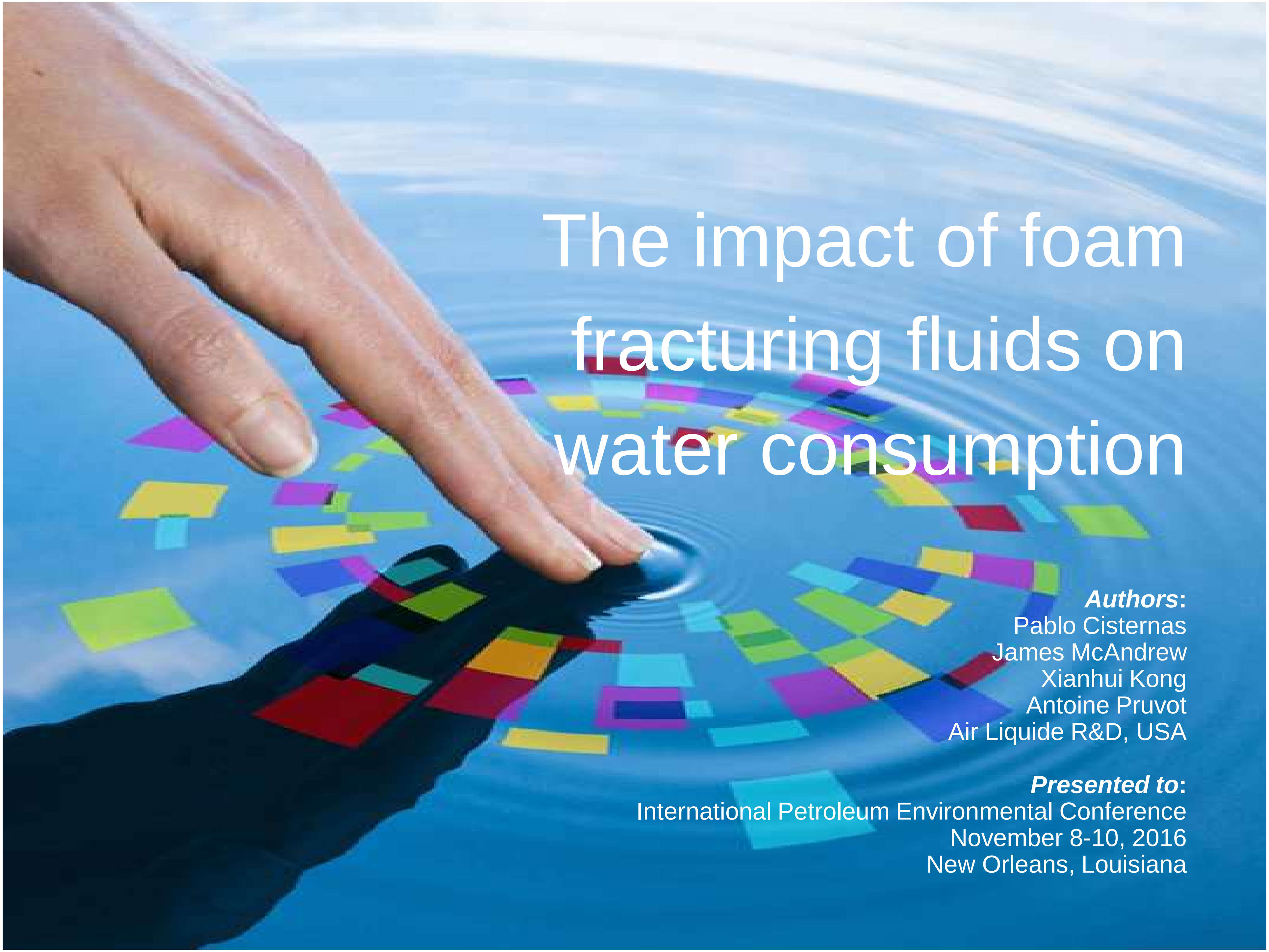

The impact of foam fracturing fluids on water consumption

***Authors*:**
Pablo Cisternas
James McAndrew
Xianhui Kong
Antoine Pruvot
Air Liquide R&D, USA

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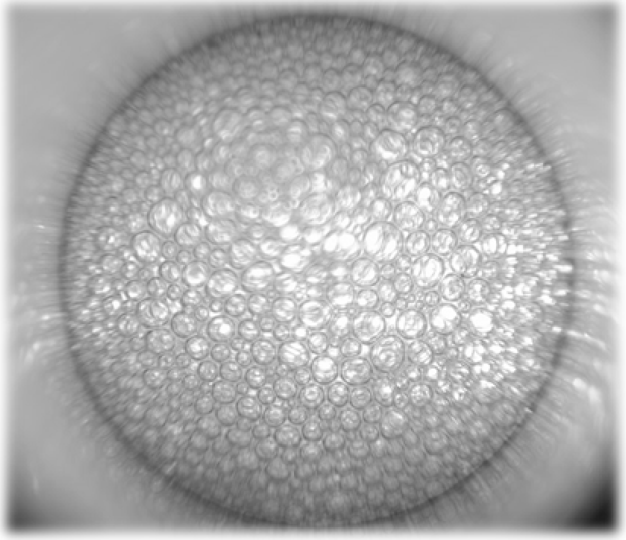
Motivation and Objective

- Motivation
  - Reduce water consumption
  - Optimize Well Productivity
    - Identify opportunities to improve well performance using foams

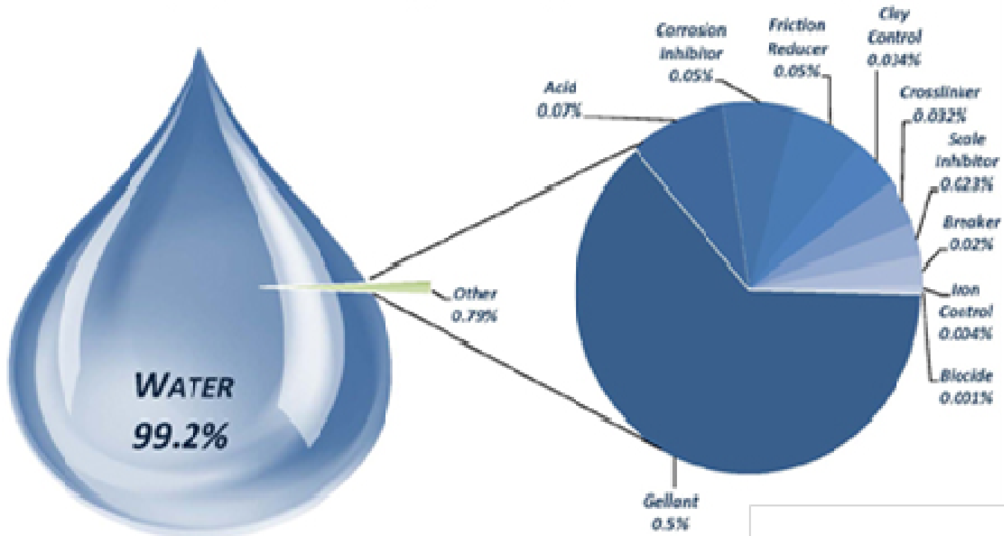


- Objectives
  - Understand foam properties
  - Evaluate foam performance for proppant transport

- This Presentation
  - Focus on water savings perspective

Water in Hydraulic Fracturing

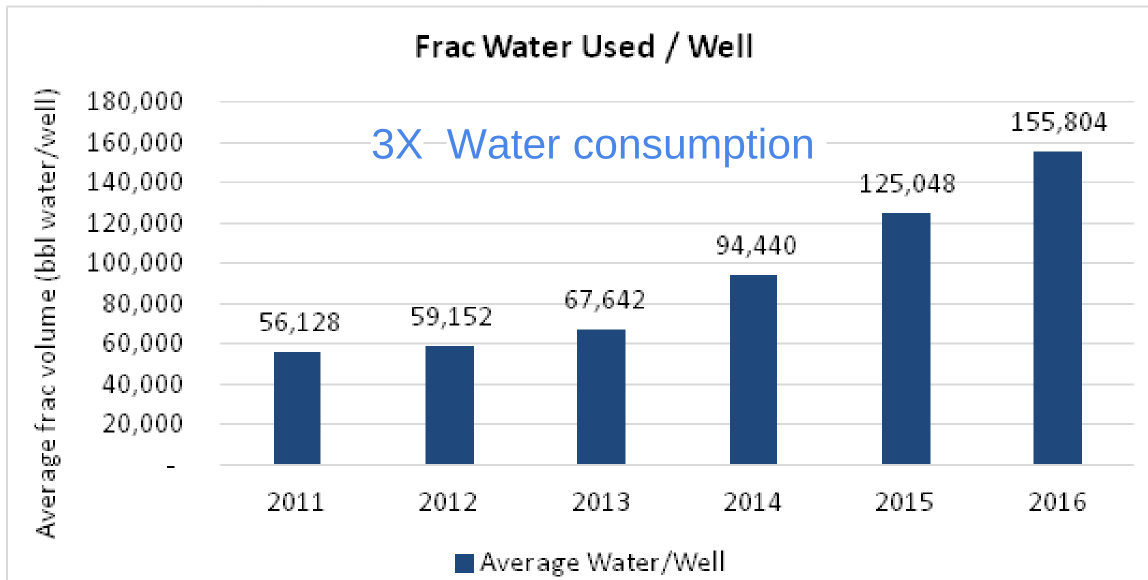
Average Hydraulc Fracturing Fluid Composition for US Shale Plays



Fracfocus

- Disposal issues
  - Chemicals, salinity, NORM
  - Earthquakes
  - Transportation

Currently: 3MM to 8MM gal/well and increasing...



FracKnowledge Frac Database.

Foam Fluids Impact on Water Consumption

- Water Replacement
  - “80-quality” foam is 80% N_2 by volume (water volume reduction)
- Proppant Placement Effects
- Leak-off Effects
- For Nitrogen foams, transport and storage requirements are also reduced by **Volume Effects**

Foam Fracturing Fluids reduce water consumption through multiple synergistic effects

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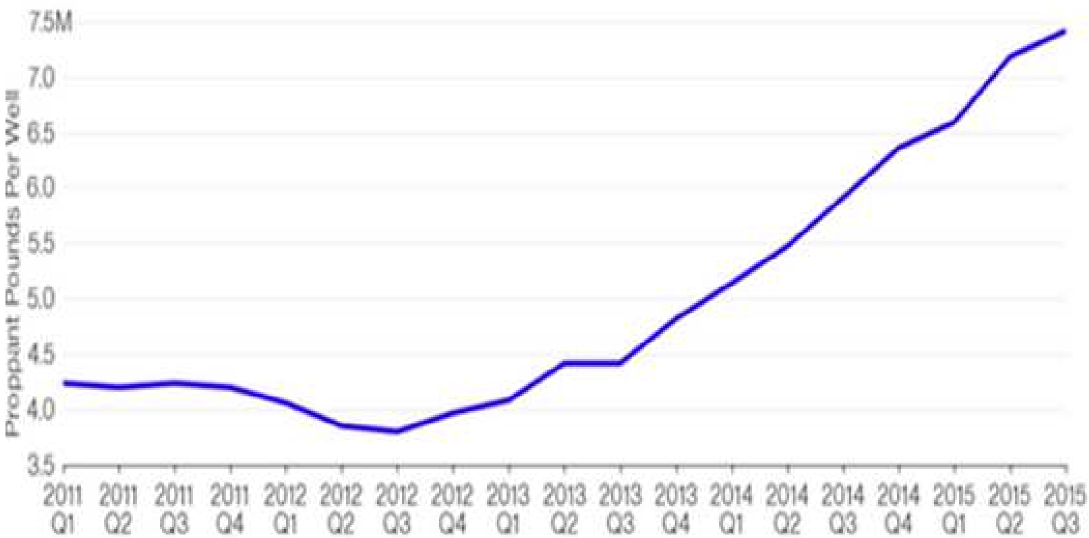
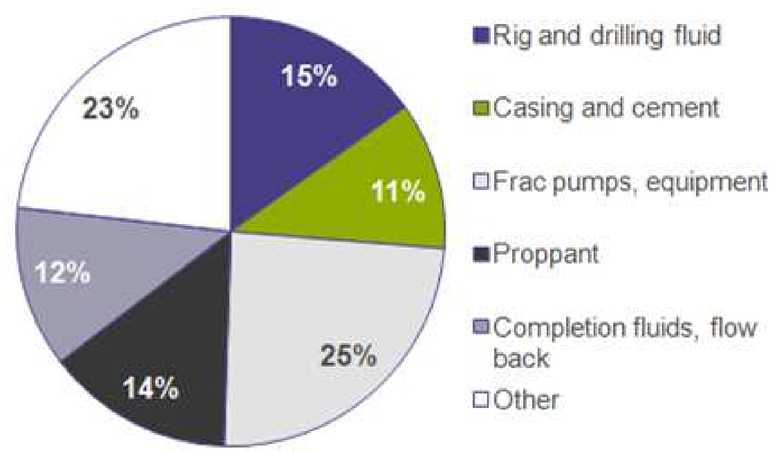
Proppant Consumption Trends



Primary Vision Inc.

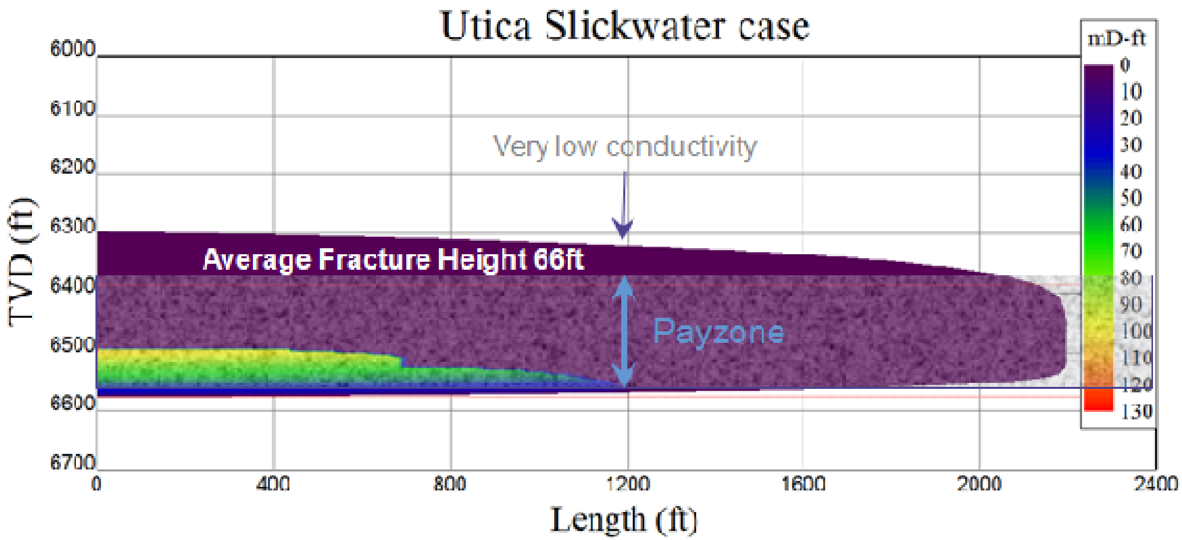
- Proppant lbs/ft trends:
  - Pioneer Published Frac Design:
    - 2014: 1000 lbs/ft
    - 2015: 1400 lbs/ft
    - 2016: 1700 lbs/ft
  - Chesapeake "Prop-a-geddon"
    - 3000 lbs/ft

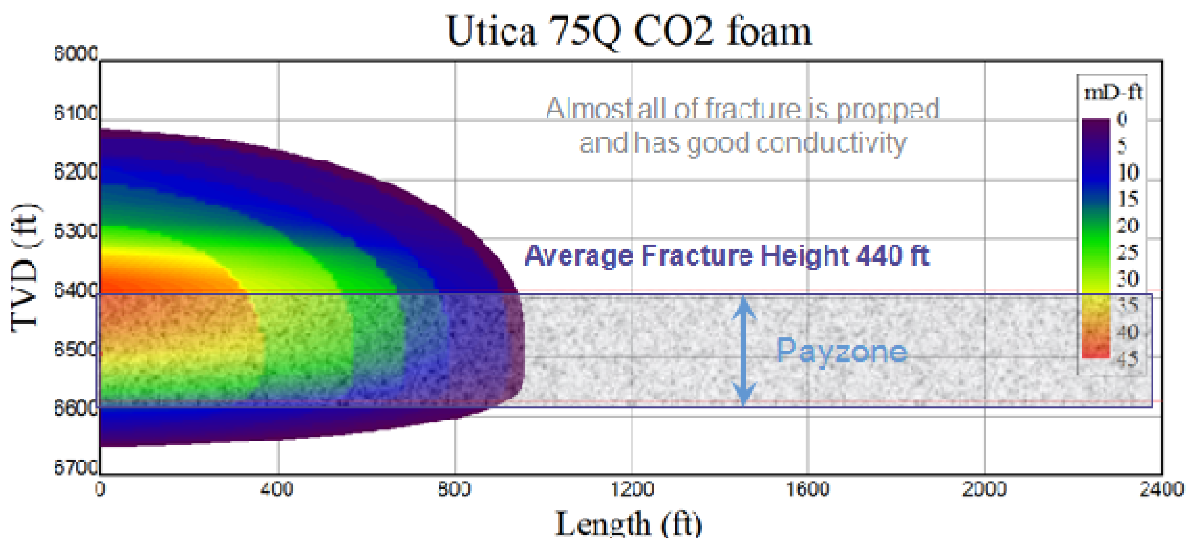
Increasing Proppant Consumption/ft is indicative of the importance of proppant placement



"Percentage breakdown of cost shares for U.S. onshore oil and natural gas drilling and completion". Source: IHS Oil and Gas Upstream Cost Study commissioned by EIA

Simulation-based Study





McAndrew et al, 2014

M-frac simulation Presented at AAPG 2014

Slickwater delivers proppant to a smaller volume than foam, despite longer fracture

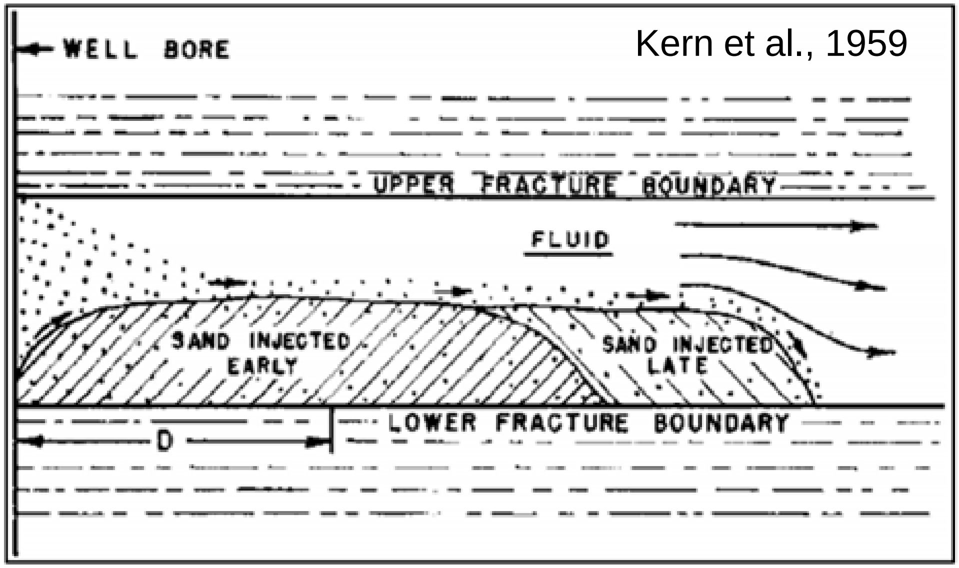
New Laboratory Apparatus

- 2,400psi (160 bar) operating pressure
- Foam Rheology and Stability Measurements
- Proppant Transport Measurement

Experimental Approach

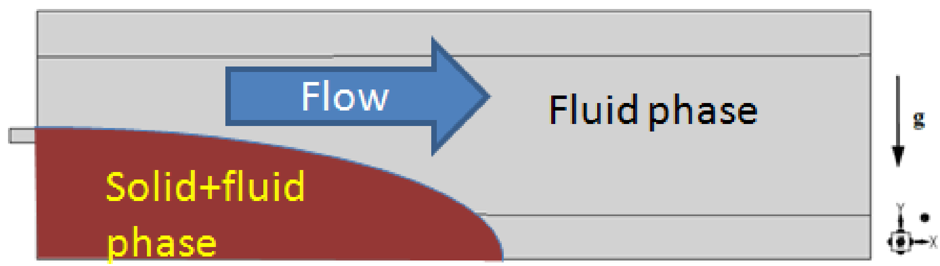
Proppant Transport Mechanism for Water

Growth and propagation of sand bed



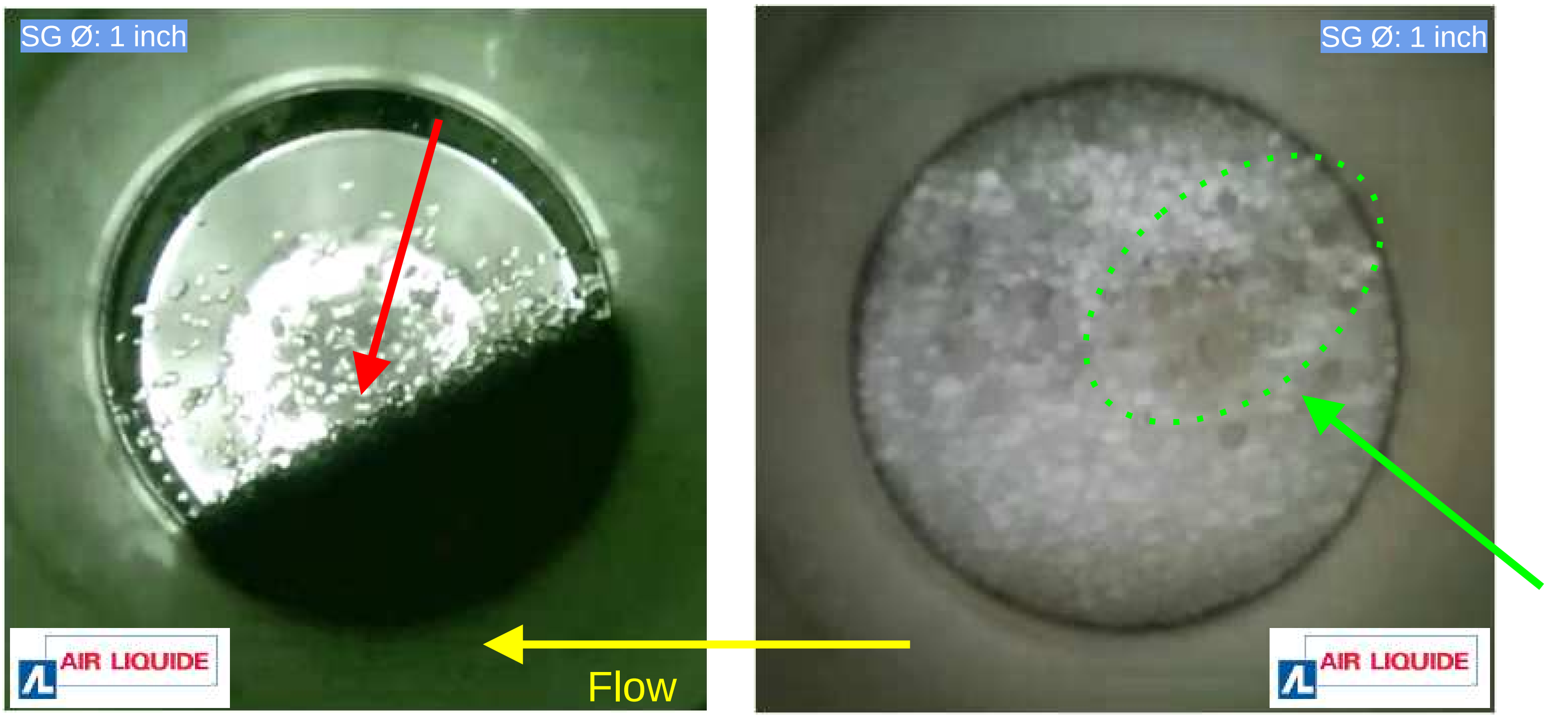
Kern et al., 1959

Water – Proppant



Proppant Transport Water vs. N_2 foam

- Images from Air Liquide Laboratory



Water – Proppant

80% Foam – Proppant

Water: Mainly translational transport

Foam: Mainly buoyant transport

Proppant Placement - Summary

- We have observed that industry is using higher Proppant lbs/ft, despite lower oil price, which highlights the importance of proppant placement
- Foam fracturing fluids provide improved proppant transport
  - Supported by simulation results
  - Direct experimental measurement starting to come on-line
  - Will be coupled with computational fluid dynamics to provide needed understanding
- **We propose** that foam fracturing fluids will provide improved productivity without massive proppant injection/massive fluid volumes, due to improved proppant placement
  - Tuning of the foam rheology will be required to optimize fracture dimensions

Foam Fluids Impact on Water Consumption

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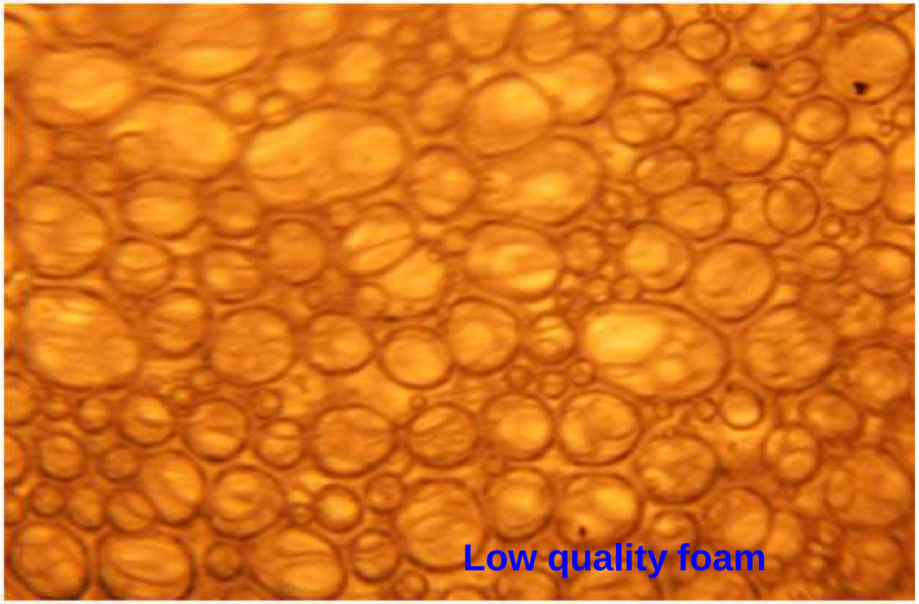
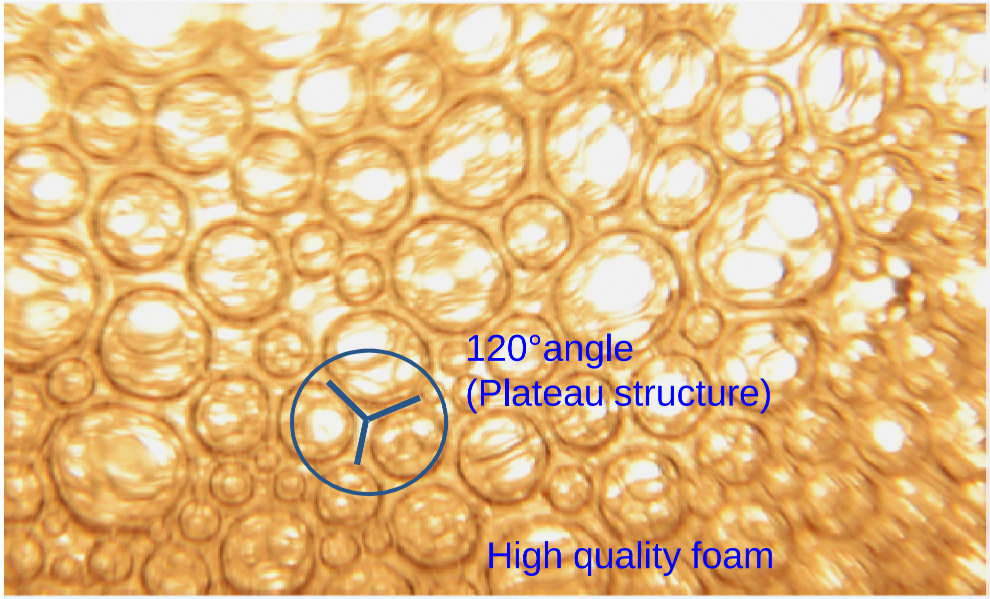
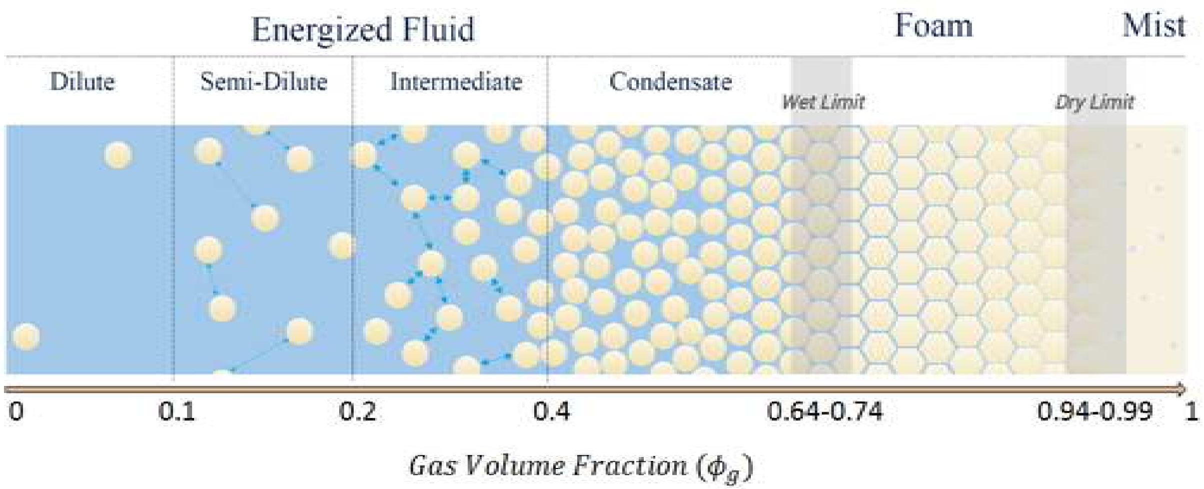
Leak-off effects

- Leak-off fluid losses are typically >50% for slickwater
- Foams reduce leakoff, not only through reduced water injection volume, but also through modification of leak-off physics
- Leak-off physics effects follow from foam quality and structure
  - Can be explained in terms of Surface Area effect on Osmotic Pressure (due to Princen)
  - Osmotic Pressure of the foam is a driving force to retain water in the fracture

Foam Quality and Structure

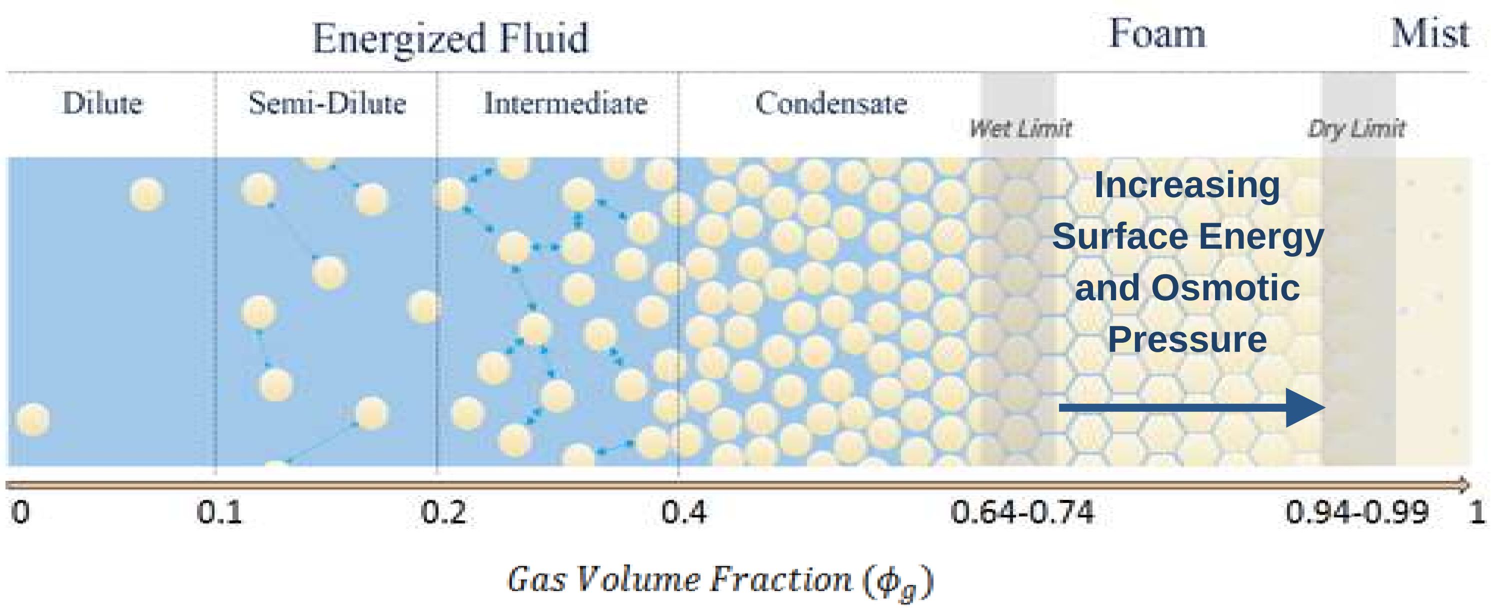






AIR LIQUIDE

Basis of Leakoff Effect: Osmotic Pressure (Princen)



- Beyond the wet limit, further loss of liquid requires a surface area increase
  - Spheres → Polyhedra

Dry Foams resist fluid loss

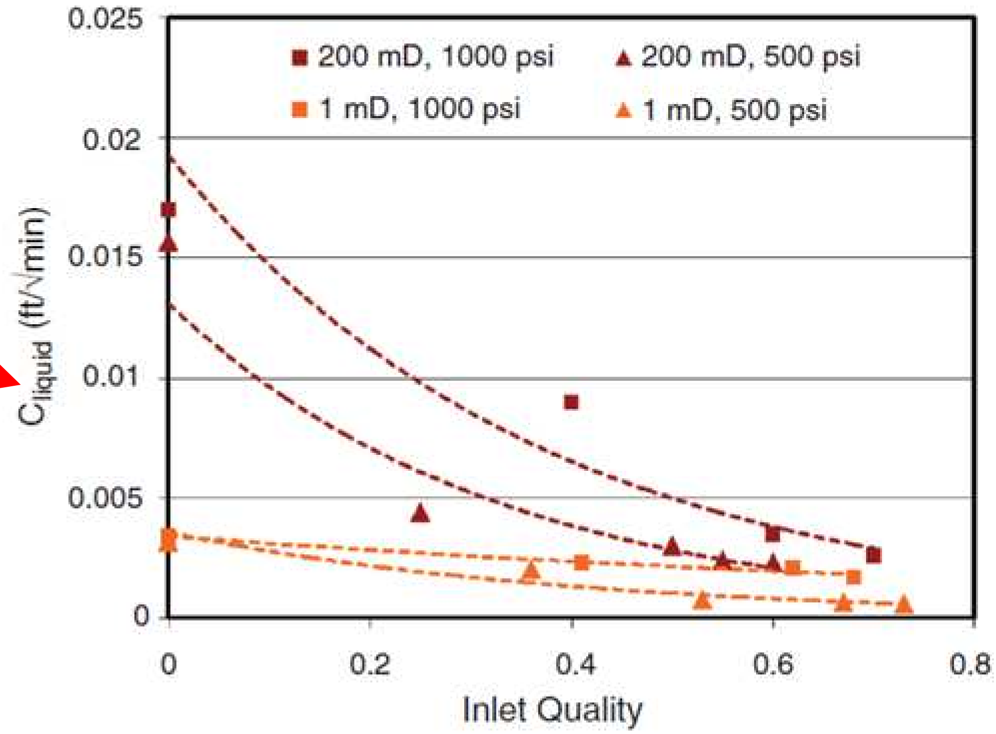
$$E = \gamma \sum_{i=1}^{n} S_i = \gamma S_{tot},$$

Experimental Observation of Leakoff Effect (Ribeiro & Sharma)

SPE 139622 Ribeiro & Sharma, 2012

- Leak-off Rate
  (Carter, 1957; Ribeiro & Sharma, 2012)

$$\sum_{j=1}^{NP} \frac{2C_{w_j}\rho_j}{\sqrt{t-\tau}}$$



- Leak-off Coefficient decreases with foam quality (x1/2 to x1/5)

Leakoff Rate is Reduced More than Expected Based on Volume Replacement Alone

Leak-off Effects - Summary

- Foam Osmotic Pressure is a driving force to retain liquid in the foam and reduce leak-off more than expected by simple volume replacement

Foam Fluids Impact on Water Consumption

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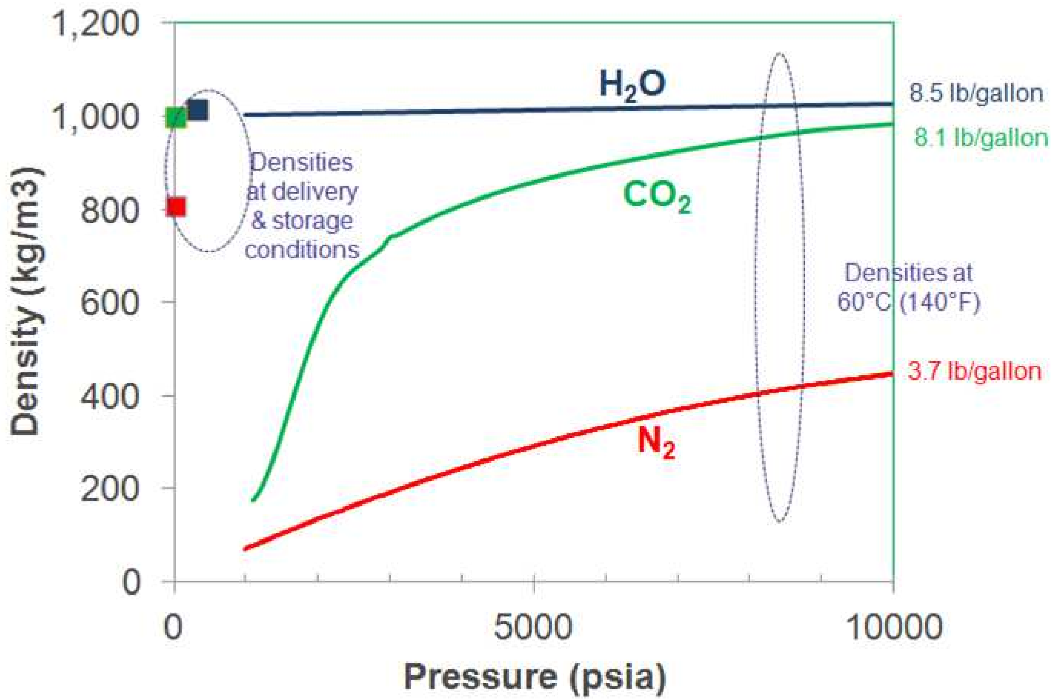
Volume Effects

- Densities of CO_2 and N_2 are lower than H_2O under downhole conditions, but similar to water under surface transport and storage conditions
- Mass of N_2 to replace a given volume of water is much less than mass of water
- This results in lower truck traffic requirements and site storage volumes

Volume Effects



Equivalent Surface Volumes of CO_2 and especially N_2 convert to larger volumes downhole

Total Fluid Volume Required for Foams vs. Water (example)

Calculated for hypothetical Utica example (75 quality foam), and presented at AAPG 2014. Estimates do not account for differences in leakoff effects, solubility or cool-down requirements

Consumption	Slickwater	CO_2 foam	N_2 foam
Proppant (lbs)	3.0E05	3.0E05	3.0E05
Total Water (gallons)	156,300	47,545	47,545
CO_2 or N_2 (US tons)	NA	340	149
CO_2 or N_2 Surface Volume (gallons)	NA	80,300	44,200
Total Volume Fluid (gallons)	156,300	127,845	91,745
Surface pressure (psi)	3200	3800	4600

Nitrogen requires the least storage and transport, slickwater the most. Surface pressure requirements are the reverse

Summary

- Foam Fracturing Fluids reduce water consumption

- Reduction in consumption is augmented by synergistic effects
  - Proppant Placement
  - Leak-off Reduction (Osmotic pressure effect)

- Environmental impact is further reduced by Volume Effects

Foam Fracturing Fluids reduce water consumption through multiple synergistic effects

Research & Development

Opening new ways

Acknowledgements

The authors acknowledge the support of this project by the Air Liquide business units and permission from Air Liquide management to publish this work.

THANK YOU FOR YOUR ATTENTION

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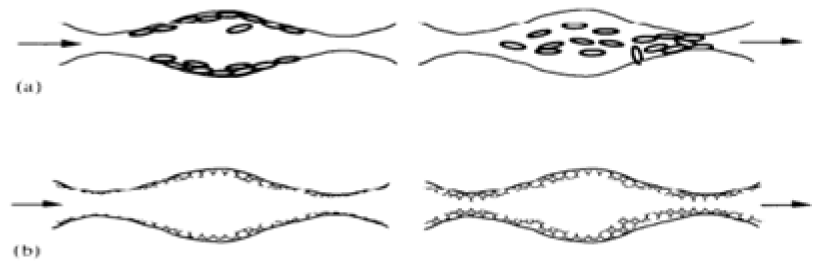
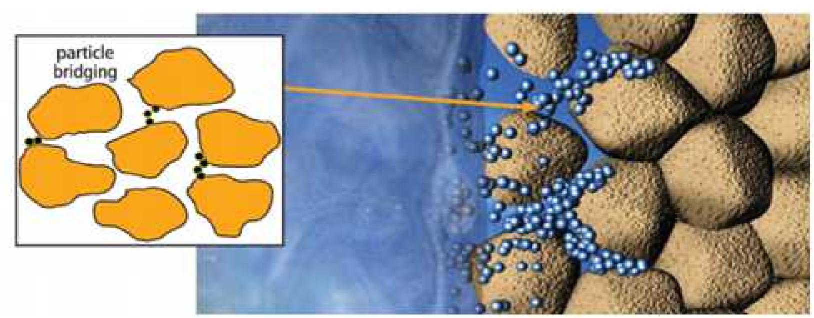
Impact of water on productivity

- Water sensitivity
  - Fines migration and clay swelling
- Water block
  - Low perm rock traps wetting phase
  - High capillary pressure to overcome for oil and gas displacing water
  - Low relative permeability
- Cleanup and proppant conductivity
  - Water based gel hard to cleanup
  - Gas bubble helps flow back
- Water availability and disposal cost
  - EUR, economics, environment



Mohan et al, 1993



Dawson et al. 2013.