Oil and Gas Services.
Energized Solutions
…Fracturing fluid selection

Robin Watts
Oil & Gas Technology Manager, Oil & Gas Services, Linde LLC
Content

1 Linde Introduction
2 Energized Fluids
3 Fluid Selection – Performance & Economics
4 Recommendations
The Linde Group Overview

Leveraging Synergies

Founded | 1879
Sales    | ~$20 billion
Employees| ~62,000
Countries| >100

Linde Engineering
Technology-focused

Air Separation | CO2/Syn Gas
Global #1      | Global #2
Olefins       | Natural Gas
Global #2      | Global #3

Linde Gas - Tonnage
World-class operations

HyCO Tonnage Plants
>70 plants

ASU Tonnage Plants
>300 plants

CO2 Plants
>100 plants

ECOVAR Std Plants
>1,000 plants
The Linde Group in North America

Sales: >$5 billion
Employees: >15,000
Locations: >400 (gas & merchant)
Customers: >100,000

Note: Sales & employees include Lincare

- Industry leading National Operations Center, New Jersey
- Linde Gas HQ: Murray Hill, NJ
- US Linde Engineering facilities:
  - Blue Bell, PA (Selas Fluid Processing)
  - Holly Springs, GA (Hydrochem)
  - Tulsa, OK (Linde Process Plants)

Deliveries: 40,000 / month
Miles: 80 million
Fleet Size:
  - Drivers: 1,200 drivers
  - Tractors: 800 tractors
  - Trailers: 1,200 trailers
  - Railcars: 650 railcars

Drivers: 1,200
Tractors: 800
Trailers: 1,200
Railcars: 650
# Energy Solutions
Serving a broad range of segments

## Industry Leading Gas (CO2, N2) Network for:

<table>
<thead>
<tr>
<th>E&amp;P: EOR</th>
<th>Well Pad Services</th>
<th>Pipelines &amp; Plants</th>
<th>LNG as a fuel</th>
</tr>
</thead>
</table>
| - N2 and CO2 EOR | - Hydraulic fracturing with CO2 and N2  
- Coiled tubing services N2 supply | - Purging, pressure testing, pigging  
- Drying, hot stripping  
- Accelerated reactor cooldown | - Drilling rigs  
- Hydraulic fracturing spreads |

- 11 years without lost time injury:  
  - *All well sites are inspected and have a documented “Risk Assessment” performed*  
  - *Dedicated off road distribution personnel and equipment*  
  - 20 operators with over 200 years of overall experience  

- 9, 16,700 gal queens capable of pumping 550 GPM at 110 PSIG  
- 8100 tons of portable CO2 storage
Innovation

R&D activities focus in particular on the impact of exploration and production processes: improve productivity (EUR), economic efficiency, reduce environmental footprint

— Mobile Gas Clean-up Unit of CO2 from early flowback Natural Gas

— LNG Drilling and Frac Spreads

— EOR Huff-n-Puff
Energized Fluids
40 years of success

Definition of an energized fluid
— Fracturing fluid that includes at least one compressible, sometimes soluble, gas phase.

CO$_2$ & N$_2$ solutions developed and successfully used for hydraulic fracturing for $>$40 years
— The original “waterless frac”
— 70 Quality CO$_2$ Foam referred to as the Gold Standard of fracturing fluids

Benefits in unconventional reservoirs
— Alternative when water-based fracturing fluid interactions with the rock formation is detrimental to hydrocarbon production.
— References on benefits King (1985), Mazza (2001), Burke et al. (2011), Gupta (2011)
Fluid Selection
Factors to consider – water issues

Water sensitivity of the formation
— Based upon mineral composition of the rock formation. Energized fluids recommended to prevent excessive fines migration and clay swelling.

Proppant conductivity & placement
— In many shales & clay-rich sands, water softening the rock considerably lowers proppant pack conductivity due to proppant embedment.
— High quality foams provide high effective viscosity for ideal proppant placement over low viscosity slick water. CO₂ and N₂ at lower qualities can be gelled to provide viscosity comparable to gelled water.
Water blocking

— In tight, under-saturated formations, fracturing water imbibed into the rock matrix pore space remains trapped due to capillary retention.

— Water saturation increases from ~10-50%. Productivity impacted as relative permeability lowers, by sometimes orders of magnitude.

— (Perekh et al. 2004, Mahadevan et al. 2005)

Water availability & cost

— Drought-prone, limited water supply, & restrictive local legislation regions overlap O&G exploration & production areas driving operators towards alternatives.

— Fully accounting for water life-cycle cost – acquisition, management and disposal – of water as a fracturing fluid means it can be more costly to use than energized fluids with CO₂ or N₂.
Fluid Selection
Increasing Demand & Supply Constraints of Water

New study found that more than 1,100 counties -- one-third of all counties in the lower 48 -- will face higher risks of water shortages by mid-century. More than 400 of these counties will face extremely high risks of water shortages.
Enhancement of the 3 E’s – Economics, EUR, Environment

— In well-designed hydraulic fracturing processes, energized fluid solutions utilizing CO₂ or N₂ can reduce costs & improve well performance to achieve a lower unit cost of production.

Selection methodology

— Avoid trial-and-error approach in the field. Utilize the best energized fracturing fluid / well productivity model and fluid life-cycle estimations to narrow approach followed by field performance data.

Economic Benefits: Tools for Energized Fluids

Simple Calculator Tool

for comparing estimated total cost of options - Acquisition, management, disposal calculations

Productivity Simulator Tool

for comparing estimated productivity factor of hydraulic fracturing fluid options

Hydraulic fracturing simulator designed to fully account for the phase behavior and compositional changes of an energized fluid.

Example 3: Marcellus CO₂, 70 Quality

Water disposal leads to water being the most expensive choice

Fracturing Fluid Cost Comparison - Marcellus, 22 stage well

<table>
<thead>
<tr>
<th></th>
<th>Incremental</th>
<th>Total Cost</th>
<th>DELTA cost of water to CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water</td>
<td>CO₂</td>
<td></td>
</tr>
<tr>
<td>Acquisition,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management (post-frac)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; Disposal Cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best Case</td>
<td>$1,564,235</td>
<td>$1,657,714</td>
<td>$93,479</td>
</tr>
<tr>
<td>Worst Case</td>
<td>$3,182,044</td>
<td>$1,657,714</td>
<td>$1,524,330</td>
</tr>
</tbody>
</table>

COST/bbl Equivalent

acquisition, management disposal $17.65 $18.70

Water acquisition rises from $3 to $13/bbl; disposal rises from $14 to $25/bbl

SPE-166113-MS • A Day in the Life of a Barrel of Water • Robin Watts
Fluid Performance & Economics
Cost Comparison of $/bbl Fracturing Fluids
Total Cost = Acquisition + Management + Disposal (simplified)

Water Marcellus/Utica

At 100% of water only volume
At 75% of water only volume
With 40% flowback
Productivity index and improved hydrocarbon productivity.

**Figure 10**—Comparison of the productivity index ($J/J_0$) for the different fluid formulations. The energized fluids outperform slick water and linear gel in this particular example.

**Figure 13**—Incremental hydrocarbon production as a function of initial fracture productivity for two arbitrary treatments with productivity indices $J_1$ and $J_2$. 

"GOLD STANDARD"
Fluid Performance & Economics
Energized Fluids performance benefits

Improve Conductivity, Reduce Water Damage, Reduce Water Retention, Minimize Water Contact

— Cleaner Proppant Pack
  minimize fines and residues in proppant pack
  reduce fines migration out of clays over time by minimizing water contact during flowback and production
— Reduce Clay Swelling
  minimize water introduced into formation
  over time by minimizing water contact during flowback and production
— Reduce Proppant Embedment
  in softer rock during high pressure pumping of slick water treatments
  over time by minimizing water contact during flowback and production
— Mitigate Water Migration (via leak-off and natural fractures) into formation
  minimize increase in water saturation which lowers relative permeability and production
— Minimize Water Blockage

**CO₂ enhanced hydrocarbon miscibility improves production**

**CO₂ superior solubility** minimizes water invasion into formation, enhancing production (especially over time – less water initially and quicker return)
**Example 2: Uinta**

A Day in the Life of a Barrel of Water – Costs

When water usage and disposal is difficult and costly, equivalent cost quickly rise and water becomes the more expensive option!

--- Best case scenario

### Fracturing Fluid Cost Comparison - Uinta, 8 stage well

<table>
<thead>
<tr>
<th></th>
<th>Incremental Water</th>
<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition, Management (post-frac) &amp; Disposal Costs</td>
<td>$540,217</td>
<td>$562,565</td>
</tr>
<tr>
<td>DELTA cost of water to CO₂</td>
<td>($22,348)</td>
<td></td>
</tr>
<tr>
<td>Cost/bbl Equivalent*</td>
<td>$14.31</td>
<td>$14.91</td>
</tr>
</tbody>
</table>

*Acquisition, Management & Disposal

--- Recycled water acquisition increases from $5 to $25 per barrel, disposal from $5 to $8/ bbl

<table>
<thead>
<tr>
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<th>CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition, Management (post-frac) &amp; Disposal Costs</td>
<td>$1,379,913</td>
<td>$562,565</td>
</tr>
<tr>
<td>DELTA cost of water to CO₂</td>
<td>$817,348</td>
<td></td>
</tr>
<tr>
<td>Cost/bbl Equivalent*</td>
<td>$36.56</td>
<td>$14.91</td>
</tr>
</tbody>
</table>

*Acquisition, Management & Disposal

**Productivity implications...**
Average daily production rates for 11 wells during ~7 months of production in a 3-county region of Utah.

With no CO₂ or lower quality CO₂, water production was 4.5 to 1.8 times greater than using higher quality CO₂. Gas production was, on average, 5% to 75% higher when using low to higher quality CO₂, compared to water.

Example 2: Uinta
A Day in the Life of a Barrel of Water – Productivity
Example 3: Marcellus CO2, 70 Quality
Water disposal leads to water being the most expensive choice

Fracturing Fluid Cost Comparison - Marcellus, 22 stage well

<table>
<thead>
<tr>
<th>Acquisition, Management (post-frac), &amp; Disposal Cost</th>
<th>Best Case</th>
<th>Incremental Cost/well</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOTAL:</td>
<td>Water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1,564,235</td>
</tr>
</tbody>
</table>

DELTA cost of water to CO2 $ (93,479)

COST/bbl Equivalent
acquisition, management disposal
Water | CO2
---|---
$17.65 | $18.70

Water acquisition rises from $3 to $13/bbl; disposal rises from $14 to $25/bbl

<table>
<thead>
<tr>
<th>Acquisition, Management (post-frac), &amp; Disposal Cost</th>
<th>Worse Case</th>
<th>Incremental Cost/well</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>TOTAL:</td>
<td>Water</td>
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<tr>
<td></td>
<td></td>
<td>$3,182,044</td>
</tr>
</tbody>
</table>

DELTA cost of water to CO2 $ 1,524,330

COST/bbl Equivalent
acquisition, management disposal
Water | CO2
---|---
$35.90 | $18.70
## Example 3: Marcellus N2, 60 Quality

Water disposal leads to water being the most expensive choice

### Fracturing Fluid Cost Comparison - Marcellus, 22 stage well

| Acquisition, Management (post-frac), & Disposal Cost | Best Case | Incremental \
<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Water</th>
<th>N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL:</td>
<td></td>
<td>$1,468,147</td>
<td>$2,004,075</td>
</tr>
</tbody>
</table>

**DELTA cost of water to N2**: $535,928

<table>
<thead>
<tr>
<th>COST/bbl Equivalent</th>
<th>Water</th>
<th>N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>acquisition, management disposal</td>
<td>$18.01</td>
<td>$24.58</td>
</tr>
</tbody>
</table>

Water acquisition rises from $3 to $13/bbl; disposal rises from $14 to $25/bbl

### Fracturing Fluid Cost Comparison - Marcellus, 22 stage well

| Acquisition, Management (post-frac), & Disposal Cost | Worse Case | Incremental \
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL:</td>
<td></td>
<td>$2,956,059</td>
<td>$2,004,075</td>
</tr>
</tbody>
</table>

**DELTA cost of water to N2**: $951,984

<table>
<thead>
<tr>
<th>COST/bbl Equivalent</th>
<th>Water</th>
<th>N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>acquisition, management disposal</td>
<td>$36.26</td>
<td>$24.58</td>
</tr>
</tbody>
</table>
In well-designed hydraulic fracturing processes, energized solutions utilizing CO₂ or N₂ can reduce costs (such as clean up and disposal) and improve well performance to achieve a lower unit cost of production.

Evaluating the total life cycle of water used in well completions and production is paramount to understanding its true costs.

If full life-cycle cost of water is $5-10/bbl, suggest looking at energized fluids to:

– reduce total costs
– improve well productivity (lowering unit cost of production)
– reduce environmental footprint via water and emissions reduction
Thanks for your attention.
BACK UP
CO2 and N2 Fracturing Fluid Properties

CO2 Phase Diagram – phase behavior changes during fracturing
CO2 and N2 Fracturing Fluid Properties
Unit Conversion – Linde Gas Calculator APP

Properties of Carbon Dioxide or CO2:
Molecular weight 44
Melting point -56.6°C
Boiling point -78.5(s)°C
Critical temperature 30°C
Relative density, gas 1.52 (air=1)
Relative density, liquid 1.03 (water=1)
Vapor Pressure 20°C 57.3 bar
Solubility in Water 0.9 vol/vol

Properties of Nitrogen or N2:
Molecular weight 28
Melting point -210°C, -345.75 F Fahrenheit
Boiling point -195.8(s)°C, -320.44 F Fahrenheit
Critical temperature 147°C
Relative density, gas 0.97 (air=1)
Relative density, liquid 0.81 (water=1)
Vapor Pressure 20°C 57.3 bar
Solubility in Water 0.02348 vol/vol
CO2 and N2 Fracturing Fluid Properties
Solubility in Water

**CO2**

**N2**
CO2 lowers the cricondenbar of the mixture and increases miscibility. If sufficient quantities of the CO2 components are added to a reservoir fluid and the reservoir pressure is kept above the phase envelope, a single dense fluid phase exists. Although the actual mechanism is more complex, it is this solubility that is the primary driving force behind miscible flood enhanced oil recovery projects.

Nitrogen, on the other hand, raises the cricondenbar and decreases miscibility. It is sometimes used for pressure maintenance. There are also a few nitrogen miscible floods.

Water, virtually immiscible in the hydrocarbon liquid phase, does not have a significant effect on the shape of the hydrocarbon phase envelope except at high temperatures and low pressures.

Figure 1. The impact of CO2 concentration on the volatile oil phase envelope
Figure 2.5 IFT data based on studies by Heurer (1957), Masterton et al. (1963), Massoudi and King (1974), Schowalter (1979), Chun and Wilkinson (1995), daRocha et al. (1999) and Hebach et al. 2002. from Hildenbrand et al. 2004.
<table>
<thead>
<tr>
<th></th>
<th>CO2</th>
<th>N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid State when pumped</td>
<td>Liquid</td>
<td>Gas</td>
</tr>
<tr>
<td>Thermal Conductivity, BTU/min*°F*ft</td>
<td>0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>Heat Capacity, BTU/lb</td>
<td>0.21</td>
<td>0.25</td>
</tr>
<tr>
<td>Critical Pressure, psi</td>
<td>1072.0</td>
<td>493</td>
</tr>
<tr>
<td>Critical Temperature, °F</td>
<td>87.8</td>
<td>-232.6</td>
</tr>
<tr>
<td>Reference Density, lbs/ft^3</td>
<td>52.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Typical Pumping Quality Range</td>
<td>30-80</td>
<td>30-70</td>
</tr>
</tbody>
</table>
### CO2 and N2 Fracturing Fluid Properties

**“Foam” Quality – Rheology and Leakoff**

<table>
<thead>
<tr>
<th>N2 or CO2 Foam Quality</th>
<th>Liquid Leak-off Coefficient (ft/sqrt(min))*</th>
<th>% Improvement over pure Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0034</td>
<td>na</td>
</tr>
<tr>
<td>25%</td>
<td>0.0023</td>
<td>32%</td>
</tr>
<tr>
<td>30%</td>
<td>0.0021</td>
<td>38%</td>
</tr>
<tr>
<td>40%</td>
<td>0.0021</td>
<td>38%</td>
</tr>
<tr>
<td>50%</td>
<td>0.0023</td>
<td>32%</td>
</tr>
<tr>
<td>55%</td>
<td>0.0017</td>
<td>50%</td>
</tr>
<tr>
<td>60%</td>
<td>0.0001</td>
<td>71%</td>
</tr>
<tr>
<td>62%</td>
<td>0.0008</td>
<td>76%</td>
</tr>
<tr>
<td>65%</td>
<td>0.0017</td>
<td></td>
</tr>
<tr>
<td>68%</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>70%</td>
<td>0.0008</td>
<td></td>
</tr>
<tr>
<td>75%</td>
<td>0.0017</td>
<td></td>
</tr>
</tbody>
</table>

*low permeability <1.5mD, pressure drop \(\leq 1000\text{psi}\)
CO2 and N2 Fracturing Fluid Properties

Relative Permeability

Figure 2: Oil relative permeability comparison in CO2 and N2 injection (A) core C3 (B) core C1 (C) core S1.
Fluid rheology, phase behavior / density, composition

- Density affects fracture geometry, horsepower requirements, proppant transport
- Compressible energized fluids expand as rock formation heats up fluid
- CO₂ more soluble than N₂ in water. During flowback, CO₂ comes out of solution in water phase, increasing gas saturation and facilitating the flow of hydrocarbon fluids to the wellbore.
- Leak-off coefficient of each phase – Stable foams of CO₂ and N₂, reduce leak-off significantly as increase foam quality

Critical reservoir parameters

- Relative permeability curves: Fluid impact on relative permeability to gas (oil) in the reservoir
- Initial gas (oil) saturation: Water lost to formation will remained trapped lowering relative permeability and hence, production
- Water sensitivity of formation: Clays do not significantly interact with CO₂ and N₂ whereas unconventional rock tends to lose mechanical integrity when place in contact with water
- Reservoir pressure: drawdown pressure must exceed capillary forces, energized fluids enhances
- Proppant embedment: shales softened by water contact increase embedment & fines migration, decreasing conductivity and lowering productivity
Dimensionless permeability in the invaded zone, Target Foam Quality where $k_d/k > 0.1$

**Effect of Reservoir Relative Permeability Curve**

Example: $S_w = 0.7$, $h_{leak} = 1$ ft
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Commercial Simulators*</th>
<th>3-D Compositional Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture Shape</td>
<td>Pseudo 3-D, 3-D planar, or fully 3-D</td>
<td>3-D planar</td>
</tr>
<tr>
<td>Fracture Initiation</td>
<td>Vertical, deviated, or horizontal wells</td>
<td>Vertical, deviated, or horizontal wells</td>
</tr>
<tr>
<td>Multiple Fractures</td>
<td>Multiple clusters available</td>
<td>Single cluster</td>
</tr>
<tr>
<td>Fracture Propagation</td>
<td>Stress intensity factors</td>
<td>Stress intensity factors</td>
</tr>
<tr>
<td>Temperature</td>
<td>Isothermal</td>
<td>From energy balance Eq.</td>
</tr>
<tr>
<td>Fluid Density</td>
<td>Constant</td>
<td>Function of (P, T)</td>
</tr>
<tr>
<td>Wellbore Hydraulics</td>
<td>Foam option</td>
<td>Multi-phase</td>
</tr>
<tr>
<td>Proppant Settling</td>
<td>Several single-phase options</td>
<td>Phase-dependent</td>
</tr>
<tr>
<td>Leakoff</td>
<td>Single-phase</td>
<td>Phase-dependent</td>
</tr>
</tbody>
</table>

*Commercial simulators also offer numerous enhanced capabilities such as cluster settling, etc.
Simulation example – low-permeability sand formation

Room to improve since relative permeability >0.1
Relative Permeability
Unconventional target of >0.1

Numerical study

\[ k_{rg} = (1 - (S_w - S_{wc})/(1 - S_{gc} - S_{wc}))^p (1 - ((S_w - S_{wc})/(1 - S_{wc}))^q) \]  \[ k_{rg} = (1 - (S_w - S_{wc})/(1 - S_{gc} - S_{wc}))^p (1 - ((S_w - S_{wc})/(1 - S_{wc}))^q) \]

\[ S_{wc} = 0.16 + 0.053 \log_{10} k_{ik} \] (where < 0 then 0)  \[ S_{wc} = 0.16 + 0.053 \log_{10} k_{ik} \]

\[ S_{gc} = 0.15 - 0.05 \log_{10} k_{ik} \]  \[ S_{gc} = 0.15 - 0.05 \log_{10} k_{ik} \]

\[ p = 1.7 \] (to 2.3 depending on lithology and \( S_{gc} \))  \[ p = 1.7 \] (to 2.3 depending on lithology and \( S_{gc} \))

\[ q = 2 \]  \[ q = 2 \]

\[ k_w = k_{ik}^{1.32} \]  \[ k_w = k_{ik}^{1.32} \]

\[ k_{rw} = ((S_w - S_{wc})/(1 - S_{wc}))^p (k_w/k_{ik}) \]  \[ k_{rw} = ((S_w - S_{wc})/(1 - S_{wc}))^p (k_w/k_{ik}) \]

\[ \log_{10} S_{wi} = -0.187 \log_{10} k_{ik} + 1.18 \]  \[ \log_{10} S_{wi} = -0.187 \log_{10} k_{ik} + 1.18 \]

Note crossover, where \( k_{rg} = k_{rw} \) is approximately 67% for all permeabilities but krg value at crossover decreases with decreasing permeability. Dark black horizontal line marks the \( k_{rg} = 2\% \) (0.02). The \( S_w \) region where both gas and water have \( kr < 0.02 \) broadens as \( k_{ik} \) decreases.
Wellbore Temperature Profile
Example 60 Quality CO2 in EagleFord
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