Pressure Swing Adsorption (PSA) for Natural Gas Separation and Emissions Reductions at Compressor Stations

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Executive Summary

ColdStream Energy (CSE) has developed the ***$MaCH_4$*** NGL Recovery Solution (NRS), a robust and energy efficient gas separation technology for natural gas processing. This technology can operate at ambient temperatures and can be remotely monitored and operated. It is a simple and economically compelling solution for maximizing NGL value for producers and gatherers, while also maximizing the efficiency and runtime of engines and respective compressors. The ability to produce pipeline quality, < 1,100 BTU/scf (HHV), lean gas at any location ensures the lowest VOC emissions possible, even when remotely located. This is an innovative and valuable technology for the energy industry with wide applicability, and especially relevant to gas gathering and compression.

The Pilot has been producing desired lean gas quality since commissioning of Pilot in December of 2023. It has had over 99% mechanical availability since commissioning and has been remotely monitored and operated since May 2024. Based on a field gas BTU value approximately 1,305 BTU/scf at this Pilot site, the total annual NGL value recovered would be greater than $1.2MM for a 7,500 HP Compressor Station.

Pressure Swing Adsorption

The NRS employs CSE's patented pressure swing adsorption (PSA) technology to recover heavy hydrocarbons and to produce lean, dry gas for on-site use. Some of the key industrial applications of PSA include (a) gas drying, (b) oxygen purification, (c) nitrogen purification, (d) production of hydrogen from steam methane reforming, (e) upgrading of landfill gas, and (f) alcohol dehydration.

PSA is an economic and reliable method used to separate mixed gas into individual high purity gases. PSA is a non-cryogenic gas separation technology which means this process can produce purified gases at near ambient temperatures, in contrast to the cryogenic distillation techniques of gas separation which take place at very low temperatures and is a process commonly employed in chemical and petrochemical processes. Also, not to be confused with absorption, adsorption is a surface-based phenomena, while absorption involves certain molecules entering the bulk phase of another material.

The advantages of the NRS technology to other natural gas separation technologies are:

- Simple process that can be remotely monitored and operated
- Low maintenance with minimal operator intervention, over 99% mechanical availability
- Large turndown ratio
- Handles BTU swings from fluctuating feed gas compositions
- Cryogenic-like recovery of NGLs without the low temperature requirements (no freeze issues)
- Minimal power requirements (single phase), especially compared to cryogenic processes
- Recovered heavy hydrocarbons remain in gaseous form (no liquids, no tanks)
- Requires no chemical consumables to operate (i.e. methanol, glycol)
- Skid mounted and field transportable
- Dehydrates the saturated feed gas and recovers heavy hydrocarbons in a single step process

In more detail, the concept of PSA for gas separation is relatively simple. When a gas mixture is introduced to an adsorbent, certain gases in the mixture selectively adhere onto the adsorbent surface. Each PSA system uses specialized adsorbent materials to capture the target gas species at high pressure, while all other gases in the mixture pass through the adsorbent bed. The process then swings to low pressure to desorb the captured gases, hence the name pressure swing adsorption. The desorbed gases are enriched with the more strongly adsorbed components of the feed gas. No external heat is needed for the regeneration of the adsorbent, making this a more energy efficient separation than traditional absorbent based technologies. As this is a regenerative process, none of the adsorbent material used is consumed.

CSE has adapted PSA for the novel use case of hydrocarbon gas processing (Fig. 1). This means extremely high recovery of C3+ hydrocarbons for monetization rather than combustion, which also means a much-reduced VOC emissions profile due to combustion if one were to use this PSA produced lean, light product as fuel gas.

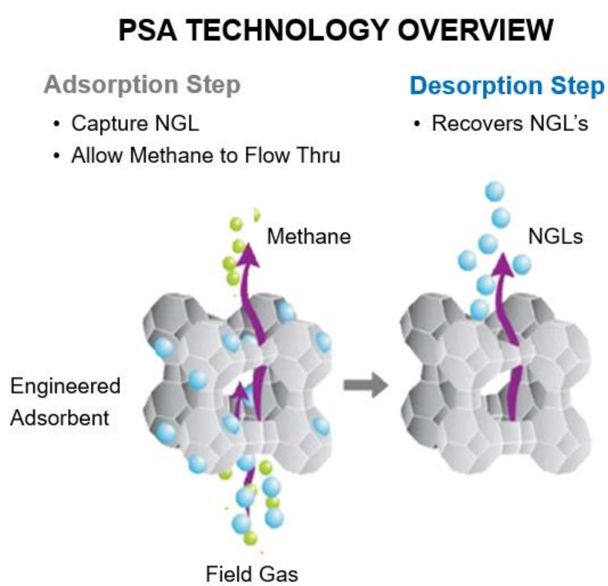

Fig. 1 – Overview of the PSA Technology

How It Works

ColdStream Energy's NRS requires three primary pipe connections: (1) high pressure feed gas, either from discharge header, 2nd stage or 3rd stage discharge of a compressor, (2) light product outlet, connecting to engine or fuel header, and (3) heavy product outlet, which takes the recovered heavy hydrocarbons back to compressor suction or suction header (Fig. 2).

High pressure, high BTU gas enters the inlet of the NRS and passes through pre-filters that remove any entrained lube oil in the gas. This high BTU gas then flows into the adsorption beds. Predominantly, the heavier hydrocarbons are adsorbed in the adsorbent beds and methane enriched gas passes through the beds into the buffer tank of the NRS or directly into a fuel gas header.

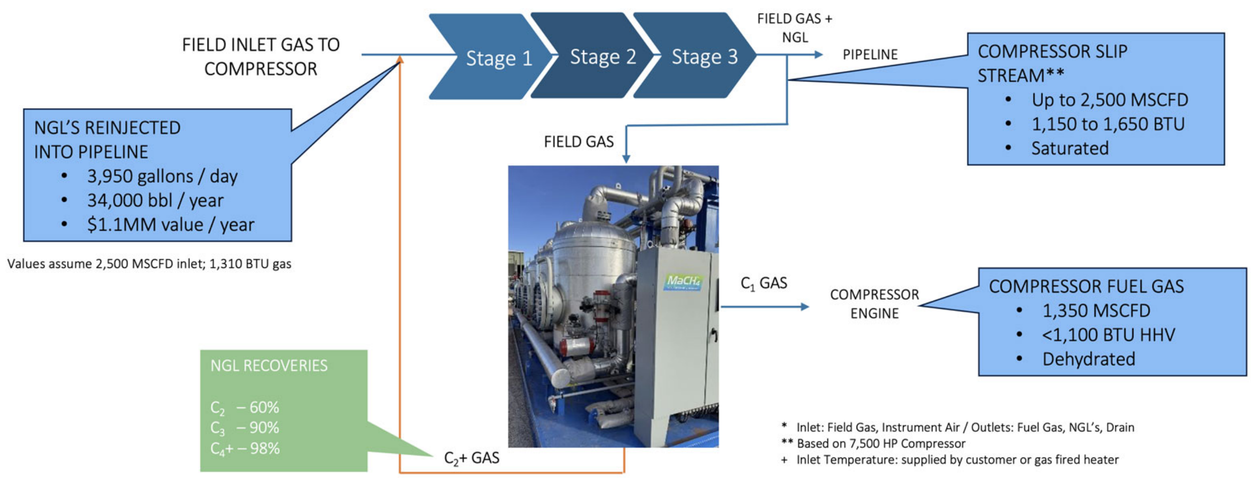

Fig. 2 – NGL Recovery Solution – Sized to support 2,500 HP compressor

The methane concentration in the lean gas produced can be tuned to meet required mol% levels to eliminate derate of the engine based on the feed gas composition. During adsorption in one bed, the other beds are at various stages of desorption just by depressurization to lower pressures. Desorption can also be referred to as "bed regeneration" and is the process in which the hydrocarbon gases accumulated during adsorption in the feed step are being stripped away. The NGL enriched heavy product gas is then returned to the compressor suction header where it co-mingles with the rest of the field gas for monetization downstream. In a prescribed cycle of adsorption and desorption, the NRS produces light product and heavy product from the different beds at different steps within the cycle so that a continuous stream of light product is always produced.

In terms of the high-cost effectiveness, the NRS is an extremely appealing approach due to its simple operation, high performance even in extreme and/or varying ambient temperatures, easy regeneration, and low energy intensity for gas separation.

Piloting the NRS Technology

ColdStream Energy partnered with Iron Horse Midstream (IHM). Coldstream's PSA technology was deployed at an IHM compressor station in Oklahoma. IHM also has an existing J-T process skid that provides fuel for the compressors on site. This was an opportunity to test the performance of the NRS and demonstrate that our technology not only could provide lean, dry gas as fuel to the station, but would also provide much better NGL recovery than the traditional J-T effect.

The Pilot has been producing desired fuel gas quality since commissioning of Pilot in December of 2023. It has had over 99% mechanical availability since commissioning and has been remotely monitored and operated since May 2024.

The 4 bed PSA system (Fig. 3) was installed next to a Archrock compressor package that supplies raw gas to the pilot from its second stage discharge. This high-pressure feed gas was then separated through the PSA system into two products, the light product (LP) – which could be used as fuel for the station; and heavy product (HP) – which is the recovered heavy hydrocarbons from the raw gas returned to the suction header of the compressor station. Running the pilot during the winter also provided a nice opportunity for CSE to demonstrate the robustness of the technology even under non-ideal operating conditions. The objective was to successfully demonstrate the pilot's ability to provide lean, high-quality fuel to one CAT G3608A3 compressor (2,370 hp) consistently and stably.

Fig. 3 – Pilot System installed at compressor station.

Table 1 shows the measured gas compositions of the raw field gas entering the NRS and the LP and HP products exiting the system. There is an on-skid gas chromatograph (GC) that continuously measures the LP and HP gas composition. All three streams were also analyzed by 3rd party labs to verify results. The NRS reduced the raw gas from 1,305 BTU/scf (HHV) to less than 1,070 BTU/scf (HHV) consistently over the pilot period. For fueling purposes, the LP has a methane number of 78 compared to a methane number of 59 for the raw gas. It is important to note that all this improvement in methane number for the LP was done without the condensation of any liquid. All products from the NRS remain in gas phase.

As shown in Table 1, over 99% of the C4+ and over 85% of the C3 is returned to the suction header for monetization downstream (grey highlighted columns). While the C2 is also returned to the station, a larger portion of the less valuable C2 is being consumed as fuel. The NRS has effectively and efficiently produced lower value hydrocarbons for combustion purposes, while capturing the more valuable hydrocarbons for sale. The raw gas volume of heavy hydrocarbons as well as the recovered heavy hydrocarbons in the heavy product (HP) are highlighted in gray, so the reader can easily identify the volumes used to calculate the NGL recovery percentages.

Stream Name			Raw Gas			LP - Fuel Gas			HP - HHC Recovery		
Gas Volume	MSCFD			720			382				338
HHV	BTU/scf		1,307			1,062			1,643		
NGL content	gpm	-	-	6.557		-	1.966		-	13.165	
Compositions				**gpm***	**mcf**		**gpm***	**mcf**		**gpm***	**mcf**
CO_2	mol%		0.68%			0.52%			0.89%		
N_2	mol%		0.70%			0.96%			0.33%		
C_1	mol%		75.27%		542.0	91.19%		348.0	53.16%		206.5
C_2	mol%	10.119	13.15%	3.51	94.7	6.27%	1.67	23.9	22.92%	6.11	66.1
C_3	mol%	10.424	5.85%	1.61	42.1	0.80%	0.22	3.0	13.03%	3.58	36.3
$i\text{-}C_4$	mol%	12.384	0.61%	0.20	4.4	0.05%	0.02	0.2	1.49%	0.48	3.8
$n\text{-}C_4$	mol%	11.936	1.91%	0.60	13.7	0.10%	0.03	0.4	4.47%	1.40	12.4
$i\text{-}C_5$	mol%	13.855	0.41%	0.15	3.0	0.01%	0.00	0.1	0.99%	0.36	3.1
$n\text{-}C_5$	mol%	13.712	0.57%	0.21	4.1	0.02%	0.01	0.1	1.43%	0.52	4.0
C_6	mol%	15.566	0.70%	0.29	5.1	0.04%	0.02	0.2	1.72%	0.71	5.0
Total	mol%		100%			100%			100%		

* gpm - gallons per MCF

Table 1 – Gas compositions of the raw gas, Light Product and Heavy Product.

Field Operational Data

The pilot was able to continuously produce pipeline quality LP gas over the pilot period, even during the inclement winter weather. Raw gas fed into the system trended between 1,260 BTU/scf to 1,315 BTU/scf (HHV) over this testing period, as verified by 3rd party gas analysis. The on-skid GC provided continuous validation that the pilot was producing high quality LP (Fig. 4). The ability to measure both feed gas, LP, and HP gas compositions in real time provided further assurance in this patented process (US 11577191, 2023; US 11872518, 2024).

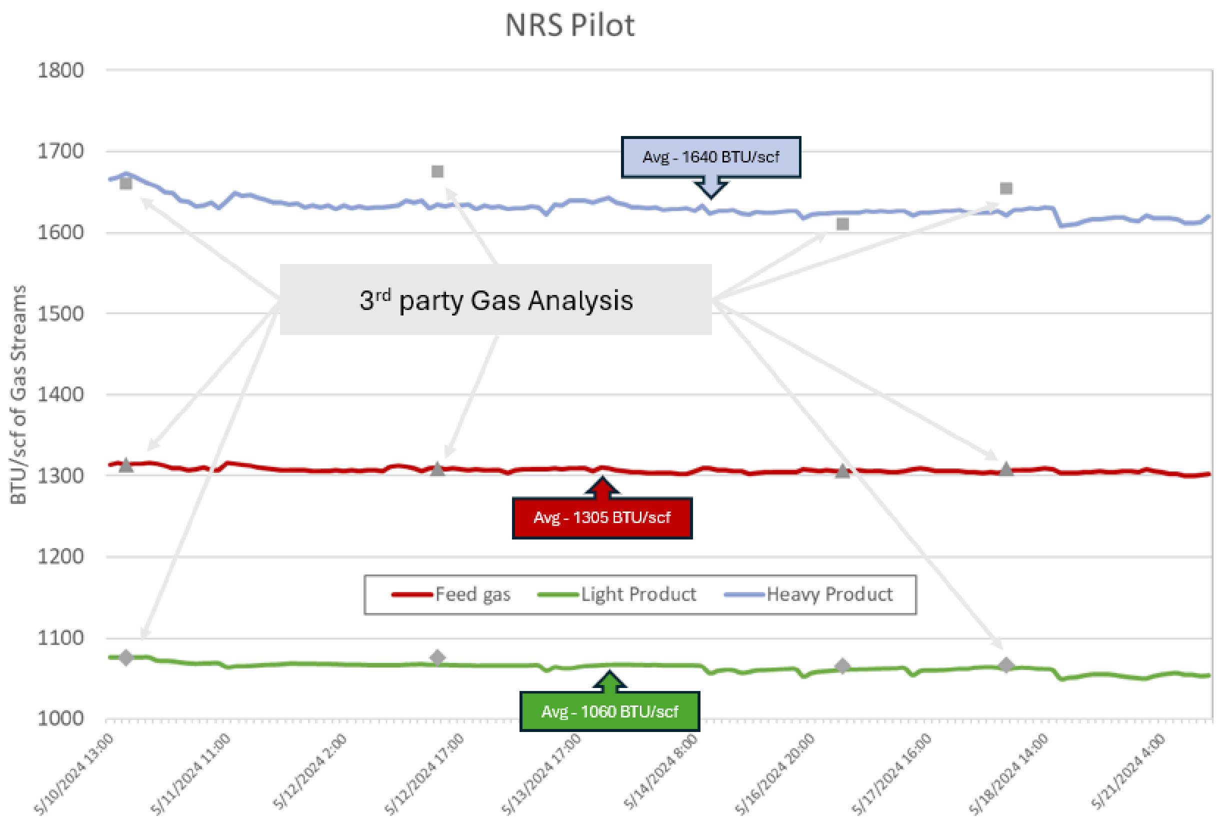

Fig. 4 – Consistent delivery of less than 1,100 BTU (HHV) of lean fuel gas.

Light Product as a-Fuel Source

The LP produced from the NRS is lean, dry and ideal as fuel gas. Pipeline quality fuel gas without liquid dropout, freeze issues, or constant methanol consumption. For comparison purposes, the pilot was able to compare fuel gas quality with an on-site J-T process. As can be seen in Table 2, the J-T is not very effective as a fuel conditioning technology. While the NRS is able to provide stable, low BTU fuel, the same cannot be said for the J-T. Periodic sampling of the J-T processed fuel showed minimal reduction in BTU content of the raw gas – at most reducing BTU content of the raw gas from 1,310 BTU/scf (HHV) to between 1,220 BTU/scf and 1,250 BTU/scf (HHV).

Stream Name			Raw Gas			J-T Fuel Gas Sample 1			J-T Fuel Gas Sample 2			LP - Fuel Gas		
HHV	BTU/scf		1,307			1,247			1,220			1,062		
NGL content	gpm	-	-	6.557			5.773			5.729		-	1.966	
Compositions				gpm	mcf		gpm	mcf		gpm	mcf		gpm	mcf
CO_2	mol%		0.68%			0.72%			0.21%			0.52%		
N_2	mol%		0.70%			0.64%			0.67%			0.96%		
C_1	mol%		75.27%		849.7	77.83%		914.8	78.71%		925.1	91.19%		1231.4
C_2	mol%	10.119	13.15%	3.51	148.4	12.68%	3.38	149.0	12.81%	3.42	150.5	6.27%	1.67	84.7
C_3	mol%	10.424	5.85%	1.61	66.0	5.28%	1.45	62.0	5.03%	1.38	59.1	0.80%	0.22	10.7
$i\text{-}C_4$	mol%	12.384	0.61%	0.20	6.9	0.56%	0.18	6.5	0.43%	0.14	5.1	0.05%	0.02	0.6
$n\text{-}C_4$	mol%	11.936	1.91%	0.60	21.5	1.50%	0.47	17.6	1.16%	0.37	13.7	0.10%	0.03	1.3
$i\text{-}C_5$	mol%	13.855	0.41%	0.15	4.7	0.27%	0.10	3.1	0.15%	0.05	1.7	0.01%	0.00	0.2
$n\text{-}C_5$	mol%	13.712	0.57%	0.21	6.4	0.33%	0.12	3.9	0.18%	0.06	2.1	0.02%	0.01	0.2
C_6	mol%	15.566	0.70%	0.29	8.0	0.18%	0.07	2.1	0.75%	0.31	8.8	0.04%	0.02	0.6
Total	mol%		100%			100%			100%			100%		

Table 2 – Comparison of fuel gas quality provided by the on-site J-T and the NRS.

VOC reductions due to better quality fuel was confirmed during stack testing on a Caterpillar G3608 A3 engine during the pilot period. Over 70% less VOCs were emitted when operating on fuel produced by the NRS compared to JT fuel gas (Fig. 5) pre-catalyst treatment. Emissions testing was completed in accordance with EPA Methods 1 and 2 in 40 CFR Part 60 Subpart JJJJ Appendix A-7. A MKS MultiGas 2030 FTIR was used for all measurements. Actual stack testing demonstrated that VOC emissions from NRS were lower than the maximum VOC rate predicted by Caterpillar's Gas Engine Rating Program (GERP). Additionally, VOC's were further reduced post-catalyst. This could mean the potential of situating more horsepower on a site before reaching permitting limits and potentially extending the life of catalyst elements within the stack.

	NRS Fuel Pre-catalyst	JT Fuel Pre-catalyst	NRS Fuel Post-catalyst	JT Fuel Post-catalyst
Fuel BTU (HHV)	1070	1235	1070	1235
(LHV)	969	1124	969	1124
VOC (g/bhp-hr)	0.33	1.15	0.15	0.57
(ton/yr)	6.57	21.41	3.01	11.45
Engine Speed (RPM)	1000	1000	1000	1000
Ignition Timing (BTDC)	16.5	16.5	16.4	16.4
Exhaust T (F)	1008	999	1009	1009
GERP VOC (g/bhp-hr)	0.64	1.32		
(ton/yr)	13.29	25.68		

Fig. 5 – Comparison of VOC emissions pre- and post- catalyst between NRS fuel and JT conditioned fuel.

Economic Analysis

The NRS recovers tremendous value for the customer by returning all the adsorbed heavy hydrocarbons gas back to the gathering system by recycling the heavy product back to compressor suction or suction header.

If one were to look at providing fuel for not just a single engine in a pilot study, but for 7,500 hp worth of compression, then the incremental value of NGLs recovered would be over $1.3MM per annum (Table 3) and 34 tons of annual VOC reductions based on an EIA 5-year weighted average (Table 4). In this 7,500 hp case, combusting the raw gas would consume 7,198 gpd of NGL's and their respective value. While using a J-T, the amount of consumed NGL's is reduced to 6,155 gpd. However, by using the NRS, NGL consumption is only 2,156 gpd, or over $956k in incremental NGL value is recovered when compared to the fuel produced from a J-T.

Stream Name			Raw Gas			J-T Fuel Gas Sample 1					LP - Fuel Gas				
Gas Volume	MSCFD			1,097			1,175					1,350			
HHV	BTU/scf		1,307			1,220					1,062				
BTU Value					1,433,779			1,433,500					1,433,700		
NGL content	gpm	-	-	6.557			5.729				-	1.966			
Compositions					Daily Consumed NGLs			Daily Consumed NGLs	Daily Recovered NGLs	Daily NGL Value			Daily Consumed NGLs	Daily Recovered NGLs	Daily NGL Value
				gpm	gpd		gpm	gpd	gpd			gpm	gpd	gpd	
CO_2	mol%		0.68%			0.21%					0.52%				
N_2	mol%		0.70%			0.67%					0.96%				
C_1	mol%		75.27%			78.71%					91.19%				
C_2	mol%	10.119	13.15%	3.51	3845.9	12.81%	3.42	3646.5	199.5	$59.84	6.27%	1.67	1834.9	2011.1	$603.32
C_3	mol%	10.424	5.85%	1.61	1762.4	5.03%	1.38	1514.9	247.5	$195.56	0.80%	0.22	239.8	1522.6	$1,202.89
$i\text{-}C_4$	mol%	12.384	0.61%	0.20	217.9	0.43%	0.14	155.4	62.6	$60.70	0.05%	0.02	17.0	200.9	$194.88
$n\text{-}C_4$	mol%	11.936	1.91%	0.60	658.3	1.16%	0.37	400.9	257.5	$249.74	0.10%	0.03	34.3	624.0	$605.31
$i\text{-}C_5$	mol%	13.855	0.41%	0.15	165.5	0.15%	0.05	59.3	106.2	$150.83	0.01%	0.00	5.3	160.2	$227.43
$n\text{-}C_5$	mol%	13.712	0.57%	0.21	225.5	0.18%	0.06	70.6	154.9	$219.96	0.02%	0.01	6.6	218.8	$310.75
C_6	mol%	15.566	0.70%	0.29	317.1	0.75%	0.31	307.5	9.6	$13.66	0.04%	0.02	18.5	298.6	$424.01
Total	mol%		100%		7193	100%		6155	1038	$950.28	100%		2156	5036	$3,568.59
				Annual Value	$0.00				Annual Value	$346,851.89				Annual Value	$1,302,534.48

Table 3 – The incremental NGL value recovered scales with the system size.

2024 EIA 5 yr weighted average NGL pricing

C2	$	0.30	$/gal
C3	$	0.79	$/gal
C4	$	0.97	$/gal
C5+	$	1.42	$/gal

Table 4 – 2024 US Energy Information Administration's 5 year weighted average NGL prices.

Conclusion

CSE has patented, developed, and successfully piloted an innovative gas separation technology for the energy sector. The adsorption-based system operates at varying ambient temperatures and requires no supervision. It is a simple and economically rewarding solution for maximizing NGL value for producers and gatherers while maximizing the efficiency and runtime on engines and generators.