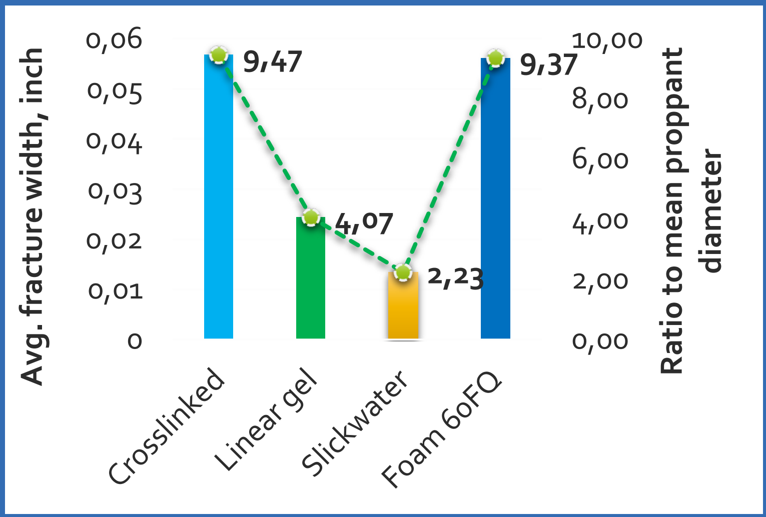
Proppant embedment

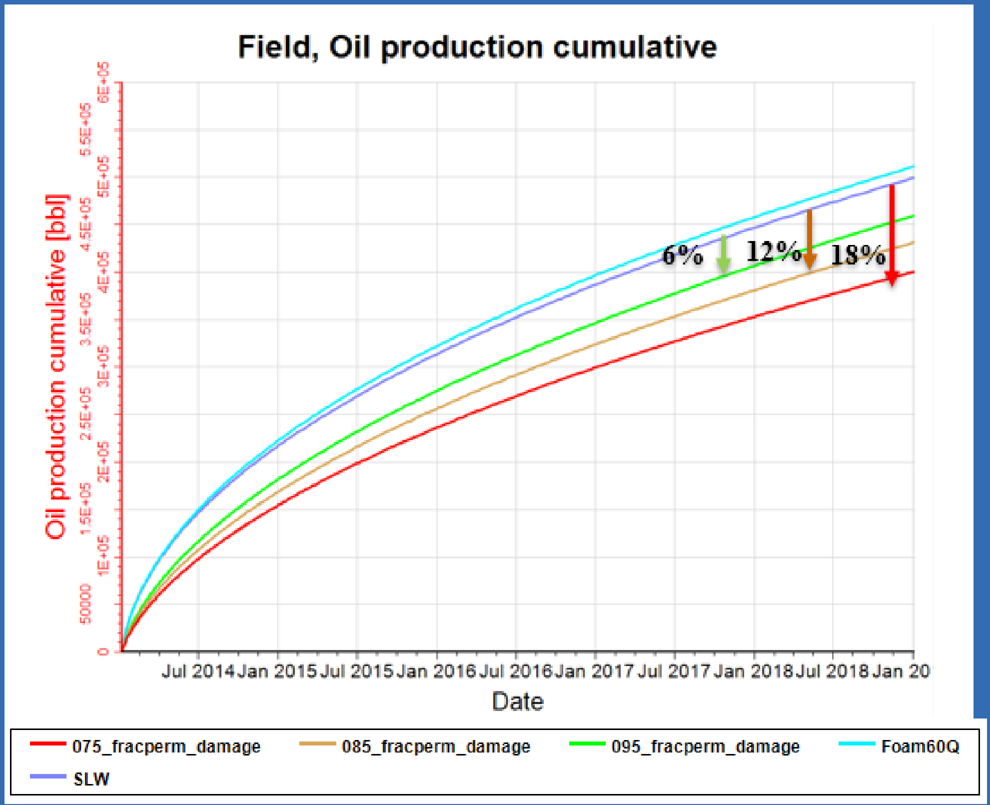
Zhang et al., 2015 : Samples from Barnett shale comprising 31% quartz and over 46% clay volume .

- 50% of the proppant embedded exposed to water.
- 15% of the proppant embedded exposed to gas.
- Conductivity loss could be in the range of 45% to 80% with a mere 10% proppant embedment.



Greater number of proppant layers→ lower embedment and lesser conductivity damage

Production for 5% - 25 % damage of conductivity in the Eagle Ford scenario shows 6%-18% drop production



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Conclusions

- Engineering design calculations for design of **surface facilities** for NG based foam fluids were conducted.
- A pilot scale facility was constructed and **fluid rheology** was established.
- **Surface pressure calculations** indicate that the application of this technology is likely to be more suitable for shallower reservoirs.
- Use of NG based foam fracturing fluid indicates benefits for improved **proppant transport** due to its higher apparent viscosity.
- NG foam fracturing fluid is shown to **improve fracture complexity** in the near-wellbore area.
- Lower aqueous phase in the fracturing fluid is known to reduce clay swelling and hence **proppant embedment**.
- **Decreased water** use, and **reduced flowback** during production are expected benefits.
- Additional details available in SPE 191863, SPE 187199.