THE LINDE GROUP

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Mobile gas cleanup unit (MGCU) economically scrubs CO_2 from early flowback natural gas to increase recovery and achieve green completions.

Contents.

Abstract.

Energized fluids containing carbon dioxide (CO_2) in various formulations have been used successfully for decades in hydraulic fracturing and individual well soak treatments known as a Huff'n Puff (HNP) to boost hydrocarbon recovery. But although the energized fluids improve ultimate recovery, they also may initially increase the amount of CO_2 contained in early flowback natural gas. Typically, when CO_2 concentrations from the hydraulic fracturing or treatment of wells exceed natural gas sales pipeline specification during early flowback, the most common practice is to flare the gas until the well cleans up enough for the specification to be met.

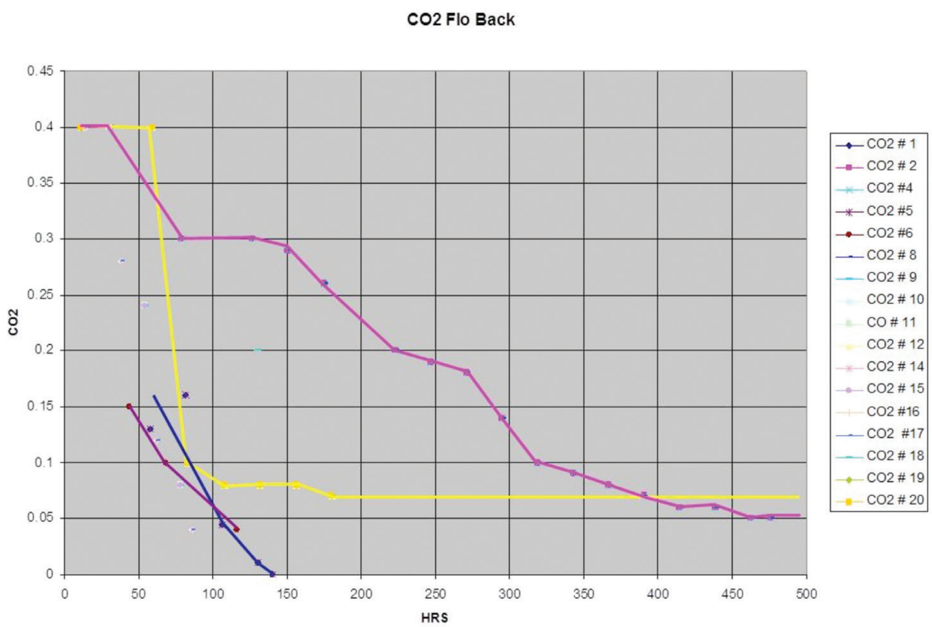
With the onset of the shale gas revolution about a decade ago, well economics placed a greater emphasis on the critical aspect of initial production. Around that same time, the U.S. Environmental Protection Agency (EPA) began seeking to reduce emissions of both methane and volatile organic compounds (VOCs) from oil and gas production fields. The agency started to identify best practices for doing so through its Natural Gas STAR partners program. As a result, the EPA began implementing new regulations that created the first air standards for hydraulically fractured wells.

Out of this effort was born the concept, and subsequent regulations, for Greenhouse Gas Reporting requirements as well as Reduced Emissions Completions (RECs) -- also known as reduced flaring or green completions. As always, the biggest challenge for producers became finding a way to improve well economics while complying with the EPA standards.

Linde North America saw the need for a cost-effective technology that could scrub CO_2 so producers could monetize early flowback natural gas of hydraulically fractured or HNP stimulated wells as well as comply with EPA's REC regulations. The company developed a mobile gas cleaning technology designed to improve well economics, with emphasis on the 3 E's: enhancing productivity (EUR – estimated ultimate recovery), environmental footprint reduction, and improved economics of the field.

This paper gives an overview of the unit's creation and performance, highlighting how the new MGCU enables oil and gas operators to most economically monetize early flowback gas by scrubbing out CO_2 to meet pipeline specifications while minimizing flaring and greenhouse gas emissions.

Graph 1: CO_2 Concentrations during well flowback over time



Introduction – Reducing Emissions

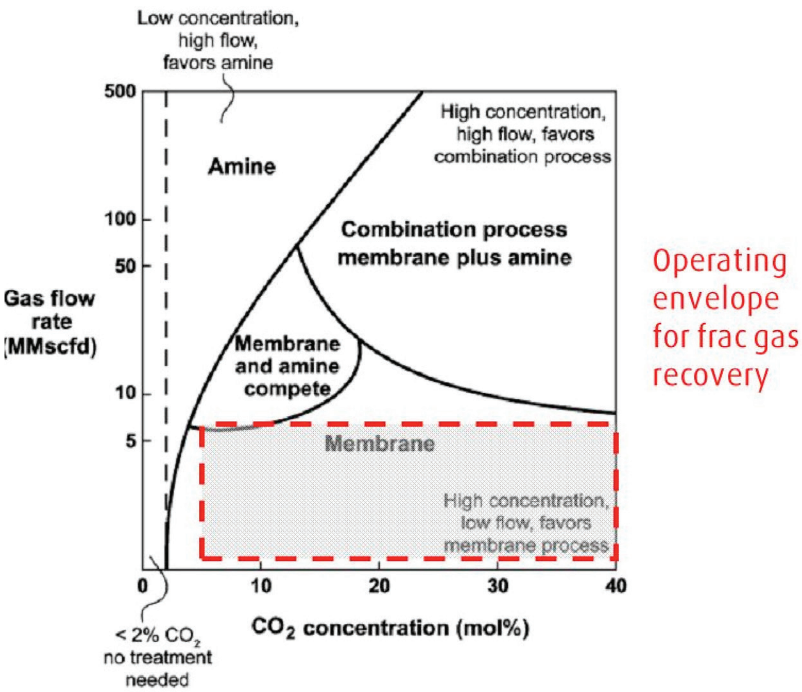
Reducing methane emissions during well completions and stimulations in its simplest form is done with flaring. It can, however, be further minimized to achieve RECs. REC equipment such as sand traps, plug catchers and separators allow for the capture and recovery of natural gas and condensate. Wyoming and Colorado were the first states to implement "flareless completions" regulations requiring such equipment. The EPA, learning from their Natural Gas STAR Partners, published a summary on the partners' success with economical RECs, including when energized fracturing with CO_2 or N_2 is performed.[1] Economics evaluated included a purchased or contracted service of REC with a daily incremental charges of $700-$6,500 per day over a three to ten-day period. Removal of excess CO_2 was accomplished utilizing a membrane separation unit where the CO_2-rich permeate was vented and recovered hydrocarbons sent to sales line. The unit was used on ten wells with an average cost per well of $32,500. The operator reported a net profit of an average of $34,000 per well.[2]

In 2011, the EPA introduced its new regulations aimed at reducing emissions of VOCs and methane from hydraulically fractured gas wells. The stated goal – reduce VOCs by 95% and recover 90% of salable natural gas.[3] Implementation of these new regulations was originally set to begin in 2012. Actual full implementation was delayed until January 1, 2015 due to recognition that ample REC equipment did not exist and needed time to become more readily available. The Center for Sustainable Shale Development (CSSD), which is focused on shale development in the Appalachian Basin, established similar standards for RECs and Green Completions with an effective date of January 1, 2014.[4] In addition to REC regulations, the EPA implemented its Greenhouse Gas Reporting requirements covering greenhouse gas emissions and its equivalent.[5] For oil and gas facilities, defined in the regulations as all emissions sources in a single hydrocarbon basin, the first report was due in September 2012. The broad definition of facility for an oil and gas operator further emphasized the need for RECs.

Natural Gas, CO_2, and Pipeline Specifications

The naturally occurring natural gas mixture contains mostly methane, along with other hydrocarbons, as well as typical amounts of CO_2 in the range of 0.1 – 1.0 mole[1] %. Exceptions do occur where naturally occurring CO_2 content far exceeds pipeline specifications. Natural gas pipelines establish maximum specifications for the amount of inert (CO_2 and N_2) concentrations they will accept into their system for transporting and processing. The concentration maximum may range from 2-4 percent for each inert or in total. When fracturing with energized fluids containing CO_2, early flowback natural gas typically contains greater CO_2 concentrations that drop off precipitously as the well cleans up. But while some wells may drop below pipeline maximum specification within hours, others may take days or weeks. See Graph 1.

Graph 2: General operating windows for amine and membrane methods scrubbing of CO_2 from natural gas



Traditional Methods of Scrubbing CO_2 from Natural Gas

Depending upon the flow rates of natural gas and the concentration of CO_2 in the stream, amine or membrane systems may be utilized to scrub out excess CO_2. Natural gas processing plants, which have high throughput volumes, typically use an amine system to scrub CO_2. Gathering systems, which collect the flow from multiple wells, also may cost-effectively process higher volumes and higher concentrations using an amine system.

But for early flowback gas from a newly fractured, or treated with CO_2, well, the variation in CO_2 concentrations and the volumetric flow of most gas wells meant that membranes represented the best opportunity for effective clean-up of early flowback gas to meet pipeline specifications. Graph 2 highlights the operating window for the various CO_2 scrubbing techniques.[6]

Not only was the ability to scrub CO_2 under varying inlet concentrations and conditions necessary, the operational costs of such a system needed to be such that an operator could make money during early flowback. The unit need to more than pay for itself with gas prices under $3/Mscf and with the lowest possible volumetric flow rates. Membrane technologies typically deployed for natural gas applications had limitations that impacted ability to be cost-effective during the early flowback scenario.

These limitations included:

- → Need for extensive pre-treatment of membranes.
- → Need to heat membranes during operations.
- → No C3+ hydrocarbon recovery.
- → Replacement upon chemical fouling.
- → Need for re-compression for acceptable recoveries.

Energized Solutions – NEW Mobile Gas Cleanup Unit (MGCU)

Operators' options, at the time these pending regulations were announced, were limited. They could either develop their own membrane system or utilize the service of a sole provider who had one membrane unit, which at that time required flow volumes greater than 4 mmscfd in order for the operator to break-even. Or they could flare.

In order to support completions programs that used CO_2, Linde North America recognized the need to develop a more cost-effective way to remove CO_2 from early flowback gas. Using a new membrane technology, Linde configured a new system called a Mobile Gas Clean-up Unit or MGCU, to meet technical and cost objectives. The simulated performance of the membranes resulted in significant recovery of inlet gas while keeping the unit's operational cost to a minimum. Depending on process conditions and feed gas composition, the unit has been proven to remove up to 98 percent of the CO_2 in the production stream.

Image 1: New Linde Mobile Gas Clean-up Unit (MGCU) for scrubbing CO_2 out of early flowback gas.

Design Parameters

The new MGCU design was based upon an operator making money during a relatively short window of operation, at low natural gas prices, and to be cost-effective at lower process volumes (including associated gas rates from oil wells).

General requirements:

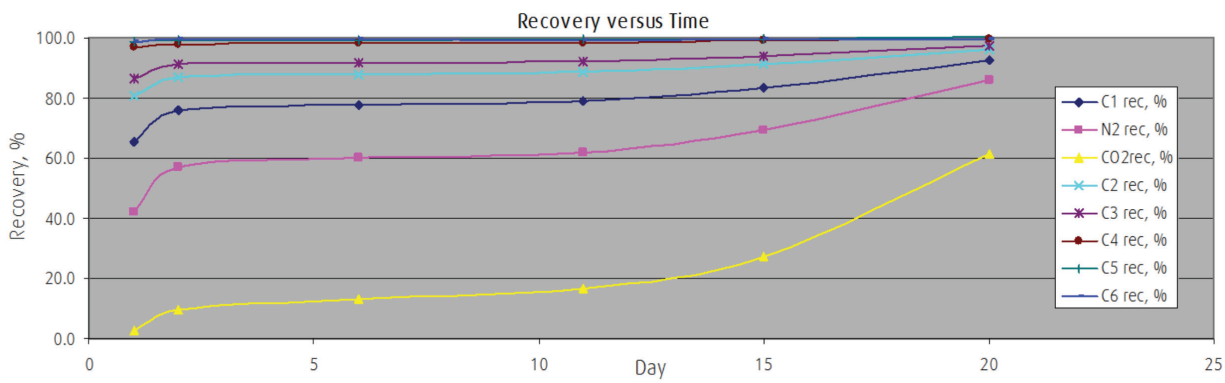
→ Recovery of methane and higher hydrocarbons from CO_2 scrubbing of natural gas
→ Product gas must meet CO_2 pipeline specifications
→ System components shall be trailer mounted/transportable on and off road, meet applicable DOT standards
→ Mobile deployment at well site, suitable for outdoor service, rugged environment, built to appropriate codes, Class I Div. 2 Hazardous Area, ASME for pressure vessels and ANSI B 31.3 (and other applicable standards)
→ Design shall be prepackaged to the maximum extent to minimize field labor (mobilization/demobilization)
→ Design shall consider access for maintenance and redundancy for key equipment that cannot be easily replaced
→ Operator can make money running unit with natural gas prices at <$3 MMBTU and flowback clean up days 5 +/- or more
→ EPA Emissions Guidelines: minimize greenhouse gas emissions (2015 new rules to be implemented) and adhere to Reduced Emission Completions concept

The unit itself is on a trailer mounted skid with a series of safety features to ensure safe, remote operations. (See Image 1: New Mobile Gas Clean-up Unit (MGCU) for scrubbing CO_2 out of early flowback gas.) It can be operational within half a day depending on location logistics. The unit also can be shutdown, purged and driven to the next location very quickly. Since natural gas production is already being sent directly to the gathering lines, and the MGCU system is being bypassed, there is no need to isolate the well.

The unit's setup requirements and tie-ins include:

→ Product sales gas to gathering line. Customer to specify pressure requirements.
→ Hydrocarbon liquids line to an appropriate customer storage tank or recirculated into gas sales line.
→ Vent lines to existing flare stack.
→ Psv vent lines to flare stack or vent stack.
→ Customer provides the rig-up crew, lines and tie-ins.
→ Condensate drain water as per site requirements.
→ Site to provide electric power for controls and lighting if available.
→ Site survey and job site & safety assessment prior to unit deployment.
→ Analytical of well gas to verify CO_2 % and H_2S levels.

Graph 3: Simulated membrane recovery rates) and well results



Inlet Process Conditions For MGCU

Estimated from membrane simulation. See Graph 3.

Inlet conditions:

- Design capacity: up to 5 MMscfd (original unit) and higher (can design up to 6 MMscfd from one unit).
- Maximum design pressure 950 psig, optimal minimum 600 psig.
- Desired inlet gas temperature 65 °F or greater.
- Maximum inlet gas H_2S content, 100 ppm.
- Maximum inlet CO_2 concentration: 50 mol %.
- Inlet gas must be free of condensate, sand, or other particulates.
- No additional hydrocarbon, or other cleanup necessary.
- No additional heating necessary.

Inlet Composition – CO_2 fracturing (changes over time - see Graph 1)

Component	Initial vol%	Final vol%
Carbon Dioxide	25.0-50.0	< 2.00
Methane (C1)	69.5-44.5	93.00
Ethane (C2)	3.50	3.00
Propane (C3)	1.00	1.00
Butane & Higher (C4)	0.50	0.50
N_2	0.50	0.50
Contaminants	Unknown	Unknown
Solids Content	Unknown	Unknown

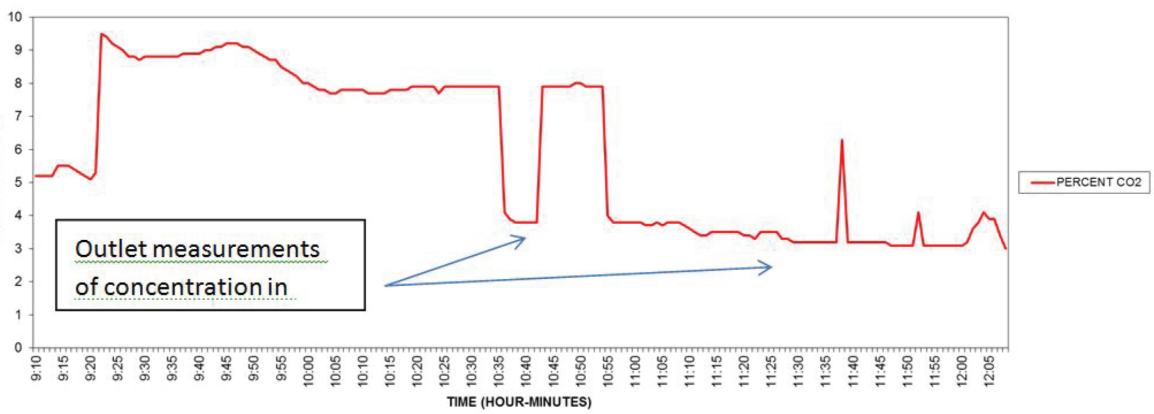
Outlet Conditions:

- Concentration-Maximum 2% CO_2.
- Outlet gas pressure: approximately 10 psig lower than inlet pressure to unit.
- Recovered hydrocarbons are either as gas or liquid (NGLs – natural gas liquids).
- Permeate pressure (to vent or flare): 0 to 15 psi.
- NGL outlet maximum pressure: 950 psig.

Performance Testing

Since the membranes are not new to the use for gas processing, the key elements for performance testing of the new MGCU were to determine if the membranes performed according to specifications of pressure, volume, and varying inlet CO_2 concentrations. Three field trials were run under various operating conditions. The following is a summary of each of those trials.

Graph 4: Trend line of CO_2 inlet and outlet conditions for MGCU on natural gas well #1 in Rockies



TRIAL 1: Oil well CO_2 HNP treatment in South Texas

Objective - After one-week soak, scrub CO_2 from associated natural gas during production. Test membranes under very low pressure and low flow conditions.

Inlet Conditions	(Natural Gas)
Pressure	65 – 70 psi
Temperature	105 – 110°F
Volume	100 – 250 MSCFD
CO_2	initial max. 24%
Outlet Conditions	
CO_2	1 – 1.5%

Results – membranes scrubbed CO_2 better than expected for such low inlet pressures.

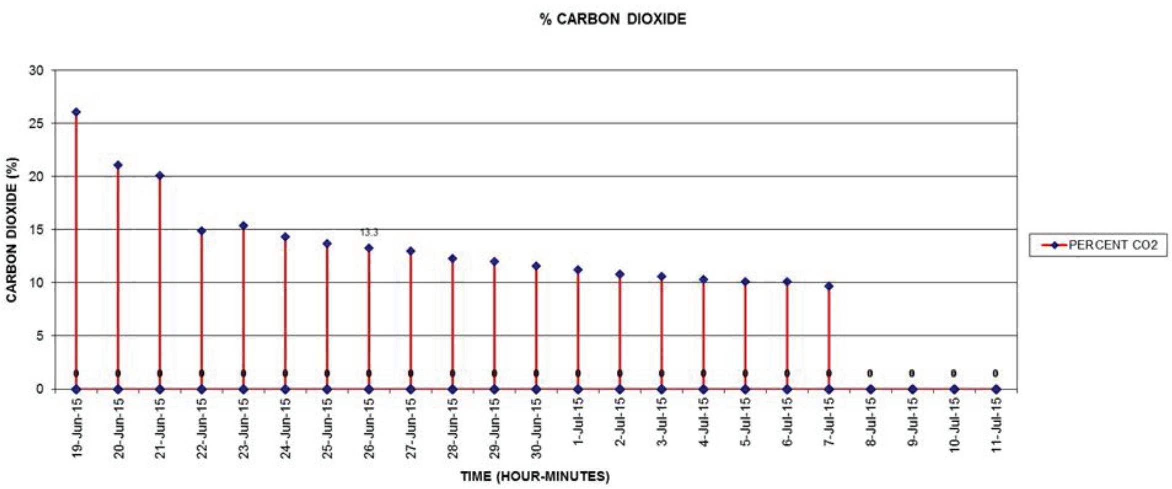
TRIAL 2: Natural Gas Multi-well pad fractured with high quality CO_2 in Rockies

Objective - Scrub CO_2 from early flowback natural gas to target of 10 percent or less concentration. Well cleanup-to-pipeline specification typically less than 24 hours. Test membranes under extreme conditions of very high CO_2 concentrations.

Inlet Conditions	(Natural Gas)		
Pressure	500 – 550 psi		
Temperature	80 – 110°F		
Volume	800 – 1,400 MSCFD		
	Well #1	#3	#4
CO_2	ave. 8.4%	extreme max. 83%	extreme max. 70%
Outlet Conditions			
CO_2	ave. 3.8%	extreme max. 24.9%	extreme max. 24.1%

Results – First well clean-up faster than anticipated. Graph 4 shows the trend line of CO_2 inlet and outlet conditions. Ran next two wells under extreme maximum CO_2 inlet concentrations (well above recommended 50 percent or less). Membranes scrubbed CO_2 better than expected in extreme inlet conditions of CO_2 concentrations while at pressures lower than designed for ideal operations.

Graph 5: Inlet CO_2 concentrations for natural gas well in South Texas. It took approximately one month for well to clean-up to targeted 8 percent CO_2 concentrations



TRIAL 3: Natural Gas well fracture with high quality CO_2 in South Texas

Objective - Scrub CO_2 from early flowback natural gas. With expected extended well clean-up time to targeted level of about 8 percent, ensure unit capable of continued performance.

Inlet Conditions	(Natural Gas)
Pressure	250 – 450 psi
Temperature	75 – 105°F
Volume	250 – 900 MSCFD
CO_2	max. 27.5%

Outlet Conditions	
CO_2	4 - 6%

Results – Under lower than specified pressures and varying flow volumes, MGCU met clean-up targeted level. Well took approximately one month to clean-up on its own below the specified target of 8 percent (see Graph 5). The MGCU remained deployed and operating with minimal oversight during that one month period.

Economics

The new MGCU design's flexibility results in operator lease charges based on length of use and volume of flow. Depending on location and costs associated with the mobilization and demobilization of the unit, an operator can experience break-even operating costs well below the maximum volumes the unit can process. Table 1 summarizes a sampling of operator maximum processing volumes versus break-even volumes when natural gas is at $3/Mcf.

Table 1: Sample operator maximum processing volumes versus break-even(BE) volumes utilizing MGCU when natural gas price is $3/Mcf

Unit Spec Max SCFD	BE flow rates M-SCFD monthly rental
6.0 mm	522
5.5 mm	444
4.2 mm	378
3.4 mm	344
2.5 mm	311
1.6 mm	294
1.2 mm	278
0.8 mm	267

Conclusion

Membranes performed better than expected, with respect to CO_2 scrubbing, even at lower than specified inlet pressures, in the initial test on associated gas from an oil well soaked after CO_2 Huff'n Puff stimulation. On the second trial, the membranes were stressed by allowing very high inlet concentrations of CO_2, beyond designed maximum specification, along with lower than optimal inlet operating pressures. Once again, the membranes performed better than expected. For the third trial, even for extended deployment in remote conditions, the unit membranes performed better than expected at less than optimal inlet pressure conditions.

The benefits of this new MGCU include:

- Compelling well economics with rapid deployment and flexibility
- High recovery of methane and higher hydrocarbons
- Minimization of flaring and greenhouse gas emissions
- Highly modular and easy to integrate
- Mobile- arrives on a trailer for quick tie-in
- Minimal cleanup with no guard bed or heating requirements

The new MGCU enables oil and gas operators to most economically monetize early flowback gas by scrubbing out CO_2 to meet pipeline specifications while minimizing flaring and greenhouse gas emissions.

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With its innovative solutions, Linde is playing a pioneering role in the global market. As a technology leader, it is our task to constantly raise the bar. Driven by our tradition of entrepreneurship, we are working steadily on developing new high-quality products and innovative processes.

Linde offers more. We create added value, clearly discernible competitive advantages and greater profitability. Each solution is tailored specifically to meet our customers' requirements – offering standardized as well as customized solutions. This applies to all industries and all companies regardless of their size.

If you want to keep pace with tomorrow's competition, you need a leader in industry technology by your side for which top quality, process optimization, and enhanced productivity are part of daily business. Linde will not only be there for you ... but with you. After all, working together to solve problems forms the core of commercial success.

Linde – Ideas become solutions.

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