Pressure Swing Adsorption For Natural Gas Separation and Emissions Reductions At Facilities

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Abstract

Compressor stations typically burn rich gas in the absence of residue lines or use a variation of fuel gas conditioning systems that moderately improve the fuel gas Methane Number (MN). This leads to the following challenges:

- Creates significant Volatile Organic Compouns (VOC) emissions
- Compressor engine horsepower (HP) is derated
- Higher compressor downtime (shut in production / reduced throughput / detonations) due to burning rich gas as opposed to lean gas
- Burning Natural Gas Liquids (NGL's) as opposed to processing and recovering them costs midstreamers / producers significant revenue

ColdStream Energy developed the **MaCH$_4$ NGL Recovery Solution (NRS)** - an innovative, energy-efficient gas separation technology designed to optimize natural gas processing – to address this challenge. Operating at ambient temperatures and capable of remote monitoring and control, the NRS System offers a simplified and economically attractive approach to maximizing natural gas liquids (NGLs) recovery and enhancing compressor station performance.

This solution enables the production of pipeline-quality lean gas (<1,100 BTU/scf HHV) at virtually any location, significantly reducing volatile organic compound (VOC) emissions. Its robust design supports high mechanical availability and operational efficiency, making it particularly valuable for gas gathering and compression applications in remote or distributed environments.

Since its commissioning in December 2023, the MaCH$_4$ pilot has consistently delivered target lean gas quality of < 1,070 BTU/scf HHV with over 99% mechanical availability. Remote operations commenced in May 2024, demonstrating the system's reliability and scalability. At a pilot site processing gas with an inlet energy content of approximately 1,305 BTU/scf, the system is projected to recover over $1.1 million in annual NGL value for a 7,500 HP compressor station.

The first commercial system already delivered at initial commissioning lean gas with less than 1,055 BTU/scf HHV, with full field results pending.

This technology represents a significant advancement in natural gas separation, offering a scalable, low-emission, and high-value solution for the energy sector.

Technical Background

Natural gas produced in association with oil — commonly referred to as associated gas — often contains a significant proportion of heavier hydrocarbons, including ethane, propane, butane, and condensate. This composition is particularly prevalent in wet and condensate-rich shale plays. Due to the remote nature of many production sites, this rich gas is frequently used on-site as fuel for heating, compression, and power generation.

However, unconditioned rich gas typically fails to meet the fuel quality standards required by combustion engine manufacturers. Metrics such as Methane Number (MN) and Wobbe Index are commonly used to assess fuel suitability, and rich gas often falls short of these benchmarks. The combustion of high-BTU gas leads to the inefficient use of valuable Natural Gas Liquids (NGLs) but also reduced compressor performance due to potential engine derates and compressor downtime due to e.g. engine knock events. Additionally, poor fuel quality contributes to elevated emissions of volatile organic compounds (VOCs), adversely affecting air quality and regulatory compliance.

These issues collectively can reduce engine reliability and lifespan, increase maintenance frequency, and result in production downtime. The economic and environmental costs of using substandard fuel underscore the need for a solution that can condition gas to meet engine specifications while preserving the value of heavier hydrocarbons.

The $MaCH_4$ system addresses this challenge by selectively removing heavy hydrocarbons from rich gas streams. This process not only improves fuel quality and engine performance but also enables the recovery of NGLs for downstream monetization. By reducing VOC emissions and enhancing operational efficiency, the NRS offers a compelling solution for producers and midstream operators seeking to optimize performance in remote and resource-rich environments.

Pressure Swing Adsorption

The $MaCH_4$ system leverages a patented application of **Pressure Swing Adsorption (PSA)** to selectively recover heavy hydrocarbons (C_3+) from rich natural gas streams, producing lean, dry gas suitable for on-site combustion. This approach enables efficient fuel conditioning while capturing valuable Natural Gas Liquids (NGLs) for downstream monetization.

PSA is a well-established, non-cryogenic gas separation technology widely used in industrial applications such as gas drying, oxygen and nitrogen purification, hydrogen production via steam methane reforming, landfill gas upgrading, and alcohol dehydration. Unlike cryogenic distillation, PSA operates near ambient temperatures, eliminating the need for complex refrigeration systems and avoiding freeze-related operational issues.

The PSA process exploits the principle of **adsorption**, a surface-based phenomenon distinct from absorption. When a gas mixture is introduced to a bed of specialized adsorbent material under high pressure, specific gas components preferentially adhere to the adsorbent surface. Upon reducing the pressure, the adsorbed species are released (desorbed), regenerating the adsorbent for repeated use. This cyclic process enables the selective separation of gas components without the need for external heat, making it more energy-efficient than traditional absorbent-based system (Fig. 1)

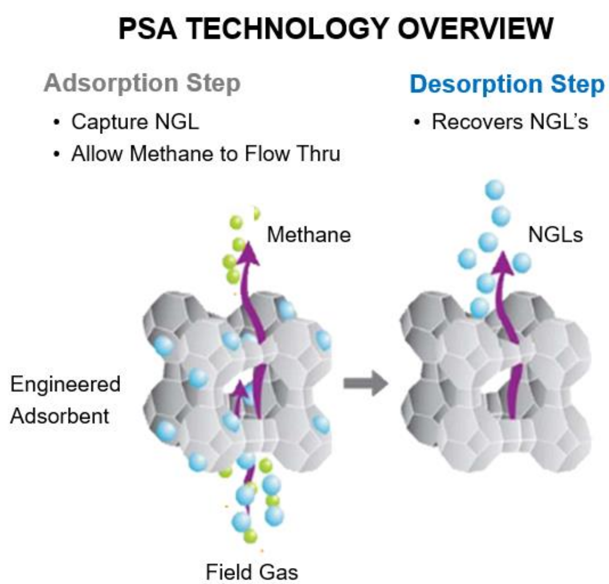

Fig. 1 – Overview of the PSA Technology

PSA has been adapted for a novel application in hydrocarbon gas separation. The NRS system achieves high recovery rates of C_3+ hydrocarbons while producing a lean fuel gas with improved combustion characteristics. This results in:

- **Reduced VOC emissions** due to cleaner combustion
- **Improved engine performance and reliability**
- **Monetization of recovered NGLs** that would otherwise be combusted

Key advantages of the NRS over conventional gas separation technologies include:

- Simple, remotely operable design with >99% mechanical availability
- High turndown ratio and tolerance to BTU variability in feed gas
- Cryogenic-like NGL recovery without low-temperature operation
- Minimal power requirements (single-phase compatible)
- No chemical consumables (e.g., methanol, glycol)
- Skid-mounted, field-transportable configuration
- Integrated dehydration and hydrocarbon recovery in a single-step process

- Recovered hydrocarbons remain in gaseous phase—no liquids or tanks required

This innovative adaptation of PSA technology provides a scalable, low-maintenance, and energy-efficient solution for natural gas producers and midstream operators seeking to optimize fuel quality, reduce emissions, and capture additional value from their gas streams.

MaCH_4 System Process Design and Operations

The MaCH_4 system utilizes a proprietary application of **Pressure Swing Adsorption (PSA)** to selectively capture heavy hydrocarbons — including propane, butane, pentanes, hexanes—and water vapor from rich natural gas streams under elevated pressure. This represents a novel and patented commercial deployment of PSA technology for hydrocarbon separation (U.S. Patents 11,577,191 [2023] and 11,872,518 [2024]).

The system comprises four or more adsorption beds, each packed with a specialized blend of adsorbent materials, along with integrated filtration and storage components. A key advantage of this configuration is its **tunable methane purity**, allowing operators to adjust the composition of the lean gas product to meet specific fuel quality requirements. Additionally, the system performs **simultaneous dehydration** of saturated field gas, producing a dry, lean gas stream that is well-suited for use in combustion engines.

The NGL Recovery Solution is fully **remotely monitored and operated**, requiring no chemical consumables and minimal operator intervention. This low-maintenance, field-deployable solution offers a scalable and energy-efficient alternative to traditional cryogenic or chemical-based gas processing technologies.

System Integration and Operational Cycle

The NRS system is designed for seamless integration into existing natural gas compression infrastructure. The system requires three primary connections:

1. **High-pressure feed gas inlet**, typically sourced from the discharge header or the second or third stage of a compressor,
2. **Lean gas outlet**, delivering the methane-enriched product to the engine or fuel gas header, and
3. **Heavy hydrocarbon outlet**, which routes the recovered NGL-rich stream back to the compressor suction or suction header (Fig. 2).

Upon entering the NRS system, the high-BTU feed gas first passes through pre-filtration units that remove entrained lubricating oil. The conditioned gas then flows into the adsorption beds, where heavier hydrocarbons — such as propane, butane, pentanes, hexanes —and water vapor are selectively adsorbed. The methane-rich gas passes through the beds and is collected in a buffer tank or directed immediately to the fuel gas system.

A key feature of the NRS system is its **adjustable methane purity**, allowing operators to tailor the lean gas composition to meet specific engine requirements and avoid derating. The system operates on a cyclic basis, with multiple adsorption beds at different stages of the pressure swing cycle. While one bed is in the adsorption phase, others undergo **desorption (regeneration)** via controlled depressurization. During this step, the adsorbed hydrocarbons are released and collected as a heavy product stream, which is reintegrated into the compressor suction for downstream monetization.

This continuous cycling ensures a steady supply of lean gas while maximizing NGL recovery. The NRS system achieves this without the need for external heating, chemical consumables, or complex cryogenic systems. Its robust design supports high performance across a wide range of ambient conditions and feed gas compositions.

The result is a **cost-effective, low-maintenance, and energy-efficient** gas separation solution that enhances fuel quality, reduces emissions, and captures additional value from rich gas streams.

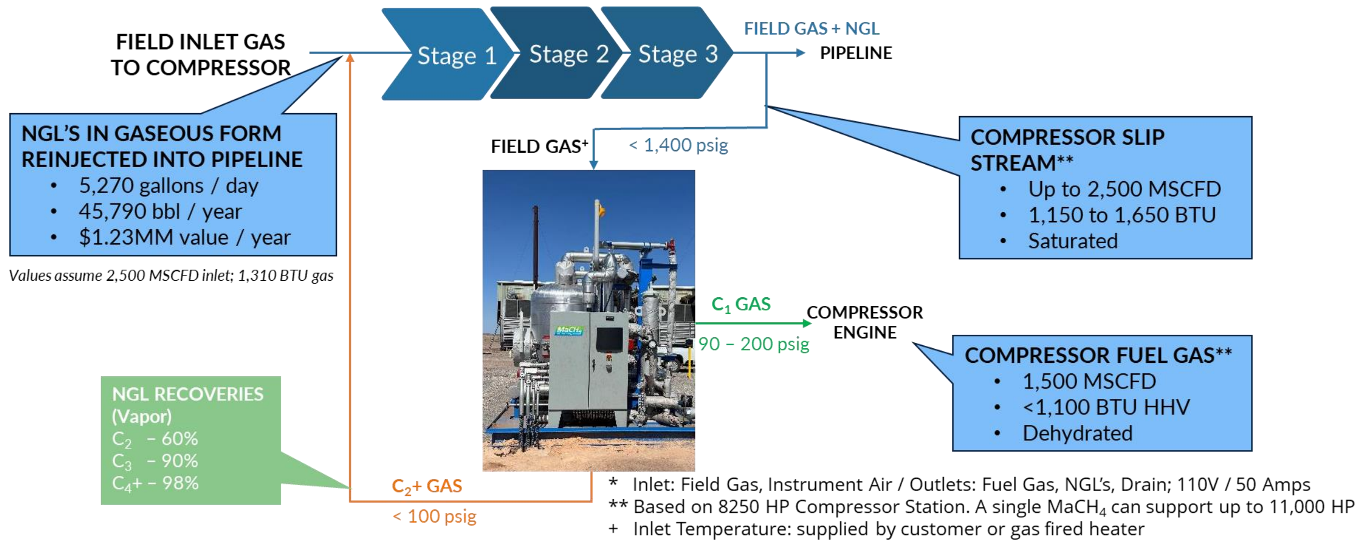

Fig. 2 – NGL Recovery Solution – Sized to support 8,250 HP per system

Pilot Deployment of the NRS Technology

The proprietary Pressure Swing Adsorption (PSA) Pilot system was deployed at a compressor station located in Canadian County, Oklahoma. The site also features an existing Joule-Thomson (J-T) process skid used to supply fuel gas to the compressors. This deployment provided a valuable opportunity to evaluate the performance of the NGL Recovery System (NRS) and demonstrate its capability to deliver lean, dry fuel gas while achieving superior natural gas liquids (NGL) recovery compared to conventional J-T systems.

Since commissioning in December 2023, the pilot unit has consistently produced fuel gas meeting the required specifications. It has maintained mechanical availability exceeding 99% and has been remotely monitored and operated since May 2024.

The PSA system, comprising four beds (see Fig. 3), was installed adjacent to an existing compressor package. Raw gas is sourced from the second-stage discharge of the compressor and fed into the PSA unit. The system separates the high-pressure feed gas into two distinct product streams:

- **Light Product (LP):** Lean fuel gas suitable for use in station operations.
- **Heavy Product (HP):** Recovered heavy hydrocarbons, which are routed back to the suction header of the compressor station.

The pilot was operated through winter conditions, allowing to validate the robustness and reliability of the NRS technology under suboptimal environmental conditions. The primary objective was to demonstrate the system's ability to consistently supply lean, high-quality fuel to a CAT G3608A3 compressor (2,370 hp). The pilot met this objective, delivering stable and reliable performance throughout the test period.

Fig. 3 – Pilot System installed at compressor station.

Table 1 presents the measured gas compositions for three streams: the raw field gas entering the NRS system, and the light product (LP) and heavy product (HP) exiting the system. Gas composition data for the LP and HP streams were continuously monitored using an on-skid gas chromatograph (GC). To ensure data accuracy and validate system performance, all three streams were independently analyzed by third-party laboratories.

Throughout the pilot period, the NRS consistently reduced the higher heating value (HHV) of the incoming raw gas from 1,305 BTU/scf to below 1,070 BTU/scf. This reduction was achieved without any phase change; all output streams remained in the gaseous phase, underscoring the efficiency of the PSA-based separation process.

The LP stream demonstrated a significant improvement in combustion quality, with a methane number of 78 compared to 59 for the raw gas. This enhancement is particularly notable given that it was accomplished without the condensation of liquids, preserving the operational simplicity and reliability of the system.

As detailed in Table 1, the NRS achieved high recovery rates for valuable hydrocarbons:

- Over 99% of butanes (C4+)
- Over 85% of propane (C3)

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-C_4	mol%	12.384	0.61%	0.20	4.4	0.05%	0.02	0.2	1.49%	0.48	3.8
n-C_4	mol%	11.936	1.91%	0.60	13.7	0.10%	0.03	0.4	4.47%	1.40	12.4
i-C_5	mol%	13.855	0.41%	0.15	3.0	0.01%	0.00	0.1	0.99%	0.36	3.1
n-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.

These components were returned to the suction header for downstream monetization (highlighted in gray). While ethane (C2) was also partially recovered, a larger fraction was retained in the LP stream for combustion, aligning with its lower market value. This selective recovery strategy enables the NRS to optimize fuel gas quality while maximizing the capture of high-value NGLs.

Although gas chromatographs (GCs) are not well-suited for quantifying water content in gas streams, the dehydration capability of the NRS pilot was clearly demonstrated using a simple Dräger tube sampling system. This method provided reliable qualitative confirmation of water removal performance.

The NRS represents a process intensification approach, integrating cryogenic-like NGL recovery and molecular sieve-like dehydration within a single unit operation. Notably, this is achieved without the use of cryogenic cooling, solid desiccants, consumables, or recirculating chemical agents. The system's ability to simultaneously perform hydrocarbon separation and gas stream dehydration underscores its operational efficiency and technological innovation.

Field Operational Data

As previously described, the Pressure Swing Adsorption (PSA) process operates cyclically through alternating phases of adsorption and desorption.

Throughout the pilot period, the NRS consistently produced pipeline-quality light product (LP) gas, even under challenging winter weather conditions. The raw gas feed exhibited a higher heating value (HHV) ranging from 1,260 to 1,315 BTU/scf, as verified by independent third-party laboratory analyses. Continuous monitoring via the on-skid gas chromatograph (GC) further validated the production of high-quality LP gas (see Fig. 4).

The ability to measure the compositions of the feed gas, LP, and heavy product (HP) streams in real time provided critical insight into system performance and process dynamics. This capability reinforces the robustness of the patented NRS technology and its suitability for field deployment in variable operating environments.

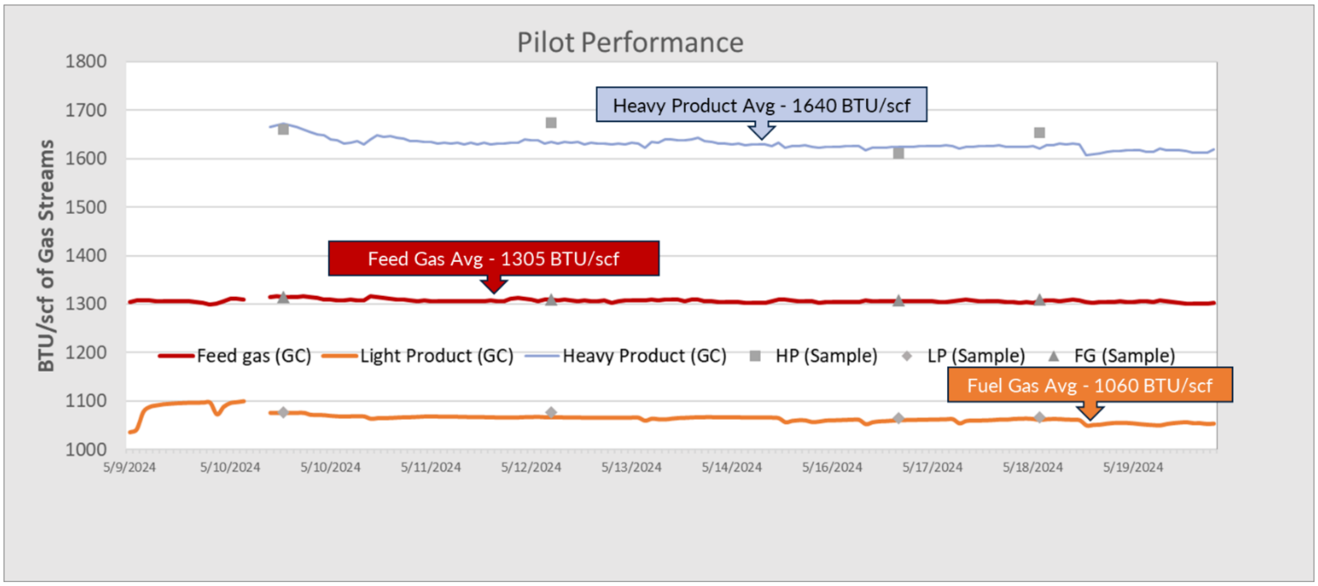

Fig. 4 – Consistent delivery of less than 1,100 BTU (HHV) of lean fuel gas.

To demonstrate the versatility of the NRS technology, the pilot system was operated in a stepwise manner to tune the higher heating value (HHV) of the light product (LP) gas across a wide range. Specifically, the LP BTU content was adjusted from 1,000 BTU/scf (corresponding to 98% methane, C_1) to 1,200 BTU/scf (82% C_1), and subsequently returned to 1,080 BTU/scf (89% C_1). These adjustments were achieved without altering the system's operating or ambient temperature, as shown in Figure 5.

All tuning operations were conducted remotely, highlighting the system's advanced automation and control capabilities. This level of flexibility enables the NRS to maintain a consistent and desirable LP BTU specification, even in the presence of fluctuating feed gas compositions. Additionally, the ability to selectively retain or reject ethane (C_2) in the LP stream provides operators with the option to prioritize either fuel gas quality or NGL recovery, depending on commercial or operational objectives.

This tunability underscores the NRS system's potential to deliver tailored gas processing solutions across a range of field conditions and market requirements.

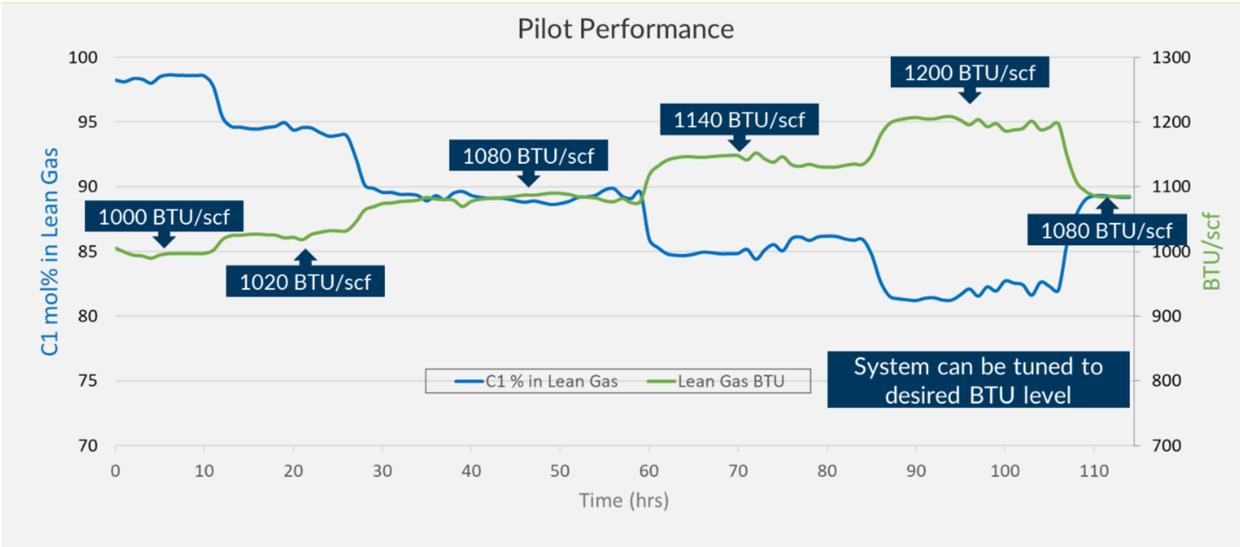

Fig. 5 – Demonstrated ability to actively manage desired fuel gas BTU content.

Light Product as a Fuel Source

The light product (LP) gas generated by the NRS system is lean, dry, and meets pipeline-quality specifications, making it highly suitable for use as fuel gas. It eliminates common operational challenges such as liquid dropout, freezing, and the need for continuous methanol injection. To assess performance, the pilot study included a comparative analysis between NRS-produced fuel gas and fuel gas conditioned by an on-site Joule-Thomson (J-T) process.

The J-T process demonstrated limited effectiveness in reducing the heating value of the raw gas. While the NRS consistently delivered stable, low-BTU fuel gas, the J-T system achieved only modest reductions—lowering the higher heating value (HHV) from approximately 1,310 BTU/scf to a range of 1,220–1,250 BTU/scf. This minimal reduction resulted in a fuel stream with a relatively high concentration of heavy hydrocarbons.

In addition, the performance of a J-T skid is heavily dependent on ambient temperatures. Table 2 shows fuel gas quality provided at a customer site in the Permian throughout the year. The field gas in this example is at 1,375 BTU/scf HHV. While the J-T is able to reduce the BTU down to 1,180 BTU/scf HHV in the cold winter months, the fuel gas reaches up to 1,276 BTU/scf HHV during the hottest months.

Month	Day Temp [°F]	Night Temp [°F]	Average Temp [°F]	JT Skid BTU
January	65	48	57	1180
February	69	51	60	1189
March	77	57	67	1210
April	83	63	73	1228
May	90	70	80	1249
June	95	75	85	1264
July	98	76	87	1270
August	99	78	89	1276
September	92	75	84	1261
October	85	66	76	1237
November	74	57	66	1207
December	68	51	60	1189
Averages	83	64	73	1230

Table 2 – Comparison of fuel gas quality provided by a J-T skid based on ambient temperatures.

The presence of these heavier components in the fuel gas can lead to increased risks of engine knocking and detonation, which can accelerate mechanical wear and compromises engine reliability, but more importantly has a direct correlation to engine downtime, as illustrated Fig. 6. These are downtime percentages reported by a customer in the Permian for CAT3608 and CAT3516 engines when run on 1,375 BTU/scf HHV field gas or in comparison with average 1,270 BTU/scf HHV provided by a J-T skid in the summer and an average of 1,180 BTU/scf provided in the wintertime. While the reported downtime in the winter is only about 0.5%, this can reach up to 1.5% downtime with J-T fuel quality provided in the summer, or even 3% when run on field gas. In comparison, the 75-Methane Number provided by the MaCH4 system is expected to eliminate any detonation related downtime.

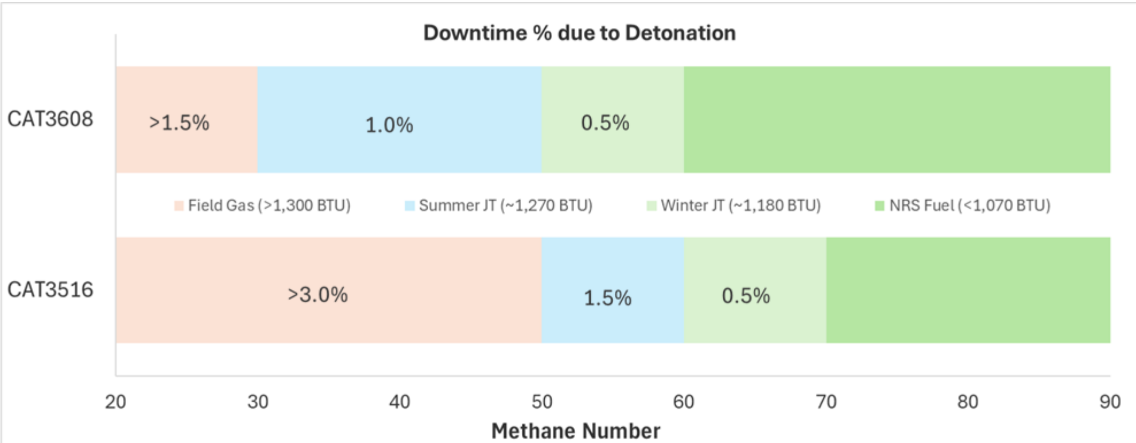

Fig. 6 – Engine downtime related to detonations as reported by a Permian customer for two engine types based on fuel gas quality

Prolonged use of high-BTU fuel gas, such as that produced by the J-T process or untreated raw gas, can lead to unplanned engine downtime, resulting in lost throughput and fee-based revenue. Additionally, the elevated heavy hydrocarbon content in these fuels contributes to higher volatile organic compound (VOC) emissions from engine exhaust. Increased VOC emissions accelerate catalyst degradation and may trigger regulatory scrutiny under air quality compliance frameworks.

Stack emissions testing conducted during the pilot confirmed the environmental benefits of NRS-produced fuel. When operating a Cat G3608 A3 engine on NRS fuel, pre-catalyst VOC emissions were reduced by over 70% compared to operation on J-T fuel gas (see Fig. 8). Testing was performed in accordance with U.S. EPA Methods 1 and 2 (40 CFR Part 60, Subpart JJJJ, Appendix A-7), using an MKS MultiGas 2030 FTIR analyzer.

Measured VOC emissions from the NRS-fueled engine were below the maximum values predicted by Caterpillar's Gas Engine Rating Pro (GERP). Post-catalyst treatment further reduced emissions, suggesting the potential to deploy additional horsepower on-site without exceeding permitting thresholds. Moreover, the use of cleaner-burning fuel may extend the operational life of catalyst elements, reducing maintenance frequency and associated costs.

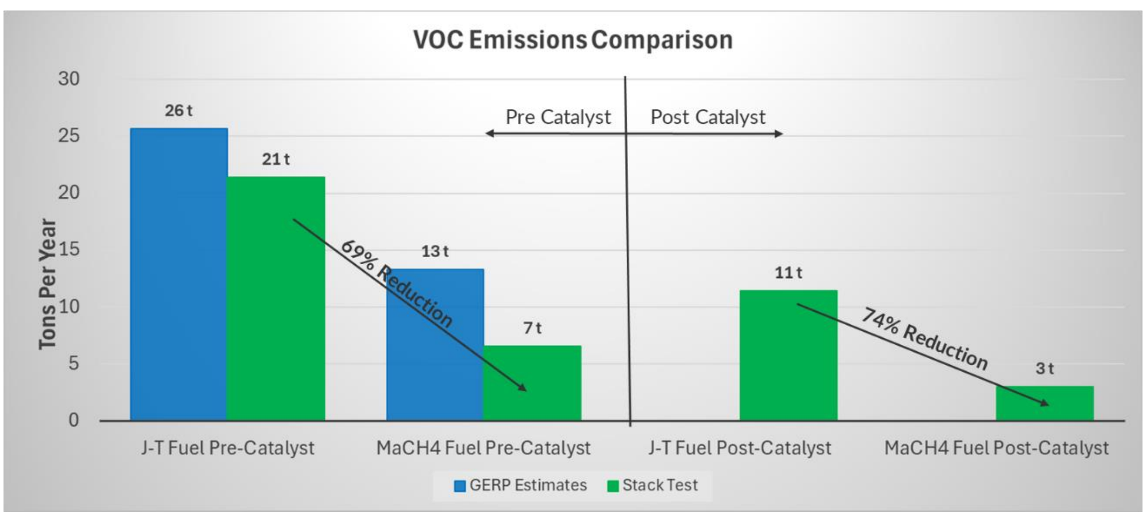

Fig. 7 – Comparison of VOC emissions pre- and post- catalyst between NRS fuel and JT conditioned fuel.

As discussed, the fuel quality in different conditions (field gas, J-T fuel gas summer, J-T fuel gas winter)-impact the detonation related downtime, but also has a significant impact on Volatile Organic Compound (VOC) emissions. The reduction of VOC's can provide the ability to install additional horsepower while staying within permit limits or to either avoid or get out of Title V requirements. Table 3 shows the VOC emissions and detonation related downtime for the previously discussed engine types as well as an estimated monthly NGL value recovered for a 10,000 horsepower station in the Permian.

10,000 HP Permian Station 1.5MM Fuel Gas			VOC Emissions				Detonation Downtime		Monthly NGL Revenue
			3516 J		3608 A4		3516 J	3608 A4	
Fuel Gas Type	BTU	Methane Number	Tons/Year	% Reduced	Tons/Year	% Reduced			
Field Gas	1375	50.7	85.5	0%	112.1	0%	3.0%	1.0%	$ -
JT Skid Summer	1266	54.3	60.9	29%	78.0	30%	1.5%	0.5%	$ 10,000.00
JT Skid Winter	1182	64.2	44.8	48%	50.8	55%	0.5%	0.0%	$ 20,000.00
MaCH4	1070	75.3	35.5	58%	22.8	80%	0.0%	0.0%	$ 102,000.00

Table 3 – Comparison of detonation related downtime, VOC emissions and NGL value recovered for a 10,000 HP compressor station at various fuel gas qualities representing field gas, JT-Skid gas (summer and winter) and fuel gas provided by the MaCH4 system

The NRS system offers a significant advancement over conventional fuel conditioning technologies. As illustrated in Figure 7, the NRS consistently delivers lean, dry fuel gas with a lower heating value (LHV) of approximately 950 BTU/scf and a Caterpillar methane number of 75 or higher — performance metrics that are difficult to achieve with traditional solutions except for using residue lines.

Unlike cryogenic systems, the NRS achieves this level of separation without operating at subfreezing temperatures, thereby eliminating the risk of hydrate formation or water freeze-ups that can disrupt operations. Furthermore, the adsorption-based process is regenerative and does not rely on chemical consumables, eliminating the need for offloading logistics or liquid waste handling commonly associated with Joule-Thomson (J-T) systems.

While all fuel conditioning systems generate some level of recycle gas, the NRS's pressure swing adsorption (PSA) process produces significantly less recycle volume than membrane-based technologies. Importantly, the heavy hydrocarbons recovered in the NRS recycle stream are returned to the operator for downstream monetization. In contrast, flash gas side-streams from J-T systems may not always be recoverable or economically beneficial.

From an environmental perspective, the NRS offers substantial advantages. By effectively removing C_3+ hydrocarbons from the combustion stream, the system reduces volatile organic compound (VOC) emissions even before post-combustion treatment. This reduction in upstream emissions can lower catalyst consumption, simplify regulatory permitting, and potentially allow for the installation of additional compression horsepower at a given site without exceeding emissions thresholds.

Engine performance simulations using a Gas Engine Rating Pro (GERP) further confirm the emissions benefits of NRS-conditioned fuel. Compared to J-T and membrane systems, the NRS consistently results in lower VOC emissions, supporting both operational efficiency and environmental compliance. In summary, the NRS system is a key alternative to residue lines (Fig. 8). Compared to residue lines, the MaCH4 system can be just moved to a new location in case of decommissioning a compressor station.

	J-T Skid	MRU	Residue Line	MaCH$_4$
				
< 1,100 BTU Fuel Gas	No	No	Yes	Yes
C_2 Recovery	< 0.5%	< 5%	N/A	60%
C_3 Recovery	< 25%	< 50%	N/A	> 90%
C_4+ Recovery	~ 50% - 80%	~ 80% - 95%	N/A	> 95%
VOC Reductions	Minimal	Moderate	Maximum	Maximum
NGL Value Discounted – Trucking	Yes	Yes	No	Minimal
Consumables and OPEX	Moderate	High	N/A	No
Permits and / or ROW Required	No	Yes	Yes	No
Independent of Ambient Temp.	Yes	Moderate	No	No

Fig. 8 – Comparison of common fuel gas conditioning technologies with the CSE system.

Key Performance Indicators

The rigorous field testing of the NRS pilot demonstrated that the technology meets or exceeds all key performance indicators (KPIs) relevant to end users (see Table 4). In addition to delivering high recovery rates of C_3+ hydrocarbons and producing high-quality, lean fuel gas, the system has exhibited exceptional reliability.

Since commissioning, the NRS pilot has maintained mechanical availability exceeding 99%, even under challenging conditions including sub-freezing ambient temperatures, station-level operational interruptions, and fluctuations in the BTU content of the raw gas feed. These results confirm the robustness and resilience of the NRS technology in real-world operating environments.

The pilot's performance validates the system's readiness for broader deployment and underscores its potential to deliver consistent, high-value outcomes across a range of field applications.

Goal/KPI	Measurement Method	Current Status
Heavy Hydrocarbon Recovery	Third-party analysis	>= 50% C2 >= 80% C3 >= 95% C4+
Light Product BTU value	On skid GC and third-party analysis	< 1,100 BTU HHV
Dehydrate Fuel Gas	Drager tube – visual observation	< 5 lb/MMscf
VOC Reduction	GERP calculation and Emissions trailer tested	70+% VOC reductions based on stack testing
Processing Capacity (500Mscfd)	On-skid flow meters	Flow control and metering operating as designed
Fuel Gas Flow	On-skid flow meters	Continuous fuel supply to engine
Pressure Stability	Pressure transmitters	All measurements are stable
Adaptation to Raw Gas Inconsistency	On skid GC and third-party analysis	3rd party gas analysis verified (1260 BTU to 1315 BTU)
Equipment Uptime (Mechanical/Electrical/Pneumatic)	Ongoing determination.	>99% uptime to date

Table 4 – System KPI's have been vigorously vetted at the pilot site

Since the initiation of pilot operations, the NRS sytem has demonstrated exceptional mechanical availability, consistently exceeding 99%. Throughout the testing period, the system has operated reliably under a range of adverse environmental conditions, including winter storms, high winds, and heavy rainfall, with no evidence of systemic design flaws or operational instability.

Scalability and Economic Impact of $MaCH_4$ Deployment

While the pilot study focused on conditioning fuel for a single engine, the economic and environmental benefits of the $MaCH_4$ system scale significantly with larger installations. The commercial units have been designed with a 2,500 Mscfd inlet and 1,500 Mscfd lean fuel gas capacity. The system is modular (processing skid, buffer tank skid, and optional inline heater) to facilitate easy transportation to a compressor station (Fig. 9). The inlet heater guarantees the required process temperatures to keep the heavy product stream in vapor form, which can also be accomplished by utilizing feed gas from the hot gas discharge.

Initial Commissioning February 25, 2025, at first customer site (Oklahoma)

- Processes up to 2,500 MCF/D and provides ~1,500 MCF/D Lean Fuel
- Processing skid – 40 ft x 11 ft x 11.5 ft, 76,000 lbs
- Buffer tank skid – 10 ft x 10 ft x 22 ft, 12,000 lbs

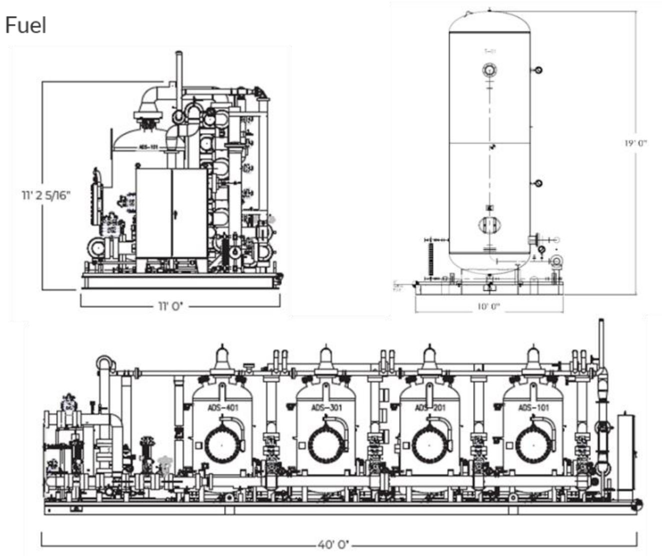

Fig. 9 – The commercial system has an inlet capacity of 2,500 Mscfd and fuel gas capacity of 1,500 Mscfd while being able to be easily moved to a compressor station.

The processing skid features 3 main connections (Fig. 10)

- Feed gas inlet from the inline heater or hot gas discharge from the 3rd stage
- Heavy product recycle gas in vapor form going back to the suction header
- Fuel gas (light product) going to the buffer tank to fuel the compressor engines.

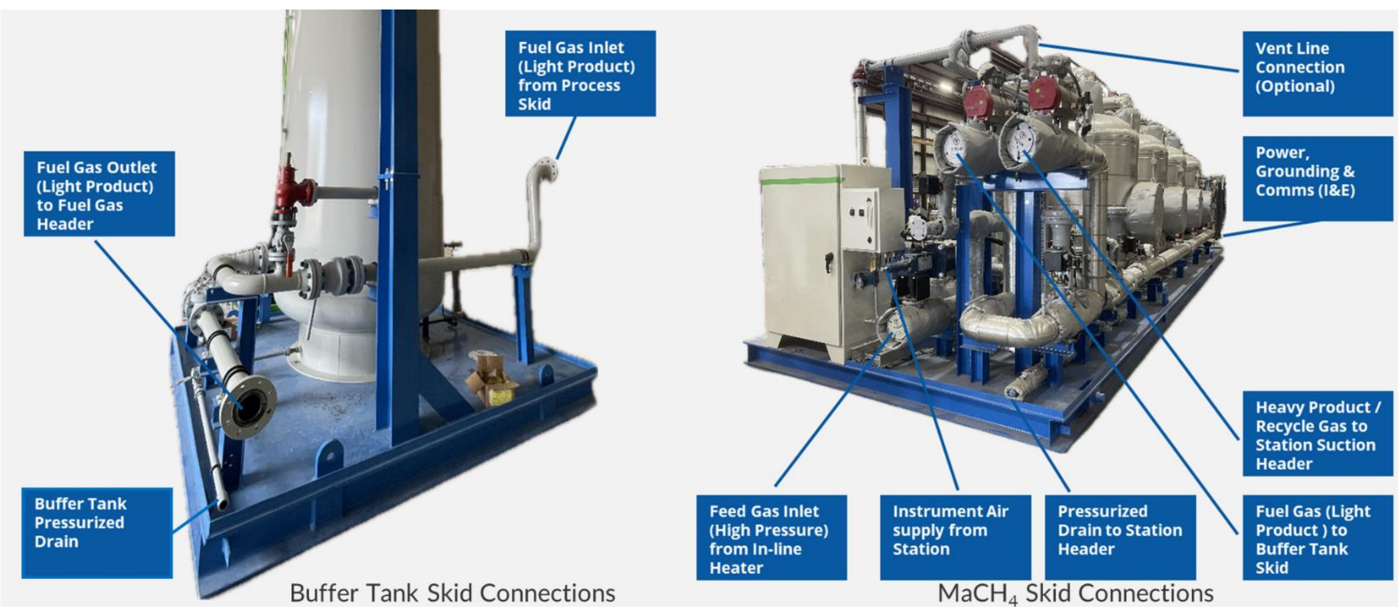

Fig. 10 – Simple connections allow for easy integration into a compressor station

Power requirements are limited to 2 x 120V / 50 Amp requirements, which can typically be accommodated at a compressor station. Finally, instrument air is required to operate the valves that manage the process.

The commercial system already demonstrated the same NGL recovery rates during initial commissioning at a compressor station in Beckham County, Oklahoma, with 1,200 BTU field gas. Initial fuel gas was produced at 1,045 BTU, which was adjusted to 1,065 BTU when fueling the engines (Fig. 11).

- Deployed at compressor station in Beckham County, Oklahoma
- First gas was provided to $MaCH_4$ System on 02/25/25
  - 1,045 BTU lean fuel gas was produced with hours of startup
- Full commissioning started on 05/28/25
  - **Delivering 1,055 BTU fuel gas with 1,200 BTU field gas**
- Fueling compressor station started 6/19/2025
  - Adjusted fuel gas to 1,065 BTU – seamless switch over

Produced 1045 BTU lean gas

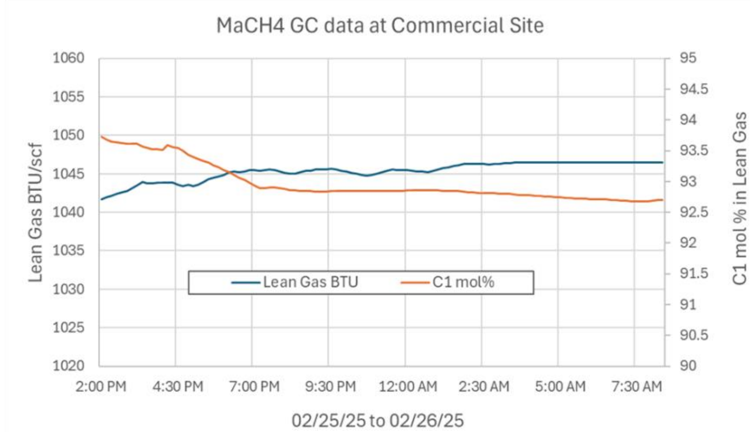

Fig. 11 – The commercial system demonstrated the ability to deliver less than 1,070 BTU fuel gas at the initial installation site in Beckham County, Oklahoma

Installing the system at a compressor station to support 8,250 horsepower (hp) of compression capacity (3x CAT3608 A4 engines) with a field gas of 1,310 BTU, the MaCH4 system enables the recovery of about $1.2 million in incremental NGL value annually and reduces volatile organic compound (VOC) emissions by approximately 35 tons per year (see Table 5) based on 5-year average EIA NGL values (Table 6). Considering system, installation and operating cost, a payback period of less than 3 years can be achieved. Deploying the system in an environment with even richer gas (1,440 BTU, typical value in the Bakken), the system can still support about 6,000 HP, generating a comparable NGL value and with a similar payback period.

	1,310 BTU	1,440 BTU
Incremental NGL Value	8250 HP	6000 HP
Net NGL Benefit	$ 1,229,595	$ 1,142,678
Throughput		
Recycle cost of compression	$ (60,200)	$ (93,411)
Operations Cost		
O&M / Electricity Cost	$ (32,628)	$ (32,628)
Incremental Value A4 Engine	$ 1,136,767	$ 1,016,640
Eliminating 8.8% derate		
Compression cost reduction	$ 144,540	$ 105,120
Incremental Value A3 Engine	$ 1,281,307	$ 1,121,760
VOC Emissions		
VOC Reductions (TPY)	(35)	(23)

Table 5 – System economics for 1,310 BTU (Permian) and 1,440 BTU (Bakken) lead to payback periods of less than 3 years.

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 6 – 2024 US Energy Information Administration's 5 year weighted average NGL prices.

A $1.1.B / Year industry opportunity and challenge

The MaCH4 system provides significant value by capturing valuable NGL's instead of burning them, reducing VOC emissions, eliminating engine derate, while enabling increased throughput due to less detonation related downtime. But only an overall industry view demonstrates the value that can be unlocked by making lean, pipeline quality fuel gas available at broad scale.

2025 Enverus data show an estimated 34,300 Mscfd of gas moved between the Permian, Bakken, DJ and Eagle Ford. This is an equivalent of 8.2 MM HP installed compression capacity. Adjusting this by 5% for electric compression, 35% already on residue lines, 20% for less than 1,310 BTU field gas, and further 20% for benefits already provided by JT Skids, still leaves about 3.5M HP run on field gas. Considering the previously discussed benefits, an estimated $500MM / year in NGL value is currently combusted instead of captured, which also results in 11,250 t of VOC emissions that could be avoided.

Furthermore, estimating a 1% detonation related downtime across the installed base, is equivalent to adding 26,000 HP in available compression capacity, which is an estimated value of $600 MM / year in gas that is not brought to market (Fig. 12)

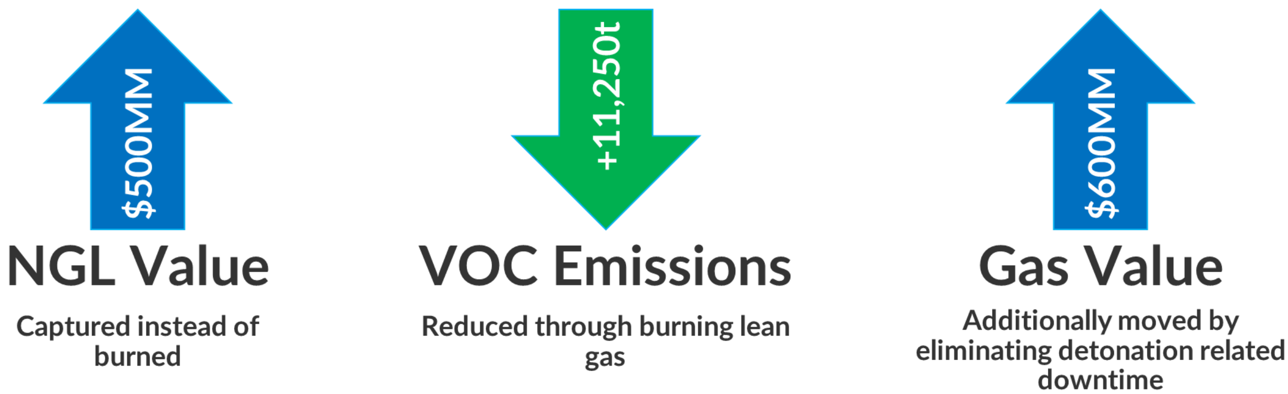

Fig. 12 – Just in the Permian, Bakken, DJ, and Eagle Ford an estimated value of $1.1B / year can be unlocked. Based on estimated 3,500,000 installed HP on field gas, adjusted for use of JT Skids. Engine downtime due to detonations estimated at average 1% and converted into lost natural gas revenue

At the same time, it is acknowledged, that contract structures will typically neither allow the midstreamer nor the producer to unlock the full value, which is estimated to be $3MM / year per installed commercial system.

- NGL Revenues
  - Whether a percentage of proceeds, keep whole, or other type of processing agreements, midstreamers and/or producers benefit from significant additional processing revenues
- Additional throughput through less downtime and optimal HP usage
  - Additional revenue to producer from oil and gas sales and additional transport revenue to midstreamer
- Environmental benefits
  - VOC reductions help the stewardship efforts of both producers and midstreamers
- Additional transport and fractionation throughput
  - Benefit to midstreamer if they own the fractionation facilities downstream of processing plant

Both midstreamer and producer can achieve significant benefits from the use of lean fuel gas on a broad basis. Collaboration between all parties involved will be required to get the returns on the investments being made.

Conclusion

The Mach4 system is a patented and successfully developed and field-tested innovative gas separation technology tailored for the energy sector. The adsorption-based MaCH4 system operates reliably across a wide range of ambient temperatures and requires minimal operator intervention, making it well-suited for remote and unmanned installations.

This system offers a streamlined, cost-effective solution for maximizing the value of natural gas liquids (NGLs) while simultaneously enhancing the efficiency and runtime of engines and generators. By combining high NGL recovery with consistent production of lean, dry fuel gas, the NRS delivers both operational and economic advantages to producers and midstream operators.

The industry has an opportunity to unlock significant value through collaborations between midstreamer and producer for a win-win scenario.