THESIS

RECIPROCATING COMPRESSOR VENT GAS CAPTURE AND RETURN TO PROCESS FOR METHANE EMISSION MITIGATION

Submitted by

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ABSTRACT

RECIPROCATING COMPRESSOR VENT GAS CAPTURE AND RETURN TO PROCESS FOR METHANE EMISSION MITIGATION

Methane emissions from natural gas compressor stations pose environmental and regulatory challenges for operators and the community, particularly regarding the possible reinstatement of the Environmental Protection Agency's Waste Emissions Charge.

Gas leakage past compressor seals accounts for a portion of these methane emissions. These gases are traditionally vented to the atmosphere or flared and can equal % of the driving engine's fuel before legally mandated replacement. This report considers the effectiveness and mechanisms of compressor vent gas capture and use. Recirculation (i.e., directing vent gases to the intake of the driving engine) and recompression (i.e., directing vent gases back to the main product pipeline) systems to capture and redirect these vent gases are compared for techno-economic feasibility.

The research involves laboratory simulation of gas recirculation using a Caterpillar G3516J lean-burn natural gas engine. Performance metrics, including engine efficiency, emissions reduction, and engine stability, are evaluated under varying operating conditions to determine the feasibility of integrating such a system at industrial sites. A techno-economic analysis is included to compare the recirculation and recompression systems, as well as conventional venting, considering potential compliance costs and fuel savings.

This research demonstrates that simulated gas recirculation via fumigation to the driving engine intake can be conducted in a safe manner, while offsetting fuel demand from the primary fuel line. During steady state introduction, the engine was shown to handle up to 35% of its fuel flow fumigated to the air intake independent from the fuel system. This fuel was shown to directly offset fuel provided to the engine by the fuel line. Additionally, tests were conducted to demonstrate that the engine can handle rapid transients in fumigation flow while maintaining controlled combustion.

The techno-economic analysis indicates that vent gas capture can provide an effective and financially viable emissions reduction strategy considering state regulations or possible federal penalties, mitigating methane release while utilizing otherwise wasted gas. Yearly emission charge savings of $95,000 and fuel savings of $7,900 could be realized per compressor during typical operation.

ACKNOWLEDGEMENTS

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CHAPTER 1 – BACKGROUND

1.1 Natural Gas Usage within the United States

Natural gas usage in the U.S. has increased dramatically in the past decades, especially in recent years. This change has been driven largely by the energy sector. In 1950, natural gas consumption was about only about 5.97 quadrillion British thermal units (quads) or 18% of total U.S. primary energy consumption. By 2023, the share of energy produced from natural gas had doubled to 36% of total U.S. primary energy consumption, while actual power produced increased to 33.61 quads, a factor of 5.6 [1]. The late-2000s shale gas boom unlocked abundant gas supply and lowered prices, making natural gas a very economical fuel for power generation. Lower gas prices and improved drilling technologies led to record gas production [2], which in turn encouraged utilities and industries to consume more natural gas. In parallel, many aging coal-fired power plants were retired or run at lower levels, and natural gas filled the gap as a cleaner, flexible alternative for generating electricity [1]. Environmental and policy factors (like air pollution regulations and climate goals) also contributed, as combustion of natural gas emits less than half the CO2 of coal per unit of electricity produced [3].

According to the United States Energy Information Administration, the United States consumed 32.50 trillion cubic feet (Tcf) of natural gas in 2023 [4], the equivalent of about 33.61 BTU and about 36% of U.S. total primary energy consumption [1]. There are five primary sectors into which natural gas consumption is divided. These are electric power, industrial, residential, commercial, and transportation. Figure 1 shows the consumption of natural gas for each of these sectors.

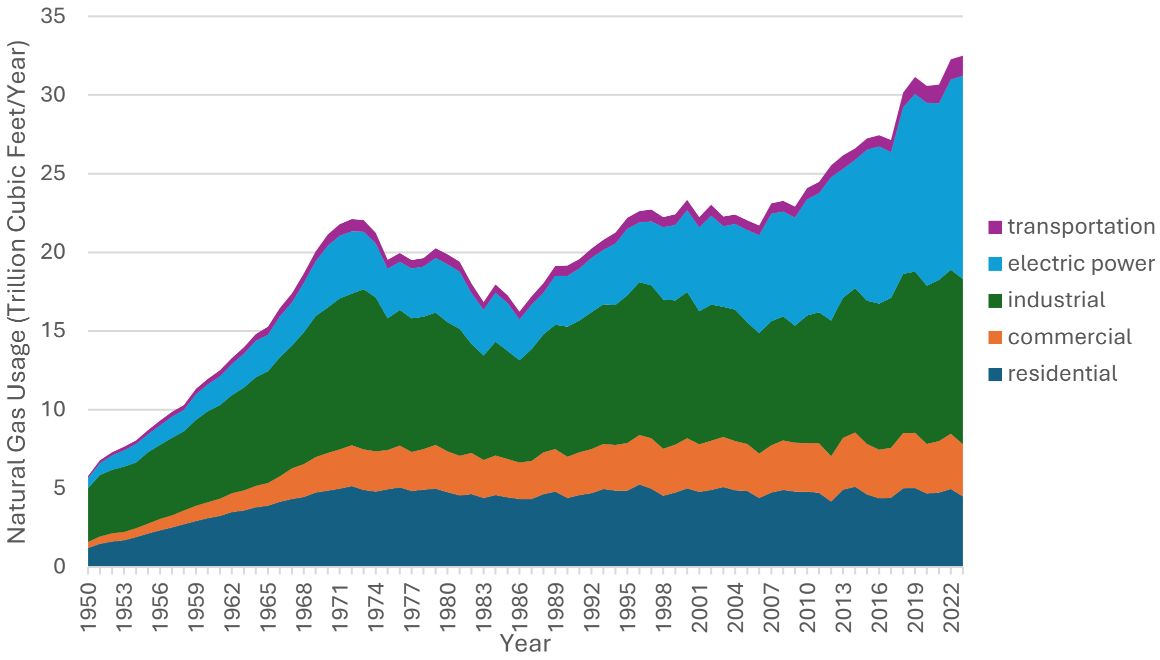


Figure 1: U.S. Natural gas consumption by sector (Stacked plot). Figure reproduced from U.S. E.I.A [4]

The electric power sector uses natural gas to generate electricity and, in some cases, supplies byproduct heat for other processes. In 2023, the electric power sector accounted for about 40% of total U.S. natural gas consumption. [4]

In 2023, the transportation sector accounted for about 4% of total U.S. natural gas consumption. Despite the name implying vehicle consumption, about 96% of the sector's natural gas consumption was to power the compressors that move natural gas through transmission and distribution pipelines. [4] The transportation sector consumed 1.27 Tcf of natural gas in 2023, while only 0.06 Tcf was used to fuel compressed natural gas powered vehicles. [5]

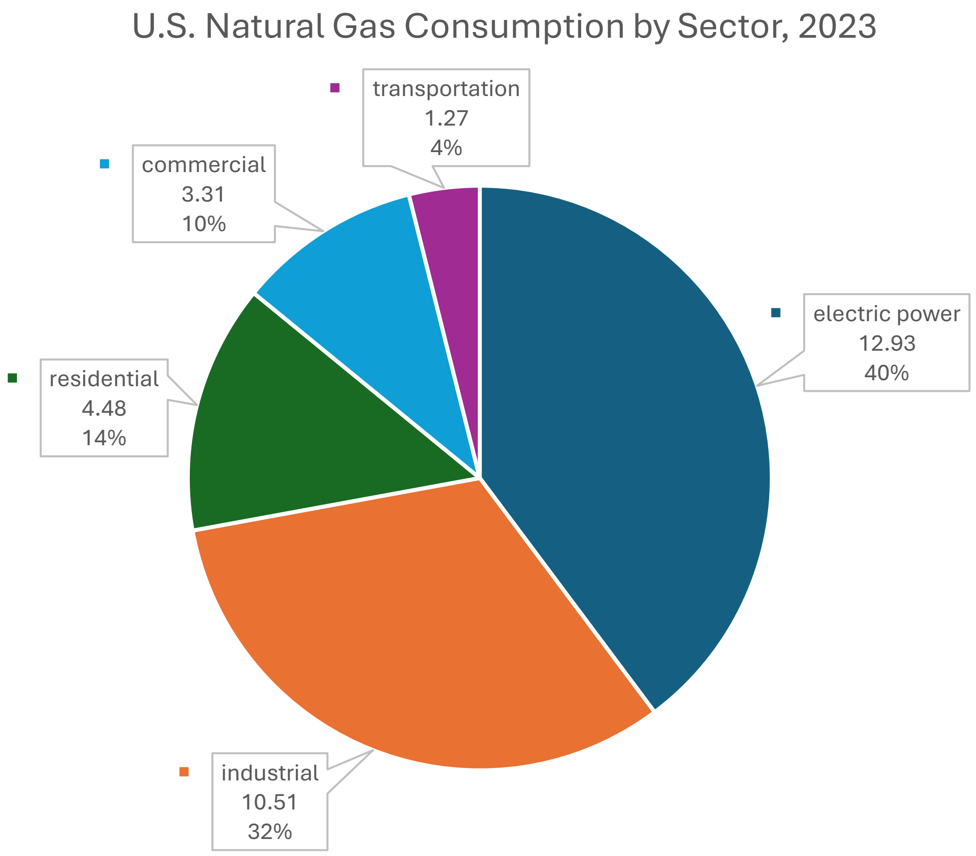


Figure 2: U.S. Natural gas consumption per sector in 2023. Figure reproduced from U.S. E.I.A. [4]

One of the most significant energy trends since the early 2000s has been the rapid displacement of coal by natural gas in electricity generation. In 2000, coal was the dominant fuel, producing approximately one quarter of primary U.S. energy, while natural gas contributed only ~20%. Since then, an aggressive shift has occurred: natural gas generation surged, overtaking coal in 2010, and by 2023, gas accounted for roughly 40% of U.S. generation versus only approximately 11% for coal. At the same time, overall power production within the country has increased significantly, requiring more consumption for the same fraction of production. These changes are shown in Figure 3. [1]

This has been driven by several factors. The increased production of natural gas from shale sources helped to make gas accessible and reduce costs. Natural gas turbines can commonly be used directly to generate power rather than coal which requires complex steam systems. Aeroderivative turbines, as the name implies, are turbines derived from jet engines. These turbines can come in much smaller form factors than heavy frame turbines. The removal of steam systems and the wide range of sizes for gas turbines provide significant convenience for operators. Smaller gas turbines can be ramped easier and with less wear, allowing for simplified load following as compared to a conventional steam turbine. They require less space and design work for installation than coal plants. Multiple smaller units make maintenance possible without requiring contracts to purchase external power. These benefits are in demand at this time, particularly with the current rapid pace of data center construction and expected continued demand for processing.

Of the common power sources, natural gas specifically replaced coal load primarily due to being the simplest solution to cleaner large scale power generation. Integrating large shares of renewable sources can be challenging due to factors such as inconsistent generation and grid stability. Using current technologies, nuclear sources are expensive capital projects which require decades to construct and could not fill the immediate requirement for energy production posed by the wind down of coal. Natural gas on the other hand can be implemented at medium scale by installing an off-the-shelf and largely self-contained system, connecting to a pipeline which is already located nearby for other purposes, and starting operation.

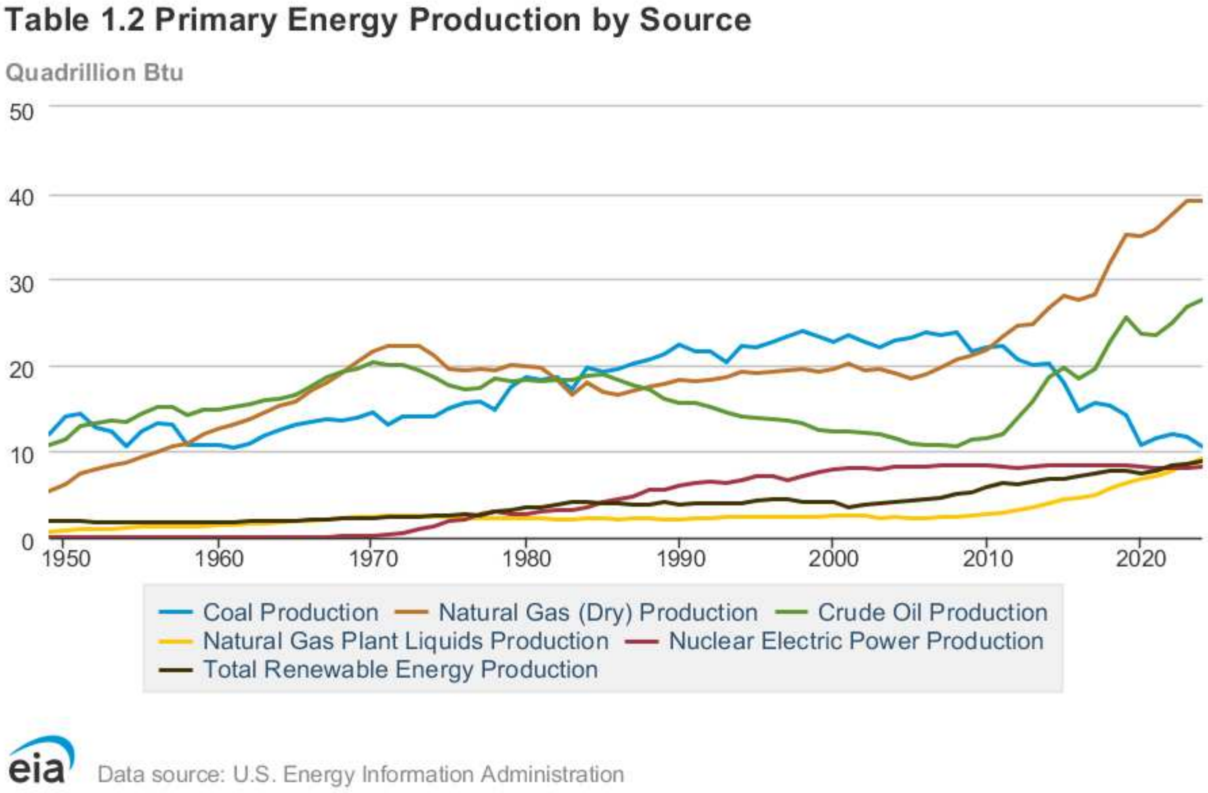


Figure 3: Primary U.S. energy production by source, 1948-2023. Figure taken from U.S. E.I.A. [1]

Since the 1970s, U.S. production of natural gas has largely followed the trend of natural gas usage, as shown in Figure 4. From approximately 1985 to 2017, the production of natural gas was insufficient to keep up with consumption, and the U.S. was a net importer of natural gas. Beginning in the early 2000s, the development of U.S. shale assets led to a significant increase in gas production. In 2000, shale gas accounted for 1.6% of total production. By 2010, this was 23.1% [6]. In 2017, the U.S. became a net exporter of natural gas. The EIA expects natural gas production to remain approximately consistent through to 2050 [7], with internal consumption decreasing slightly and international exports continuing to increase.

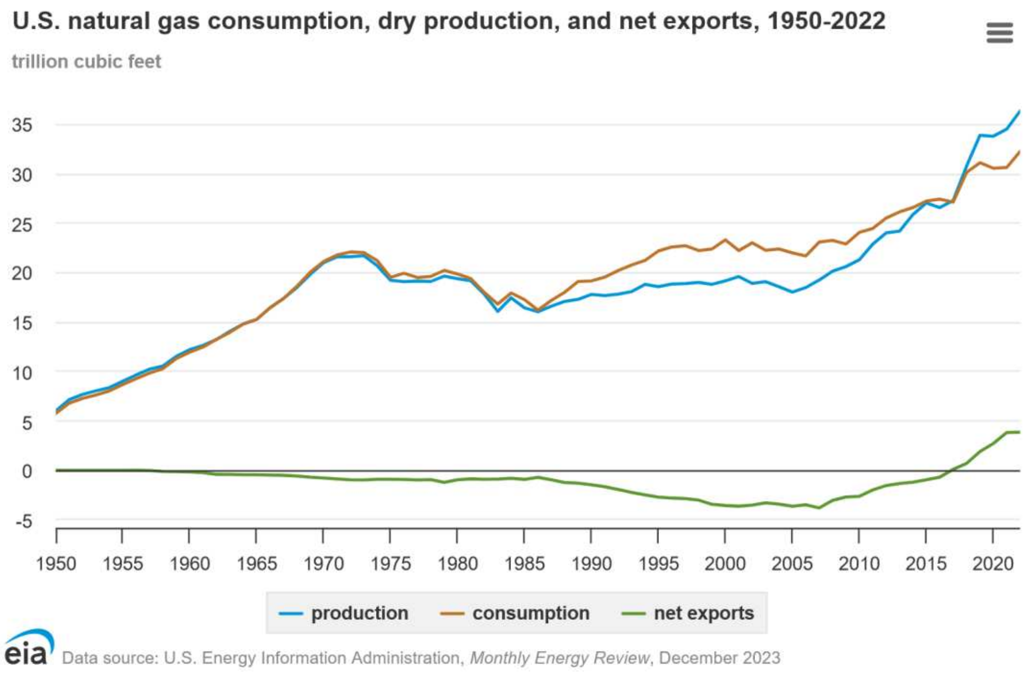
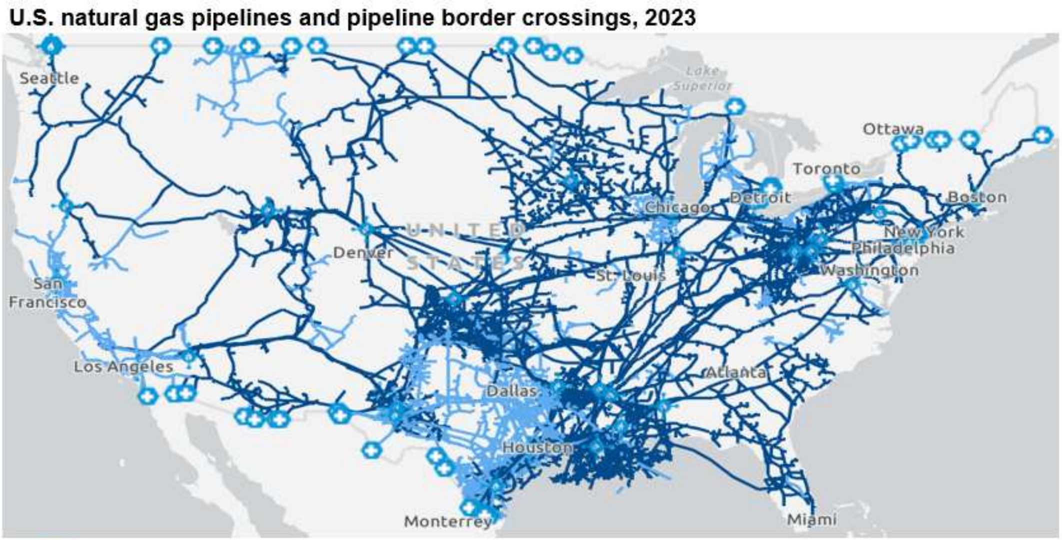


Figure 4: U.S. natural gas consumption, dry production, and net exports 1950-2022. Figure taken from U.S. E.I.A. [2], [7]

1.2 Natural Gas Transport within the United States

Natural gas in the U.S. is delivered through a network of pipelines which span the country, as well as connections to both Canada and Mexico. Almost all gas transported through the country travels through these pipelines. There are approximately 3 million miles of gathering, transmission, and distribution pipelines, [8] shown in Figure 5, which transport gas through the entire process from production to consumer. [9] The first step for these pipelines is gathering, made up of small diameter piping from natural gas wellheads. This gas is pressurized and combined into upstream pipelines which deliver gas to processing plants. These plants remove contaminants, including liquids, dangerous gases such as hydrogen sulfide, and some hydrocarbons heavier than methane. This gas is then safe for transport through large interstate pipelines which transport gas across the country. Finally, the gas is received by a distributor and delivered to customers.


U.S. natural gas pipelines and pipeline border crossings, 2023

Source: U.S. Energy Information Administration, U.S. Energy Atlas, January 29, 2024
Note: Light-blue lines are intrastate pipelines, dark-blue lines are interstate pipelines, and + are border crossings.

Figure 5: Natural gas pipeline within the U.S. Light blue lines represent intrastate pipelines, dark blue lines represent interstate pipelines, and + represent country border crossings. Figure taken from U.S. E.I.A. [9]

The large midstream pipelines responsible for interstate transportation generally operate with a pressure around 1000 pounds per square inch-gauge (PSIG). This pressure allows more gas to be moved within the same pipeline and provides energy required to force gas through the pipeline. This energy is lost as the gas travels, so the pipeline must also be recompressed periodically to compensate for pressure loss, typically around every 100 miles.

Compressor stations are installed at regular intervals along the pipeline. Large compressor units (>1000 hp) at each station boost the gas back to transmission pressure. These compressors are typically driven by industrial engines or gas turbines, although with stricter emissions regulations, they are increasingly driven by electric motors. [10] The driving engines run directly on pipeline gas, providing abundant fuel even in remote locations. This repeated pressurization can deliver gas interstate or across the continent. There are generally two types of compressors which are used to compress this gas.

1.3 Reciprocating Compressors

The more conventional style is a reciprocating compressor. These are relatively low speed devices which are conventionally driven by an internal combustion engine. A cutaway of a reciprocating compressor is shown in Figure 6. On the right side of the figure is the reciprocating compressor piston, which travels in a cast cylinder. Valves above and below the cylinder allow gas to be drawn in, pressurized, and discharged. A piston rod is connected to the left side of the piston. This rod transfers linear force from the crosshead in the center of the image to the piston. To avoid uneven loads and maximize efficiency, these pistons are double acting, so compress gas on both the extension and retraction strokes. The crosshead piston rod design allows the piston rod to travel linearly while the connecting rod (not shown) within the crankcase rotates around the crosshead. The simple linear motion of the piston rod after the crosshead allows the piston rod to be sealed more easily than the connecting rod which both rotates and slides. These seals are referred to as rod packings.

On historic compressors, “packings” were formed by packing material into a “packing box” around the piston rod until it was tight enough to block air. On a modern compressor, these packings are typically made from polymers such as PTFE (Teflon) or PEEK. [11] These materials provide high wear resistance and a low coefficient of friction on the rod. Other materials such as bronze can be used for supporting rings, such as back up rings to support the polymer rings, or bushing rings which help align the piston rod. Harder materials would encourage wear on the piston rod itself, which is a more expensive component that is harder to replace. [11]

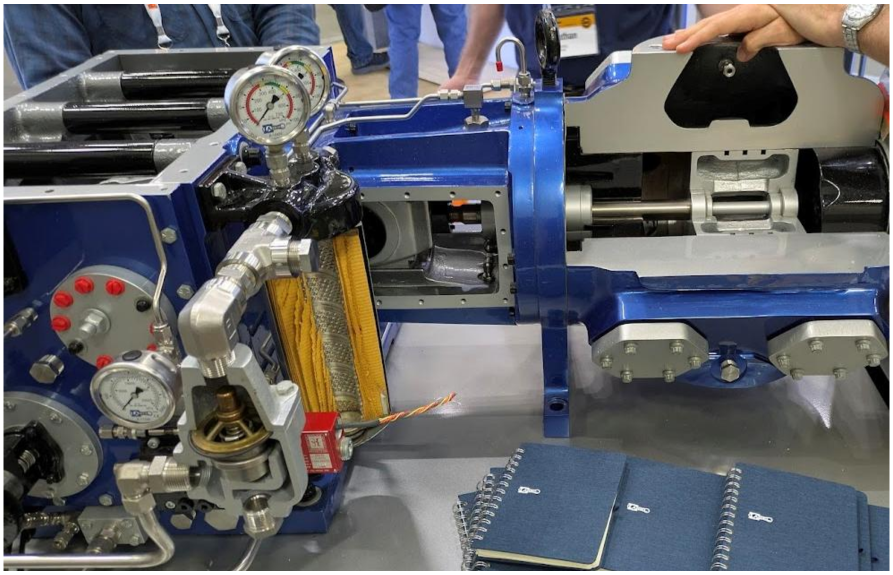


Figure 6: Photo shows a cutaway of a reciprocating natural gas compressor. On the right, the large casting makes up the cylinder, with suction and discharge valves placed on the top and bottom. Within the cylinder is the piston, connected to the piston rod, and then crosshead. The crosshead is attached to a connecting rod (not shown) which travels into the crankcase on the left of the image. Photo taken at 2025 Gas Machinery Conference.

Reciprocating compressors have been installed in the U.S. pipeline system since the 1930's. Many original engines are still in place due to extensive maintenance. Pressure ratios can range from 2 to 4; without accounting for temperature changes, the gas discharged from a cylinder can reach 2 to 4 times the pressure of the gas ingested. High pressure ratios are important in the upstream sector, where low well pressures must be increased to transmit gas. The ability to produce high pressure ratios and operate across a range of engine speeds to match flow conditions makes reciprocating compressors essential equipment in upstream and midstream infrastructure and gas processing facilities.

1.4 Centrifugal Compressors

Centrifugal compressors are a somewhat newer style of compressors which use a series of impellers to pressurize the gas. Gas flows into the device and is ducted towards a rotating impeller, which forces it outwards and into a channel or diaphragm. These diaphragms then direct the gas towards the next impeller. The series of impellers each compress the gas further until reaching the outlet. Figure 7 shows a centrifugal compressor. There are three impellers mounted on a central shaft which act on the gas in series. The diaphragms are built into the inner casing.

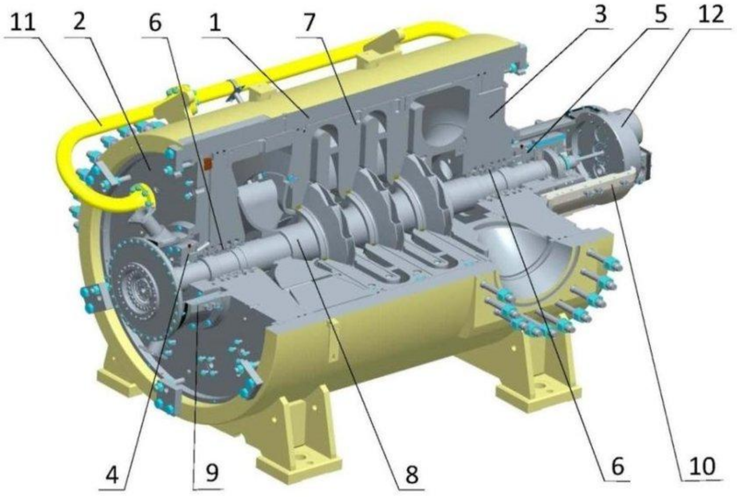


Figure 7: General view of centrifugal compressor: 1 – outer casing; 2 – front cover; 3 – rear cover; 4 – journal bearing; 5 – journal-thrust bearing; 6 – dry gas seal; 7 – inner casing; 8 – rotor; 9, 10 – enclosure; 11 – pipeline; 12 – oil pump. Figure taken from IOP Science. [12]

Centrifugal compressors cannot produce compression ratios as high as a reciprocating compressor; they do not provide positive displacement compression so gas can stall within the compressor rather than pressurize. These are higher speed machines which have come into use coupled to gas turbines. Turbines typically produce much higher speeds and more power than an internal combustion engine. Centrifugal compressors are designed around this higher power which correlates to higher flow per package. These properties make them desirable primarily for the midstream sector, where a compression ratio of two requires substantial power but can increase the pressure by several hundred PSI.

As gas compression systems are designed to both operate on and transport natural gas, these packages are sources of methane emissions.

1.5 Gas Compression Site Leakage

Within a gas compression site, there are many sources for methane emissions. Several sources have been previously targeted by emissions regulations and eliminated but particularly in the case of moving components, some sources can be reduced but not eliminated fully.

Work by CSU's Methane Emissions Technology Center (METEC) lab [13] categorizes these leaks as fugitive gas, maintenance emissions, and vented or combusted gas. The first category, fugitive gas, includes gas which could be eliminated by proper maintenance, modernized systems, or future research. Maintenance emissions are produced whenever a section of pipeline must be taken offline and depressurized. These are known as blowdown operations. If a dedicated system is not available to transfer these gases elsewhere, they are typically released to atmosphere. Depending on the volume of the section, ranging from the volume of an individual compressor to large sections of transmission pipeline, this can account for significant emissions. Finally, vented and combusted gases are those that are emitted by a process which is integral to the design of the system. Driving engine exhaust is the largest source in this category.

The largest source of methane emissions at a natural gas compression site is expected to be combustion slip through the engine – gas which is not burned completely, at an emission factor of 2.32 kg/h/unit. The second largest source per unit are compressor vents which have an expected emissions factor of 1.84 kg/h/unit. [13]

The primary methane emission sources on natural gas compressors are the seals for the moving components. On both types of compressor, these are routed to a vent which the site is expected to route further.

1.6 Rod Packing Leakage

Figure 9 shows a cutaway diagram of a typical reciprocating compressor. The lower half of Figure 9 shows the layout of the pressure packing rod seals. These seals consist of a series of rings placed around the piston rods and contained within packing cups. Packings are considered dynamic seals, as their method of operation requires allowable motion within the packing cups. While the compressor is pressurized, the process gas can flow around the outside of the rings. Each successive packing blocks a portion of the pressure which reaches it. The first packing will see the full pressure of the process gas, but the second will receive a fraction of that and the third a fraction of that. Gas contacting the ring forces the ring against the packing cup axially and onto the rod radially which seals the packings onto the rod. A benefit of this mechanism is that sealing pressure increases proportional to the pressure of the gas within the cylinder. Additionally, compared to a static seal tensioned around the rod, the packing rings are not fixed and can shift inwards or outwards in the radial direction to compensate for thermal expansion, ring wear, or any build up on the rod. As the packings wear, the multiple segments of the rings are allowed to close together, continuing to seal the rod. These seals are designed to travel with the rod in the axial direction to a certain extent, during which motion some gas will escape. This gas is collected in the packing vent line before escaping past the entire stack of packings. Gas leaking past the entire packing is collected in the distance piece, which houses the piston rod. On a traditional compressor setup, both the packing vent and distance piece vents are combined to a single source and disposed of through either flaring or venting.

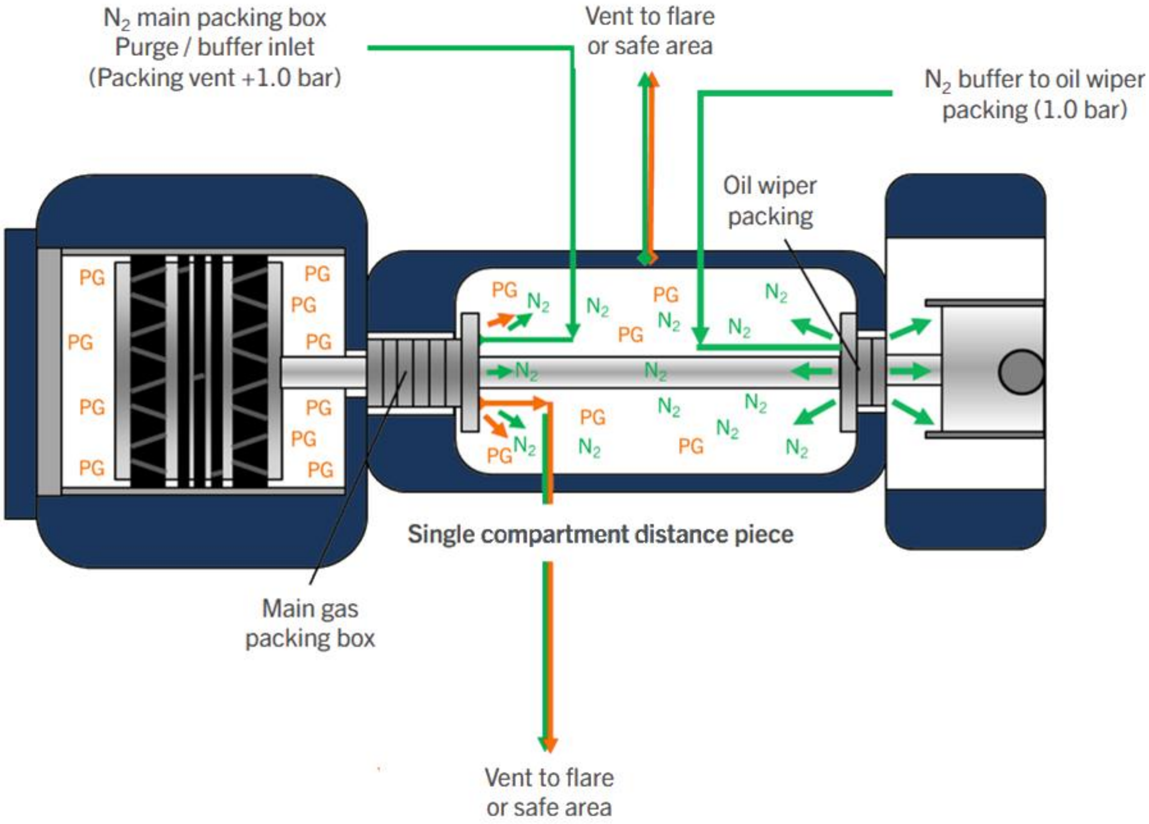


Figure 8: Cutaway diagram of a reciprocating natural gas compressor indicating gas venting. Process gas labeled as PG, atmospheric and purge gas labeled as N_2. Figure taken from Hoerbiger. [11]

Venting this gas in multiple stages as it passes through the packings, distance piece, and crankcase, is required to minimize pressure in the distance piece and then compressor crankcase. Process gas in the crankcase may form a combustible mixture, damage components, or dissolve into the oil, reducing lubricity. Figure 8 shows the expected gas composition within a compressor throw. [11]

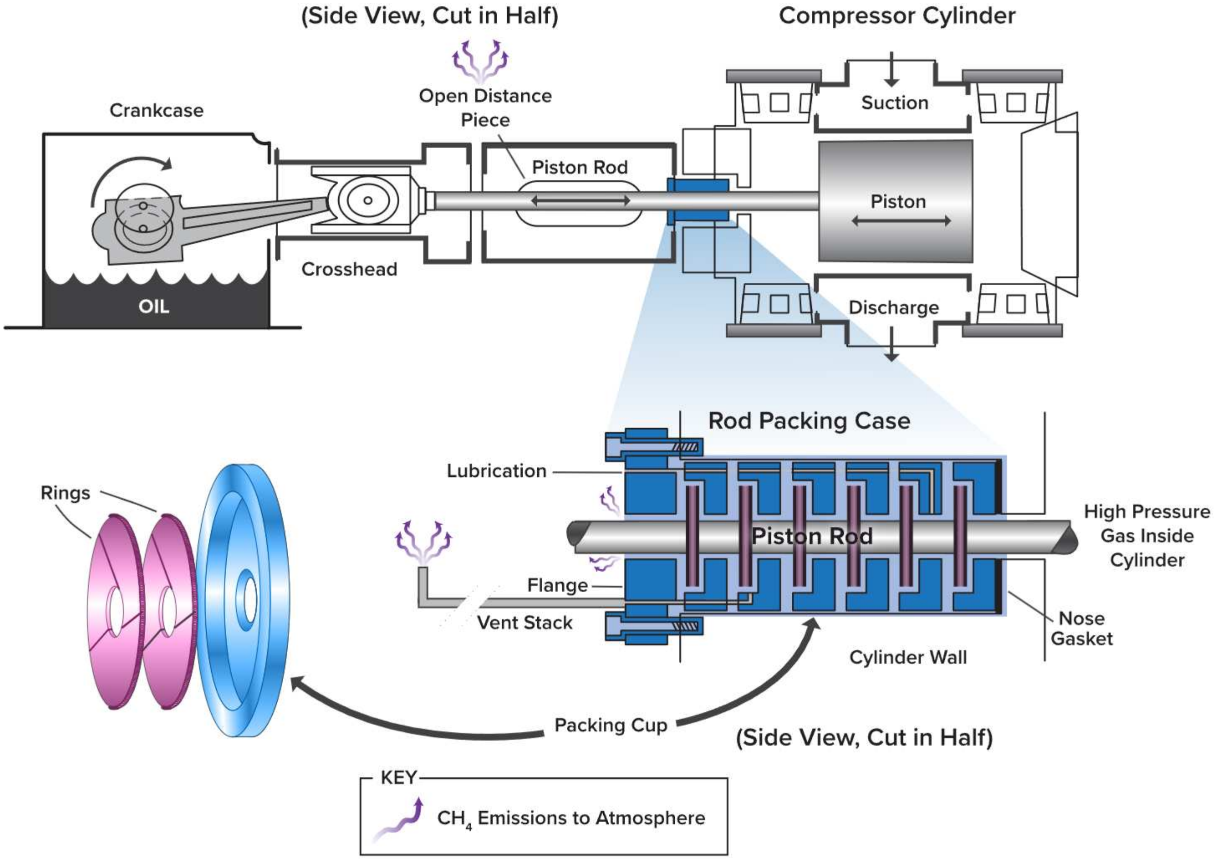


Figure 9: Cutaway of reciprocating compressor cylinder with magnified view of rod packing. Figure taken from U.S. E.P.A. [14]

1.7 Gas Seal Leakage

The sealed motion components on a centrifugal compressor are rotating elements instead of sliding elements. Therefore, they have different seals. These are referred to as wet or dry gas seals, depending on whether the seal uses oil or gas, respectively, to block process gas from leaking. A diagram of a wet gas seal is shown below in Figure 10. The process gas contacts the seal on the right side and flows through a series of baffles, referred to as labyrinth seals, which are designed to prevent any straight flow path, progressively reducing pressure in the process gas. After these seals, the primary seal consists of oil forced into a chamber. Gas reaching this point is entrained into the oil, which is then removed from the seal and delivered to degassing and then storage tanks, where it can be recirculated back into the seal. Gas from the degassing tank is sent to the site vent and flared or vented as with the packing vents.

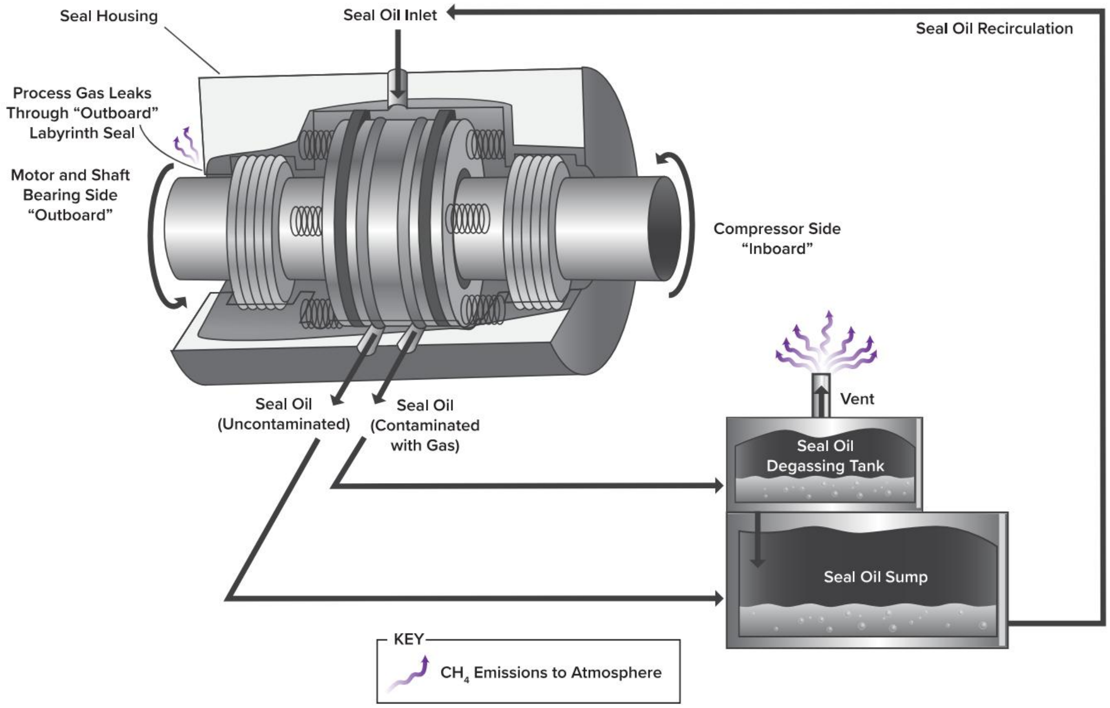


Figure 10: Wet gas seal cutaway diagram. Figure taken from U.S. E.P.A. [15]

Dry gas seals, shown in Figure 11, are a more recent development and instead rely on a film of gas captured between two rings. The rings are pressed together with springs, and one rotates with the shaft while the other remains stationary, pressurizing gas between them into a hydrodynamic layer. This gas is typically trapped using microscopic texturing on the face of the rings, which provides space for the gas between the rings when the compressor is shut down. During startup, trapped gas is forced outwards due to shear forces from the close counterrotating faces, creating a high-pressure region within the seal. Pressure within this region counteracts the pressure of the process gas, preventing it from leaking past the seal.

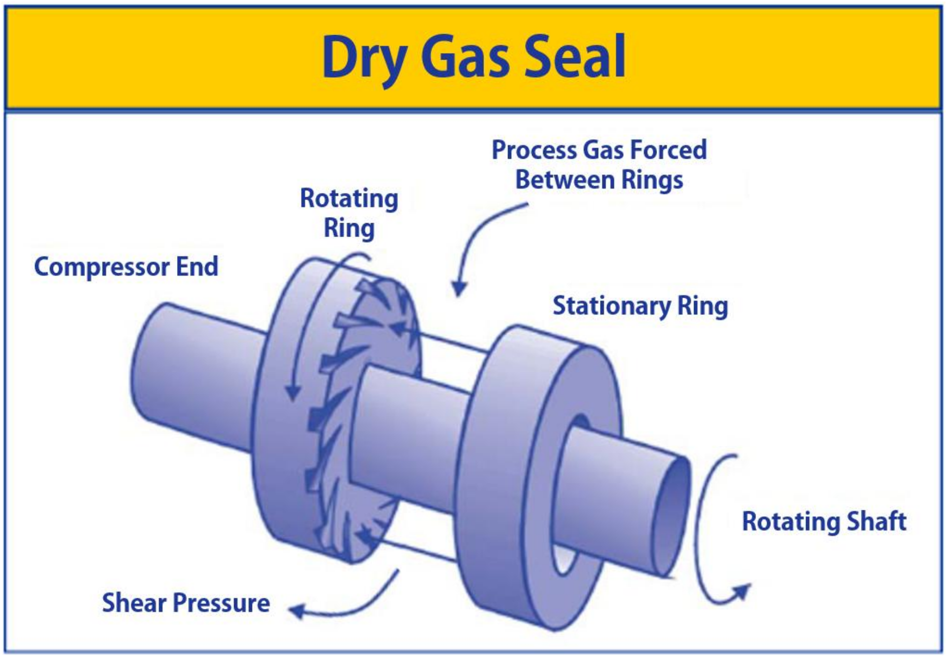


Figure 11: Dry gas seal diagram. Figure reproduced from U.S. E.P.A. [16]

1.8 Emissions Regulations

Across the United States, federal and state air programs have tightened requirements for combustion sources in the natural-gas sector. These focus on pollutants with the largest public health or climate impacts. Some common targets include nitrogen oxides, carbon dioxide, and methane.

Nitrogen oxides (NO_x) are targeted because they are a precursor to ground-level ozone generation and form nitric acid in the presence of water, causing acid rain. Both byproducts of NO_x reactions and the gases themselves are linked to respiratory and cardiovascular harm, so regulators have enforced lower allowable NO_x emissions from engines. [17]

Carbon dioxide (CO_2) is regulated as the primary long-lived greenhouse gas from fuel combustion. Greenhouse gases absorb heat which would transmit out through the atmosphere and radiate some back to the Earth's surface. Figure 12 shows that CO_2 is the primary influence on atmospheric warming. This is largely due to the long duration which

CO_2 can remain in the atmosphere, increasing in concentration since the industrial revolution.

Methane (CH_4) is important as a short-lived but highly potent greenhouse gas and a contributor to ozone formation. In gas operations, significant CH_4 can come from process gas leak sources. Methane does not remain in the atmosphere as long as CO_2 but over a short timeframe can produce a warming potential 28 times higher [18].

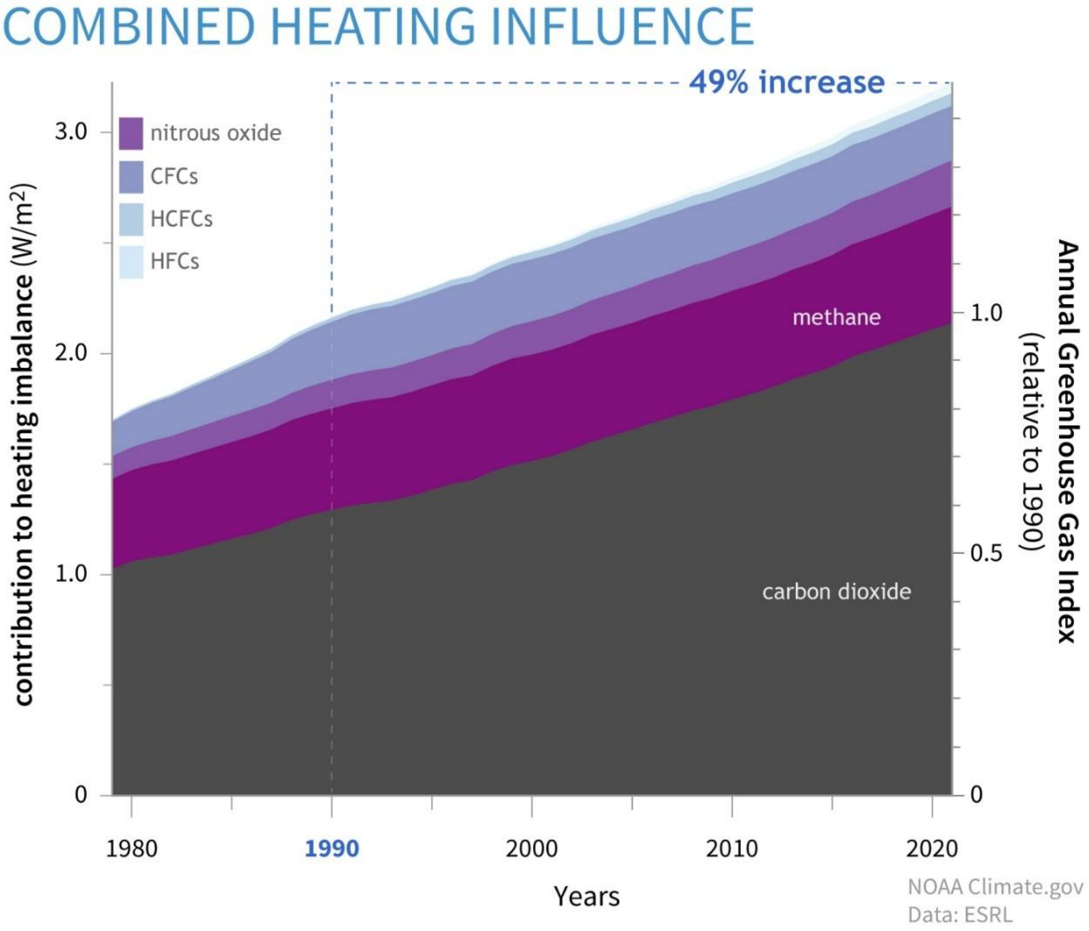


Figure 12: This graph shows the heating influence caused by the major human-produced greenhouse gases: carbon dioxide (gray), methane (dark purple), nitrous oxide (medium purple), chlorofluorocarbons (CFCs, lavender), hydrochlorofluorocarbons (HCFCs, blue), and hydrofluorocarbons (HFCs, light blue). Relative to conditions in 1750, today's atmosphere absorbs more than 3 extra watts of energy per square meter of Earth's surface. Graph by NOAA Climate.gov

based on data from NOAA Global Monitoring Lab. For the complete list of chemicals in the CFC, HFC, and HCFC groups, see Figure 3 in the Full AGGI Report. Figure taken from NOAA Climate.gov based on data from NOAA ESRL. [19]

Recent policy trends have shifted from general leak management to specific quantified results. As standards continue to tighten, operators are increasingly expected to provide evidence that emissions reduction solutions achieve quantifiable reductions. Methane emissions from natural gas compressor stations represent a significant source of greenhouse gases emitted in the oil and gas sector, attracting increased scrutiny from the Environmental Protection Agency (EPA) and the public. In particular, the Inflation Reduction Act (IRA) of 2022 introduced substantial financial penalties for methane emissions that exceed defined thresholds, motivating operators to implement cost-effective mitigation strategies.

1.9 Packing Vent Handling

Among the various contributors to facility-wide methane emissions, vented gases from compressor rod-packings represent one of the few remaining large emissions sources that are isolated from engine combustion mechanics. The vents on a reciprocating compressor are typically broken into three components. These are the distance piece vent and drain, as well as the packing vent.

The packing vent/drain is the primary source of gas as it collects gas and lubricants within the packing itself. After this, the distance piece vent collects gas that leaks past the entire packing. Finally, the distance piece drain is designed to capture any oil which leaks from the packing lubrication system. This is not designed as a vent but will allow a small amount of gas flow. On a conventional package, the packing vent and distance piece vent may be combined to a single line of sufficient size. Due to low pressures and high concentrations of oil, the distance piece drain must be routed separately until it reaches an oil tank.

Generally, this means that a site will merge the distance piece vents and packing vents from a single compressor into one line a short distance from the compressor. This line will run in parallel with the distance piece drain lines until they reach an oil separation tank. Other methane sources will also be routed to this tank. From this tank, one large line will exit and connect to either a package vent or sitewide flare. A package vent is typically formed from a short pipe run (which minimizes pressure loss) that exits the package high enough to disperse the gas. Flares, which are usually site wide, can include air or gas assist components which are used to ensure negative pressure within the line and encourage complete combustion.

These vents are usually a significant source of methane as they combine many leak sources to a single point. In targeting emissions reductions, this can be a desirable trait and presents an opportunity for emissions reduction through gas capture. The simplest of these capture options is a system which collects the vent gas and recirculates it through to the engine intake. Both the gas released from the compressor vents and the engine’s fuel gas come directly from the pipeline. This means that the vent gas, if delivered to the engine’s fuel system, should be able to directly offset the pipeline gas which would be used otherwise.

CHAPTER 2 – LITERATURE REVIEW

2.1 Emissions Regulations

2.1.1 EPA Classification

For these systems to be accepted for future site permitting, there are two EPA classifications under OOOO which these systems could be considered: emission "control" or "route to process" [20], [21], [22]. This paper aims to provide evidence that recirculating the gas back to the driving engine is a "route to process" strategy, as the recirculated gas directly offsets the engine's primary fuel flow (i.e., the engine does not run richer, as the control system automatically reduces the primary fuel flow as the compressor vent gas is introduced).

Under EPA regulation, the "control" classification applies to a system that reduces methane release into the atmosphere. This often involves the destruction of methane through combustion (i.e., flaring). Common controls include flares and catalysts. When methane undergoes combustion, it is converted primarily to carbon dioxide (CO_2) and water, dramatically cutting the GHG potential. Methane (CH4) is a potent greenhouse gas (GHG) capable of trapping heat 28-36 times more effectively than CO2 in a period of 100 years [18]. These systems are governed by 40 CFR 60.5412. Per this statute, a control device is required to operate at all times while gas is vented and must maintain 95% volatile organic compounds (VOC) destruction. [22]

By contrast, the "route to a process" classification applies to technologies wherein the methane is not emitted or destroyed but recovered for the productive and original use of the gas. From 40 CFR 60.5430, "Routed to a process or route to a process means the emissions are conveyed via a closed vent system to any enclosed portion of a process where the emissions are predominantly recycled and/or consumed in the same manner as a material that fulfills the same function in the process and/or transformed by chemical reaction into materials that are not regulated materials and/or incorporated into a product; and/or recovered." [22] This means that the emissions must remain within the system they are lost from and be treated in the same manner as the original product, so cannot be utilized for another purpose (e.g., as fuel for an on-site boiler). With rod packing recirculation and recompression systems, the system bounds are drawn at the individual package level, allowing the engine to serve as the destination for compressor emissions and still maintain the route to process designation. A system designed to operate under route to process must maintain a 95% uptime during the year as per 40 CFR 60.5411 [22]. Importantly, when emissions are returned to process, they cease to be "waste", and the methane is treated as a product, thereby reducing reporting requirements.

The key distinction is that control typically involves treating or destroying methane emissions, whereas route to process involves capturing methane for use. Both approaches serve to prevent uncontrolled venting, but their outcomes differ: a control primarily serves to reduce methane to a less harmful form, while route to process preserves the methane as a resource. The two categorizations also differ in their required uptime. A control device must operate continuously whenever the system is emitting, including during all operating modes [21]. In contrast, a route-to-process system operating at 95% uptime is permitted up to 438 hours of downtime per year [22], which may include periods such as engine idle, when recirculating gas to the engine could be undesirable.

2.1.2 Waste Emissions Charge

The Inflation Reduction Act, passed in 2022, directed the Environmental Protection Agency to introduce a charge per ton of methane equivalent emissions. For boosting stations, this charge is applied to any losses above 0.05% of delivered gas [23]. After this limit, any gas released is charged at an increasing rate each year from $900 in 2024 until the final pricing of $1,500 per ton in 2026 as shown in Table I[23]. At this rate, a site already at the 0.05% threshold would be charged $95,000 yearly for a 6-throw compressor venting 1 SCFM of gas per throw, using listing B1 in appendix B, despite being below the mandatory replacement threshold.

Although the Inflation Reduction Act established a federally mandated methane emissions charge through Section 136 of the Clean Air Act, the EPA's implementing rule, the Waste Emissions Charge (WEC), was revoked by Congress in May 2025 using the Congressional Review Act. As a result, the regulatory framework enabling collection and enforcement of the charge has been dismantled, leaving the statutory mandate intact but unenforceable. This creates legal uncertainty: the EPA is required by law to impose a methane charge but is barred from issuing a new rule in similar form unless reauthorized by Congress [24]. For operators, this means methane charges under the IRA are suspended, though the underlying law still exists. Any future work on engine packages will need to be evaluated with this regulatory limbo in mind, as a reinstatement or reauthorization could resurrect enforcement at the post 2026 rate with minimal advance notice.

Table I: Waste methane emissions charges established by the Inflation Reduction Act of 2022. Table reproduced from U.S. Congressional Review Service. [23]

Methane Charge Measure	2024	2025	2026	After 2026
Dollars per metric ton of CH_4 emissions	$900	$1,200	$1,500	$1,500
Dollars per metric ton of CO_2 emissions	$32	$43	$54	$54

2.1.3 40 CFR Part 60 OOOO

The U.S. Environmental Protection Agency's 40 CFR Part 60 Subpart OOOO series, commonly known as the "Quad O" regulations, comprises a sequence of New Source Performance Standards (NSPS) and emission guidelines targeting air emissions from the oil and natural gas industry. These rules were developed in stages (2012, 2016, and 2023) to address pollutants such as volatile organic compounds (VOCs), methane (CH_4), and sulfur dioxide (SO_2) from various sources in the crude oil and natural gas sector. Each subpart (OOOO, OOOOa, OOOOb, and OOOOc) corresponds to a tighter regulatory update, progressively strengthening emission controls on the oil and gas industry. Below is an overview of each subpart's sources and segments regulated, and a comparison of requirements and emission standards introduced in each rule.

2.1.3.1 OOOOa

In June 2016, EPA finalized Subpart OOOOa as an update to the NSPS, expanding the regulation's scope to include methane as a targeted pollutant and to cover additional sources and segments. [25] "The regulation mandates regular leak detection and repair (LDAR), comprehensive reporting, and compliance with strict emission standards for various components, including storage vessels, compressors, and pneumatic controllers." [26]

The final rule established, among other things, methane and VOC standards for emission sources and equipment in the transmission and storage segments of oil and

> gas systems not regulated under the 2012 Rule, including hydraulically fractured oil well completions, pneumatic pumps, and fugitive emissions from well sites and compressor stations; and methane standards for hydraulically fractured gas well completions and equipment leaks at natural gas processing plants that are currently regulated under the 2012 Rule for VOCs, but not for methane emissions.
>
> The final rule took effect on August 2, 2016 for new sources that were constructed, modified, or reconstructed after September 18, 2015 and that are subject to the rule. EPA noted that sources complying with the 2012 Rule likely would not be required to install additional controls for methane, as VOC controls also curb methane emissions for those sources. [27]

As per 40 CFR 60.5385(a)(1) [28], packings must be replaced before 26,000 hours (2.96 years) of operation, or per 40 CFR 60.5385(a)(2) [28], 36 months (3 years) from the date of installation. As well, per 40 CFR 60.5385b(a)(3) [28], packings must be replaced within 90 days of any packing vent rate measurement above 2 SCFM or above an average of 2 SCFM per packing if multiple packings are manifolded together. In summary, packings will be replaced 3 years from installation or 90 days from a vent measured above 2 SCFM. Packings are expected to reach the 2 SCFM rate at approximately the 3-year limit.

2.1.3.2 EPA 2020 Technical Rule

In September 2020, the EPA issued its final 2020 Technical Rule which amends OOOOa and revised the certification process for closed vent systems. This rule came into effect on November 16, 2020. It updates definitions of a closed vent system and provides an updated certification process for closed vent systems. This updated process focuses on self-certification rather than application to the EPA. This rule defines the current regulations and definitions for closed vent systems for all future subparts (OOOOa, OOOOb, OOOOc).

The following excerpt includes relevant content from 40 CFR Part 60 OOOOa with updates merged from the 2020 Technical Rule.

> ‘What additional requirements must I meet to determine initial compliance for my covers and closed vent systems routing emissions from centrifugal compressor wet seal

fluid degassing systems, reciprocating compressors, pneumatic pumps and storage vessels?’

You must meet the applicable requirements of this section for each cover and closed vent system used to comply with the emission standards for your centrifugal compressor wet seal degassing systems, reciprocating compressors, pneumatic pumps, and storage vessels.

(a) Closed vent system requirements for reciprocating compressors and centrifugal compressor wet seal degassing systems.

(1) You must design the closed vent system to route all gases, vapors, and fumes emitted from the reciprocating compressor rod packing emissions collection system to a process. You must design the closed vent system to route all gases, vapors, and fumes emitted from the centrifugal compressor wet seal fluid degassing system to a process or a control device that meets the requirements specified in § 60.5412a(a) through (c).

(2) You must design and operate the closed vent system with no detectable emissions as demonstrated by § 60.5416a(b).

(3) You must meet the requirements specified in paragraphs (a)(3)(i) and (ii) of this section if the closed vent system contains one or more bypass devices that could be used to divert all or a portion of the gases, vapors, or fumes from entering the control device.

(i) (A) You must properly install, calibrate, maintain, and operate a flow indicator at the inlet to the bypass device that could divert the stream away from the control device or process to the atmosphere that is capable of taking periodic readings as specified in § 60.5416a(a)(4)(i) and sounds an alarm, or initiates notification via remote alarm to the nearest field office, when the bypass device is open such that the stream is being, or could be, diverted away from the control device or process to the atmosphere. You must maintain records of each time the alarm is activated according to § 60.5420a(c)(8).

(B) You must secure the bypass device valve installed at the inlet to the bypass device in the non-diverting position using a car-seal or a lock-and-key type configuration.

(c)

(1) You must design the closed vent system to route all gases, vapors, and fumes emitted from the material in the storage vessel affected facility to a control device that meets the requirements specified in § 60.5412a(c) and (d), or to a process.

(2) You must design and operate a closed vent system with no detectable emissions, as determined using olfactory, visual, and auditory inspections or optical gas imaging inspections as specified in § 60.5416a(c).

(d)

(1) You must conduct an assessment that the closed vent system is of sufficient design and capacity to ensure that all emissions from the affected facility are routed to the control device and that the control device is of sufficient design and capacity to accommodate all emissions from the affected facility, and have it certified by a qualified professional engineer or an in-house engineer with expertise on the design and operation of the closed vent system in accordance with paragraphs (d)(1)(i) and (ii) of this section.

> (i) You must provide the following certification, signed and dated by a qualified professional engineer or an in-house engineer: “I certify that the closed vent system design and capacity assessment was prepared under my direction or supervision. I further certify that the closed vent system design and capacity assessment was conducted and this report was prepared pursuant to the requirements of subpart OOOOa of 40 CFR part 60. Based on my professional knowledge and experience, and inquiry of personnel involved in the assessment, the certification submitted herein is true, accurate, and complete.”
>
> (ii) The assessment shall be prepared under the direction or supervision of a qualified professional engineer or an in-house engineer who signs the certification in paragraph (d)(1)(i) of this section. [25] [29]

2.1.3.3 OOOOb

Subpart OOOOb is the next-generation NSPS for new and modified oil and gas sources, developed under the Biden Administration as part of a major climate initiative to cut methane emissions. Like its predecessors, subpart OOOOb governs new, modified, or reconstructed sources in the oil and natural gas field. However, it is the first of the subparts to also target existing emissions sources [20] in the form of prohibitions on gas flaring and pneumatic valve emissions. It retains all the source types regulated under OOOOa: well completions, compressors, pneumatics, storage tanks, equipment leaks, etc., while introducing more stringent emission standards and practices to drive further methane and VOC reductions. This rule also increases the frequency of leak monitoring enacted by OOOOa. [26] The rule explicitly aims to “sharply reduce emissions of methane and other harmful air pollution from oil and natural gas operations”, estimating a reduction of 58 million tons of methane emissions from 2024 to 2038 [30]. This is an approximately 80% reduction in methane from regulated sources relative to projections without rule implementation. [30] [20]

2.1.3.4 OOOOc

Subpart OOOOc, often called “Quad Oc,” was introduced in the same December 2023 rulemaking as Quad Ob. However, unlike the previous subparts, OOOOc is not an NSPS for new sources; rather, it establishes emissions guidelines and compliance schedules for existing oil and natural gas facilities. NSPS rules like OOOO, OOOOa, OOOOb apply directly at the federal level to only new or modified equipment, whereas an emission guideline serves as a target for states to implement standards on existing equipment that was built before the new-source cutoff. Subpart OOOOc thus represents the first time EPA has set nationwide methane controls for the vast fleet of existing oil and gas infrastructure that predates the OOOO rules. This is a critical component of EPA’s methane strategy, since existing wells, pipelines, compressors, and tanks account for a large share of industry emissions.

2.1.3.5 OOOO Summary

OOOO regulations build off one another, adding additional constraints per subpart.

All OOOO subparts are currently under reconsideration by the EPA.

- Subpart OOOO (Quad O):
    - New, modified or reconstructed sources after August 23, 2011 but on or before September 18, 2015
    - Targets VOCs
- Subpart OOOOa (Quad Oa):
    - New, modified or reconstructed sources after September 18, 2015 but on or before November 15, 2021
    - Additionally targets methane

    - Packings must be replaced after 36 months of installation, 26,000 hours of operation, or 90 days of detected leaks above 2 SCFM, whichever comes first.
- Subpart OOOOb (Quad Ob):
    - New, modified or reconstructed after December 6, 2022
- Subpart OOOOc (Quad Oc):
    - Existing sources, including sources that commenced construction, reconstruction or modification before December 6, 2022

[31]

2.1.4 Colorado Regulation 7

Colorado has committed to reducing its greenhouse gas emissions to 26 percent below 2005 levels by 2025, 50 percent below 2005 levels by 2030, and 90 percent below 2005 levels by 2050 [32]. Senate Bill 19-181 specifically targets natural gas loss through flaring or venting. The state endorsed the World Bank's Zero Routine Flaring by 2030 initiative in early 2021 [32].

These goals have been implemented in the form of Colorado's Air Quality Control Commission (AQCC) Regulations. The primary regulation which adds requirements to federal regulations is Regulation Number 7, "Control of Ozone via Ozone Precursors and Control of Hydrocarbons via Oil and Gas Emissions." This regulation regulates NO_x and VOC emissions to tighter standards than federal regulations. The primary concern for operators affected by this regulation is the control of NO_x emissions. It is often easy to reduce methane emissions at the expense of increased NO_x, so this regulation forces operators to reduce both below strict limits.

All gas sources, regardless of category, are covered by the limits provided here, as compared to OOOO which defines specific sources and their regulations, which can provide room for alternative interpretations of sources.

For the remainder of this document, ‘packing leakage’ and ‘packing vent gas’ will be used interchangeably. This is at odds with the Regulation Number 7 definition, which states that “In contrast with venting, leaking as used in Section XVII.F. more specifically relates to unintended emissions from components at well production facilities and natural gas

Non-Compressor Service

Component	Number Measured	Number Simulated	Emission Factor (scfh whole gas)	Confidence Interval (scfh whole gas)	Fraction of Emissions Due to Largest 5% of Emitters
Connector Flanged	31	1	7.88	[+42%/-36%]	18%
Connector Threaded	82	0	5.77	[+31%/-28%]	25%
PRV	23	0	10.8	[+123%/-80%]	54%
Regulator	43	0	8.01	[+33%/-30%]	18%
Valve	99	0	7.89	[+46%/-37%]	38%

Compressor Service

Component	Number Measured	Number Simulated	Emission Factor (scfh whole gas)	Confidence Interval (scfh whole gas)	Fraction of Emissions Due to Largest 5% of Emitters
Connector Flanged	41	1	12.2	[+57%/-40%]	33%
Connector Threaded	107	5	14.5	[+52%/-38%]	47%
PRV	35	1	21.2	[+82%/-57%]	43%
Regulator	37	0	13.9	[+38%/-32%]	21%
Valve	39	1	41.1	[+109%/-64%]	58%
Common Multi-Unit Vent	13	0	66	[+86%/-71%]	
Common Single-Unit Vent	23	0	76	[+52%/-45%]	20%
Blowdown Vent	30	1	21.3	[+150%/-70%]	59%
Pocket Vent	23	0	7.81	[+80%/-61%]	34%
Rod Packing Vent	390	7	28.2	[+37%/-24%]	46%
Starter Vent	21	0	296	[+193%/-96%]	86%
Rod Packing Vent (OP)	366	7	28.5	[+35%/-24%]	47%
Rod Packing Vent (NOP)	17	0	23	[+65%/-49%]	
Rod Packing Vent (NOD)	7	0	11.5	[+42%/-37%]	

Tank Service

Component	Number Measured	Number Simulated	Emission Factor (scfh whole gas)	Confidence Interval (scfh whole gas)	Fraction of Emissions Due to Largest 5% of Emitters

Common Multi-Unit Vent	15	0	119	[+90%/-68%]	
Common Single-Unit Vent	42	2	48.4	[+86%/-58%]	45%
Thief Hatch	65	0	30.1	[+54%/-41%]	41%
Other					
Component	**Number Measured**	**Number Simulated**	**Emission Factor (scfh whole gas)**	**Confidence Interval (scfh whole gas)**	**Fraction of Emissions Due to Largest 5% of Emitters**
OEL	23	0	5.58	[+67%/-51%]	31%
Other	42	1	24	[+67%/-49%]	44%
Pump	12	2	35.5	[+74%/-53%]	

compressor stations.” [33] In the case of rod packing gas, the vent gas is from a leak source, but is by this strict definition, intentional design, and therefore not a leak.

2.2 Packing Leakage

As the packings consist of a series of dynamic seals, they are designed to pass a small, continuous flow during operation. Any capture or recirculation system must therefore be sized for a range of leakage rather than a single nominal value. To establish that envelope, the next section reviews packing-leakage literature.

For operators, packing vent measurements are typically conducted once a year to fulfill Greenhouse Gas Reporting Program requirements, during which a team will visit each site to take required measurements. The operator must immediately report any problem detected by emissions measurements and is given 90 days to remedy the issue. Given this 90-day policy, there is some incentive for operators to take flow measurements as sparsely as possible to avoid the possibility of measurements outside of allowed limits. Additionally, flow meters can be quite expensive, especially considering that a compressor has many different vent lines. A common method to ensure that the operator can detect important changes in flow is to measure the temperature of packing vent gases. An RTD or thermocouple is significantly less expensive and provides enough data to determine if a packing is blown. As gas within the compressor is compressed, the temperature increases. Higher flows of packing vent gas will likewise increase the temperature within the vent lines. Due to the complexity of external conditions, this measurement does not provide a high fidelity flow measurement, but detecting changes in temperature provides a cost effective indicator of packing failure. For a variety of reasons, true flow measurements have been conducted and published for many different compressors. There are some jurisdictions which require continuous measurement, as well as both operators and suppliers conducting measurements to evaluate new technologies. A sample of these are reported below.

According to Ariel Corporation documentation, rod packings after break-in are expected to leak between 5-10 SCFH, which correlates to approximately 0.1-0.2 SCFM. The leakage rate observed from packings before the break in period will be higher. As the packings break in, they will form more tightly against the packing rod, reducing leakage.

This break in effect occurs while the compressor is in operation. When the compressor is shut down, the dissimilar materials of the piston rod and packing contract at different rates and the rings cannot seal as well. This leads to increased leakage during compressor shutdown. For operators, this leakage rate can become significant enough to encourage compressor blowdown after less than an hour of pressurized hold.

Purged packings are available, which introduce a continuous flow of inert gas, typically site nitrogen, to prevent process gas from reaching the distance piece. This can be beneficial when operating with “sour” or “acid” upstream gas. “Ariel requires the use of “Purge packing” for sour gas services with 100 ppm and greater H_2S content.” [34] Sour gas is any gas with high quantities of hydrogen sulfide (H_2S). [35] Hydrogen sulfide gas readily reacts with water to form sulfuric acid [36] which can be damaging to packings and componentry within the distance piece. “The purpose of purge gas is to block and contain hazardous, toxic, flammable or corrosive gases, and to prevent such from entering the compressor frame where damage to the running gear, or personnel safety hazards can occur.” [34] Gas with high quantities of H_2S is also considered to be acid gas, but this category is defined by direct acidity of the gas and not the possible byproducts so also includes gas with high CO_2 or other acidic constituents. [37] These purged packings force extra gas into the later stages of the packing seals, which increases pressure and therefore leakage. The total leakage on a purged packing is stated as 8-13 SCFH through the packing vent and an additional 3-5 SCFH of purge gas entering the distance piece. Figure 13 and Figure 14 show a purged packing arrangement. As compared to Figure 6, the distance piece on this compressor has two compartments. The compartment closer to the packing includes a line coming in from the top of the compressor to deliver the purge gas to the packing. Between the two compartments is an additional series of packing which isolates the purge and process gas from the second section through a first distance piece vent. This second compartment then houses another distance piece vent before getting to the third set of packings, which is an oil wiper packing to prevent carryover to the crosshead.

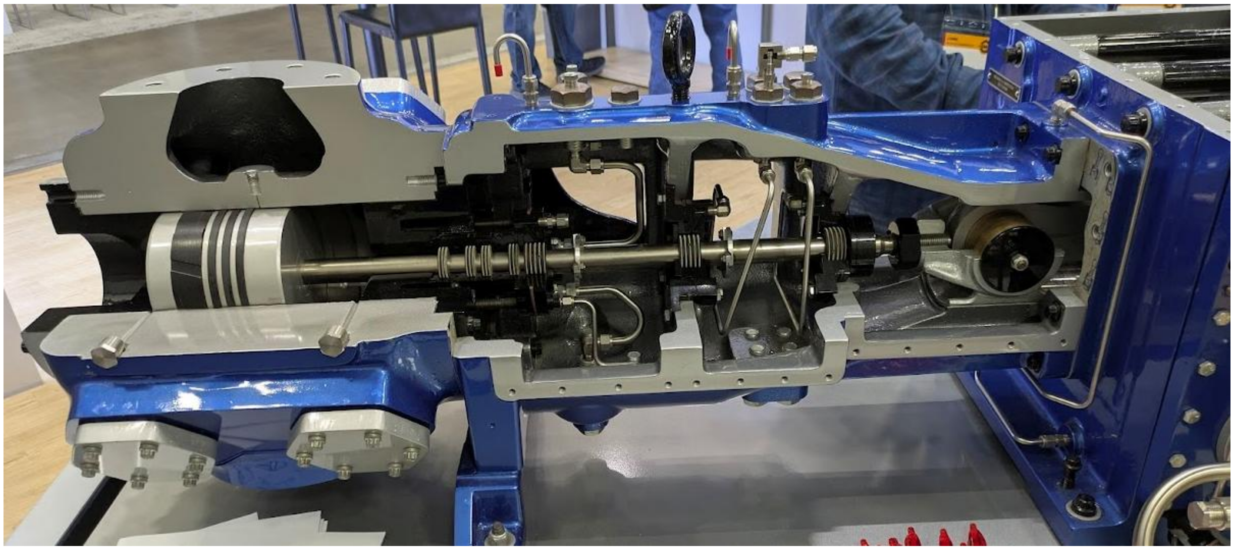


Figure 13: Photo shows a cutaway of a reciprocating natural gas compressor. On the left, the large casting makes up the cylinder, with suction and discharge valves placed on the top and bottom. Within the cylinder is the piston, connected to the piston rod, and then crosshead. The crosshead is attached to a connecting rod, which travels into the crankcase on the right of the image. This compressor includes a purge packing system and extra distance piece compartment to prevent hazardous gas from reaching the crankcase. Photo taken at 2025 Gas Machinery Conference.

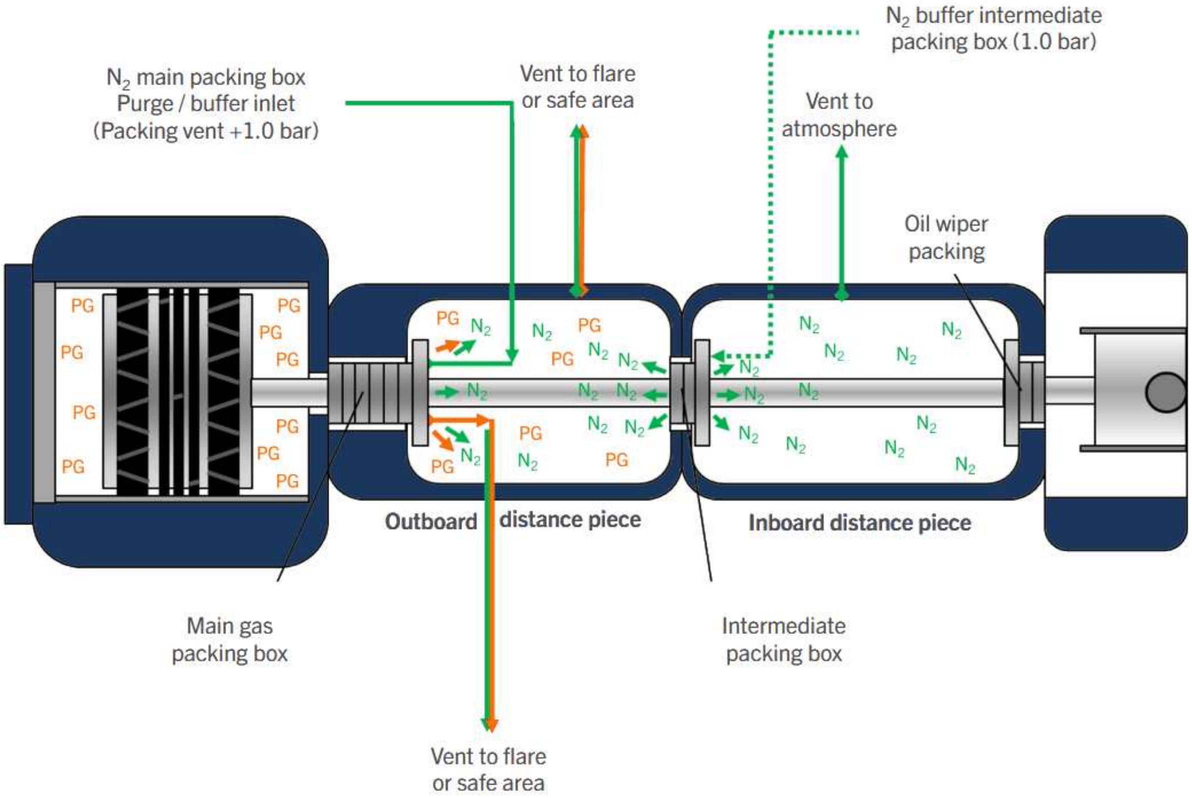


Figure 14: Cutaway diagram of a reciprocating natural gas compressor with a two compartment seal. Process gas labeled as PG, atmospheric and purge gas labeled as N_2. Figure taken from Hoerbiger. [11]

As the packing rings wear, the rings will shift inwards, creating the dynamic seal. They will however not fit as tightly on the rod, "As the packing wears out vent leakage will increase to as high as 120-180 SCFH (2-3 SCFM) and purge gas may increase up to 30 SCFH to maintain a positive pressure over the vent pressure. Likewise, distance piece flows will increase respectively." [34]

Figure 15 shows the wear progression of three different seal types across a timeframe of two years in data provided by Williams Companies [38]. Packings are expected to reach the 2 SCFM rate at approximately the 3-year limit. Type 1 packings are OEM packings, installed with the compressor. Type 2 and 3 packings are two different types of low emissions packings, which show a longer break in period but then maintain minimum emissions throughout most of their lifespan. Low emissions packings are generally more expensive and require more careful selection but ensure lower emissions. They can also cause higher rod friction so may require cooling.

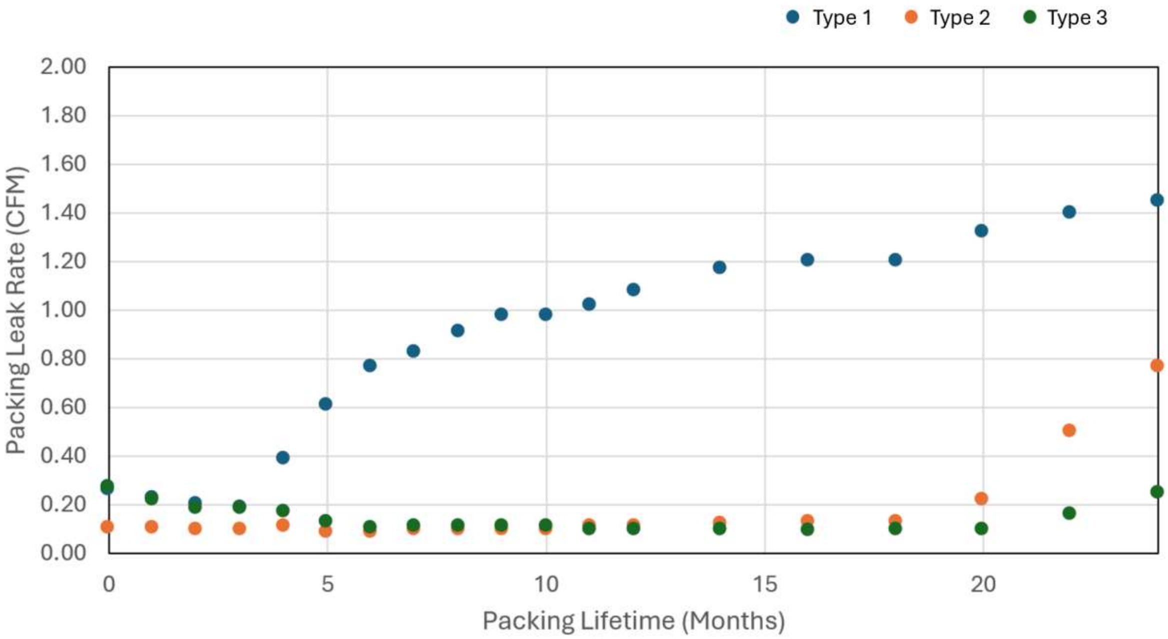


Figure 15: Rod packing leak rates over a period of 24 months for three different packing types. Figure generated from data provided by Williams Companies. [39]

Packing flows vary widely across a short period and even a new packing with a low average leak rate may present large and unpredictable peaks. Figure 16 shows the results from packing vent monitors placed on three different engines at a field site. Data was collected once per day, so it has large variability based on compressor condition throughout the test. The packing vents have been combined to a single line per compressor before measurements. The flow rates shown represent the leakage for four packings per vent. Vents 1 and 2 are on Caterpillar G3616 engines and vent 5 is on a Caterpillar G3606. Vent 1 shows an engine running at low pressure, and therefore low leakage. Vent 2 shows a more expected flow rate, oscillating greatly but producing a constant average flow. This also shows a compressor shutdown from 4/2022 to 6/2022, during which the packings do not leak. Finally, vent 5 shows an engine with normal operation, producing a steady, if slightly decreasing, leak rate across the entire duration of the test.

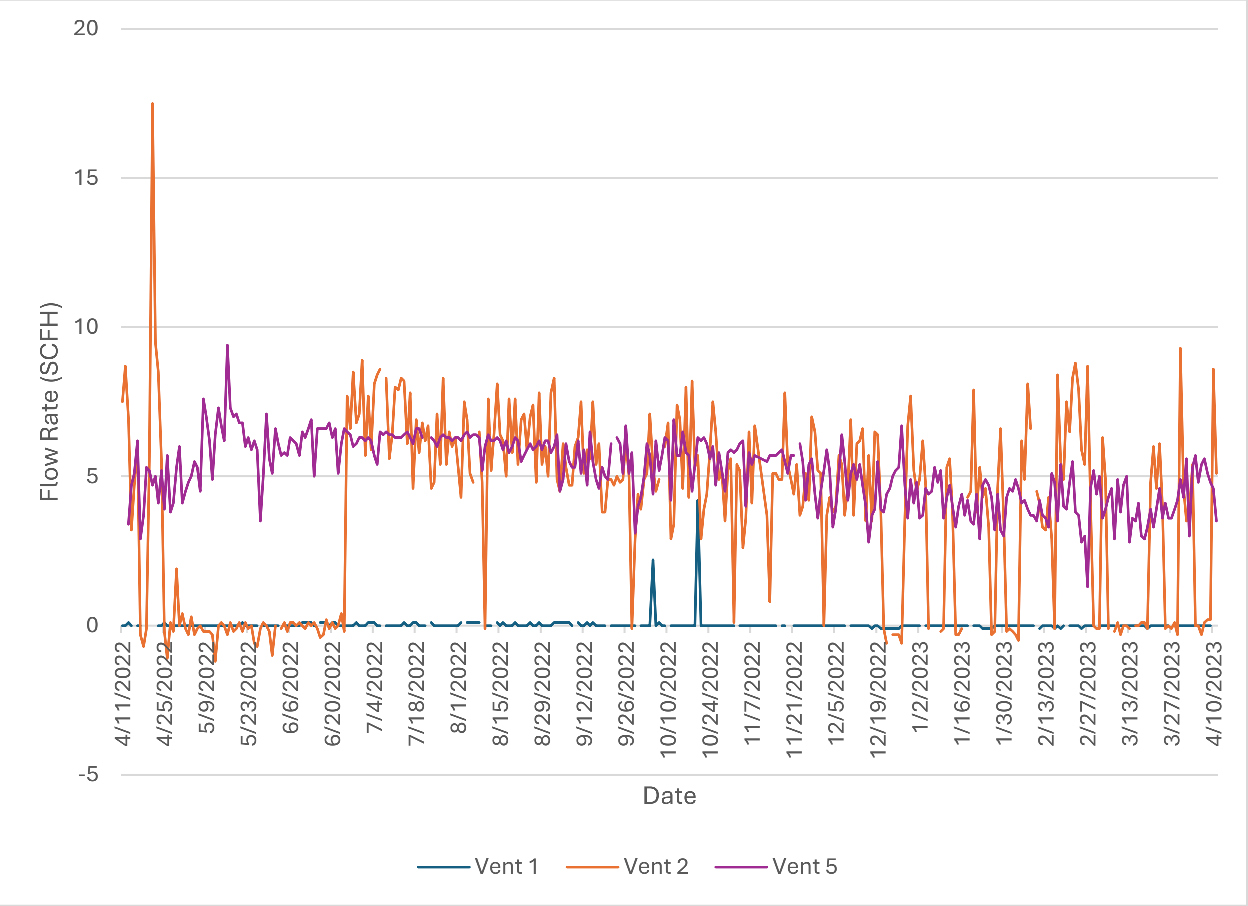


Figure 16: Results from field testing evaluating packing vent monitors for three field engines. Figure generated from data provided by Williams Companies. [40]

Most compressors range from two throws to six, leading to an expected leak range from 0.2 SCFM to 12 SCFM on a compressor. For several further calculations within this document, 1 SCFM per packing is picked as an average leak rate across the packing lifetime. Figure 17 shows the leak rates of 0.1 SCFM per packing to 2 SCFM per packing, as compared to other methane leak sources on an engine-compressor package. The crankcase vent on an engine captures any gas blow-by from the piston rings, very similar to vent gas on a compressor. Exhaust slip is methane which exits the cylinder during the exhaust stroke, due to incomplete combustion. The exhaust slip and crankcase vent data was collected during previous CSU work on a crankcase vent recirculation system installed on a Caterpillar G3516, as described in section 2.4. [41]

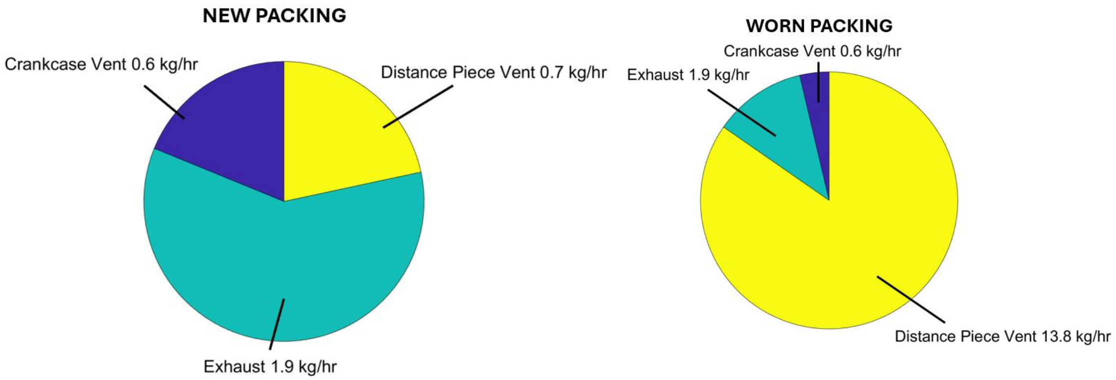


Figure 17 (a): Engine methane losses by source for a compressor with new rod packing seals. (b) Engine methane losses by source for a compressor with worn rod packing seals. Figure generated from data produced by Colorado State University. [41]

Data collected by Colorado State University's (CSU) Methane Emissions Technology Evaluation Center (METEC) on a national study of gas sector leak sources was used to produce Table II. Each entry on this table is composed of combined leak rates for a single compressor, regardless of throws. The first row composes all compressors measured, (390) while the following rows break this further into operating state. For an operating compressor, the average leak rate of measured devices is found to be 28.5 SCFH (0.475 SCFM). This gas, marked as "whole gas", includes the entire flow of the vents, including both methane and other natural gas constituents. An interesting note is that nearly half of all detected emissions come from only 5% of the measured compressors.

Table II: Whole Gas Leaker Emission Factors. Table reproduced from Colorado State University METEC Lab. [42]

Component	Number Measured	Emission Factor (scfh whole gas)	Confidence Interval (scfh whole gas)	Fraction of Emissions Due to Largest 5% of Emitters
Rod Packing Vent	390	7.81	[+37%/-24%]	46%
Rod Packing Vent (OP)	366	28.5	[+35%/-24%]	47%
Rod Packing Vent (NOP)	17	23	[+65%/-49%]	

Table III shows average emissions per device. “Population, or average, emission factors represent the distribution of emission rates common to a component type or category. In use, emissions are estimated by multiplying a count of all components of one type by the population factor for that component type.” The data in this table compensates for differences in the number of units counted and the number of units sampled. It also compensates for units with detected emissions which were not measured. This data is expected to provide the average result for a representative field compressor and is intended to allow operators to estimate their leakage based on the number of devices installed. In this case, the average expected vent rate for the packing vents is 0.462 SCFM.

Table III: Whole Gas Average Emission Factors. Table reproduced from Colorado State University METEC Lab. [42]

Component	Activity Basis	Emission Factor (scfh WholeGas)	Confidence Interval (scfh WholeGas)
Rod Packing Vent	One Per Compressor	27.7	[+25%/-11%]
Rod Packing Vent (OP)	One Per Compressor	25.2	[+25/-11%]
Rod Packing Vent (NOP)	One Per Compressor	1.14	[+39/-28%]

2.3 Commercial System Comparison

The conventional destination for rod packing gasses would be a system vent, either as a single engine package or as a site. These gases are commonly directed to atmosphere but may be flared depending on the location. Both solutions will result in significant methane emissions. According to Evans, et al., “For flares without steam or air assistance, [destruction and removal efficiency] (DRE) values of >98% can be maintained providing the [net heating value] (NHV_{vg}) of the gas is known and maintained at >300 BTU/SCF and the flare is kept lit." [43] Other sources put this efficiency lower, such as a Baker Hughes report stating 93.9% for downstream flares [44]. Upstream gas containing a lower heating value and flared in a system without air or steam assistance, would therefore be even lower. This efficiency can be solved using an enclosed combustor, which is likely to become the only acceptable form of methane destruction following adoption of further regulation. These combustors, due to much more stable combustion conditions, as well as control of the combustion process [45], can reach the 95% DRE value required by Colorado's AQCC Regulation 7 [33] and 98% DRE value required by OOOO [25].

Two alternatives for productive use of compressor vent gases are commercially available. The first directs the vented gases from the compressor to the intake of the driving engine, as shown in Figure 18 (a), where they are fumigated through an orifice and subsequently burned in the engine. This method has been referred to throughout this document as "recirculation." The second system captures the gases and directs them to a small booster pump where their pressure is increased to match the inlet pressure of the venting compressor, as shown in Figure 18 (b).

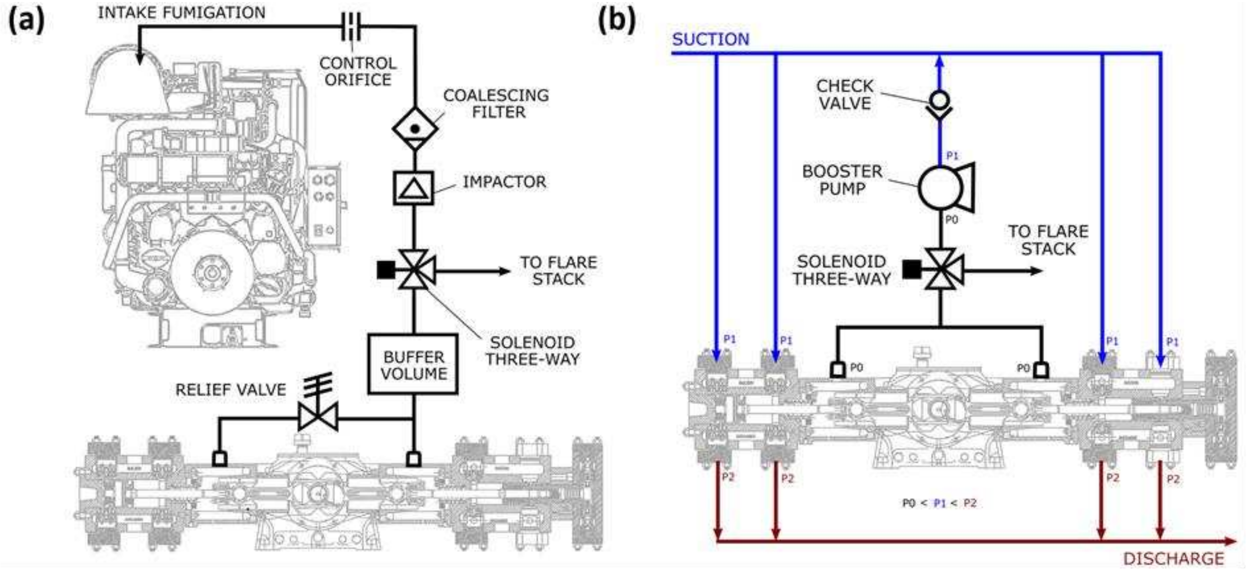


Figure 18 (a): Simplified primary flow pathway explored in this research for a packing vent gas recirculation system. (b): Simplified primary flow pathway for a packing vent gas recompression system explored in this research.

These gases are reintroduced upstream of the compressor and sent down the pipeline with the rest of the product stream. This method is commonly referred to as "recompression."

Recompression and recirculation each have distinct advantages and limitations. Hybrid systems which implement components from each and equivalent systems for centrifugal compressors, also exist. This section, purposed as an overview and analysis of the commercially available compressor vent capture systems, distinguishes commercial vent gas capture systems into three types: recirculation, passive recompression, and active recompression.

Recirculation offers a simple and more cost-effective solution of vent gas elimination by redirecting vent gas back into the engine intake for combustion, reducing methane emissions without the need for complex equipment. This strategy can effectively reduce waste and emissions under normal operating conditions and is attractive for retrofitting due to low capital cost. However, it is more limited by operating conditions than a recompression system.

Recirculation cannot be used when the pipeline or compressor system is shut down, as the engine must be running to draw in and burn the vent gas. This limitation can be reduced by linking multiple compressors to a single vent system, but this increases complexity. In addition, linking multiple engines to a single recirculation system may introduce regulatory complexity considering the requirement for a return to process system to keep the gas within the system it was lost from. The requirement for emissions control to always operate while the system is online may also prevent classification as a control due to complexity and safety concerns encountered in recirculating gas during engine startup and idle. Electric-driven compressors cannot utilize recirculation at all, as they lack an internal combustion engine to consume the vent gas. According to Smillie et al. [10], approximately 10% of compressor stations in the United States utilize electric drive compressors and thus would be incompatible with recirculation systems. Even among engine-driven systems, two-stroke engines are generally incompatible with recirculation because their scavenging stroke vents most of the intake charge directly to the exhaust. Attempted use of a recirculation system on a two-stroke engine will not provide methane destruction or useful work from the captured gas and will increase exhaust methane slip which may be more harmful in a regulatory capacity than the original vented gas.

A recirculation system routes vent gas into the engine intake, where it is consumed as supplemental fuel, eliminating methane emissions without the need for additional compression equipment. The recirculation system is cost-effective both in terms of capital and operating expenses. This requires only low-voltage DC power for instrumentation and safety systems and minimal maintenance. Its simplicity and low footprint make it attractive for field retrofits.

In contrast, recompression systems capture and repressurize the vented gas for reintroduction into the fuel line or another section of the process stream. While more expensive and technically involved, recompression is better suited for systems with intermittent operation or those requiring integration across multiple engines or compressor units. These systems can function independently of engine operation, making them more versatile in certain field applications but at the cost of higher capital and maintenance requirements.

Passive recompression, as termed in this paper, describes a system which recompresses gas by drawing down some volume of compressor discharge gas to recompress the vent gas to suction pressure. There are two common designs. The first uses a venturi ejector powered by high-pressure discharge gas to draw in low-pressure vent streams and redirect them to either the engine's fuel line or compressor suction. The second design uses a gas-actuated linear compressor with the same purpose, utilizing discharge gas to compress vent gas. These systems run off low voltage control power making them well-suited to remote or unmanned sites. Unlike a recirculation system, passive recompression systems can be used with any driver type, engine or electric, and under all operating conditions, including during shutdowns. They do, however, require pressure in both the discharge and suction lines to compress gas. If one line is blown down, the compressor and other line must be as well. The systems reduce compression efficiency by redirecting already compressed gas from the discharge line to suction, incurring a small energy penalty. In addition, the capital cost is higher than recirculation due to the additional componentry. Versatility and low maintenance requirements make it a strong middle-ground option, particularly in locations where power is limited but continuous capture is required.

An active gas recompression is designed to capture rod packing emissions across all operating scenarios. A standard active recompression system consists of an electric motor to drive a small compressor that draws in vent gas and recompresses it directly to the suction side of the main compressor. This system is compatible with all compressor types, including two-stroke and electric-driven units, and remains operational during blowdowns and pressurized standby periods. Because it does not rely on the driving engine for gas recovery, it avoids any loss of engine throughput. However, the system requires continuous electrical power and is expected to be the most expensive option by a significant margin, both in capital cost and power consumption. They are best suited for facilities with reliable electrical infrastructure and a strong regulatory or commercial incentive to eliminate emissions during all conditions. Gas is collected from the rod packing vents before recompression and delivery back to the compressor suction line, engine fuel line, or discharge.

Table IV summarizes this system comparison for ease of access.

Table IV: Comparison summary of vent gas capture system operating conditions.

System Type	Driver Compatibility	Handles Blowdown / Hold	Power Requirement	Relative Cost	Key Tradeoffs
Control	All compressor types, including 2-stroke and electric	Yes	Low (control power only)	Medium	Does not prevent emissions, though reduced to CO2
Recirculation	4-stroke pre-mixed engine-driven compressors only	No	Low (control power only)	Low	Lowest cost and complexity; cannot operate if engine is off or unavailable
Passive Recompression	All compressor types, including 2-stroke and electric	Yes	Low (control power only)	Medium	Broad compatibility; small energy loss from motive gas; modestly higher cost
Active Recompression	All compressor types, including 2-stroke and electric	Yes	High (20 HP electric motor)	High	Fully independent of engine; highest capture capability; highest power and cost

In addition to the reciprocating compressor rod-packing systems described above, a comparable set of methane mitigation technologies has been developed for centrifugal compressors. The same core concepts of either burning or reintegrating vent gas have been adapted to centrifugal compressor dry gas seal vents [46]. The enclosed burner system shown in Figure 19 (Left) operates under the EPA classification of control, capturing primary seal vent gas into an accumulator before routing it to an enclosed combustor capable of 98% destruction efficiency. As in the reciprocating options, this approach is used to reduce cost and complexity from a recompression system. Alternatively, there is a route to process solution through a dry gas seal recompression system shown in Figure 19 (Right), which uses a motor-driven reciprocating compressor to re-pressurize and reinject the vent gas upstream or downstream of the process pipeline. A system is also available to recover additional process gas alongside the dry gas seal leakage. These centrifugal compressor systems mirror the functionality of the reciprocating compressor strategies evaluated in this report, offering similar emissions reductions with equivalent hardware adapted to centrifugal equipment.

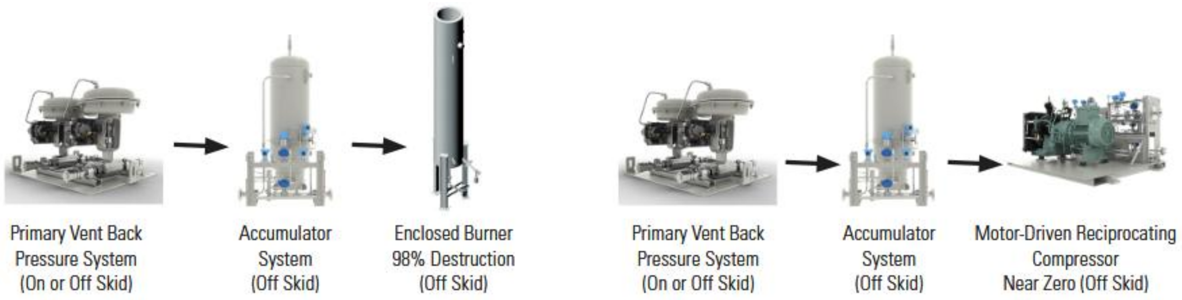


Figure 19: (Left) Enclosed burner system for dry gas seal control. (Right) Recompression system for dry gas seal route to process. Figure taken from Caterpillar. [46]

2.4 Previous CSU G3516 Work

The engine used for this research, described further in section 4.1.1, is a Caterpillar G3516J ultra-lean burn natural gas engine. It is designed to drive a natural gas pipeline compressor. CSU has previously used this engine to test recirculation of crankcase breather gases, a process very similar to rod packing vent gas recirculation evaluated in this research. This work was funded by the Department of Energy award DE-AR0001536 under the ARPA-E REMEDY program.

This work consisted of several tests in which both oil entrainment in crankcase gases and the composition of crankcase gases were measured in lab and field settings. The work reported here will focus on two primary relevancies to rod packing recirculation: gas fumigation design and evaluation of entrained oil.

2.4.1 Fumigation Design

Beginning with fumigation system design, the laboratory setup for closed crankcase vent recirculation (CCV) is shown in Figure 20. This work laid the foundation for the laboratory tests on surrogate vent gas recirculation as discussed in Section 4.1 of this document. The large gray piping elbow shown in the top left of Figure 20 was designed and fabricated for the purpose of fumigating vent gas to the engine’s air intake.

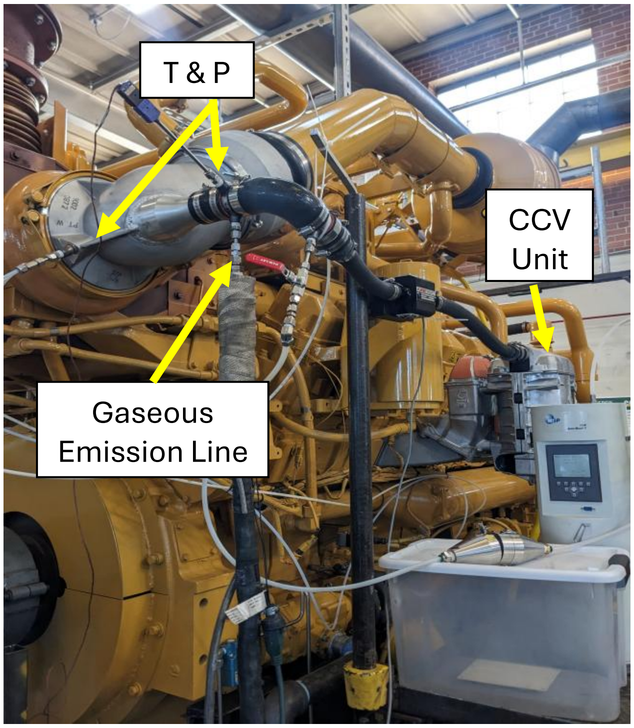


Figure 20: Laboratory test setup for G516J closed crankcase vent recirculation. Image taken from CSU crankcase vent gas recirculation. [47]

This elbow is a component of the engine air intake directly between the primary fuel mixing drum and the turbocharger compressor. Being downstream of the mixing drum means that the fuel is already premixed at this point so the presence of additional natural gas will not cause damage to components and additional fuel will not cause an explosive mixture at an unexpected point. The turbocharger compressor draws a low-pressure region within this elbow so gas can be introduced without relying on external pressure or complex induction geometry.

Within the laboratory setting, this system behaved as expected, reducing the methane slip by reintroducing crankcase gas to the engine air system. As fabrication is already completed and testing found no adverse effects from gas reintroduction at this point, the same reintroduction hardware will be used for intake fumigation of surrogate rod packing vent gas.

2.4.2 Oil Concentration

For the installed CCV system, oil capture consisted of three stages, a two-stage centrifugal swirler and then impactor which remove larger and then medium-sized droplets, respectively, and then a coalescing filter to capture vapor. Figure 21 shows the installed crankcase recirculation system, including three stages of oil removal before routing to the engine air intake.

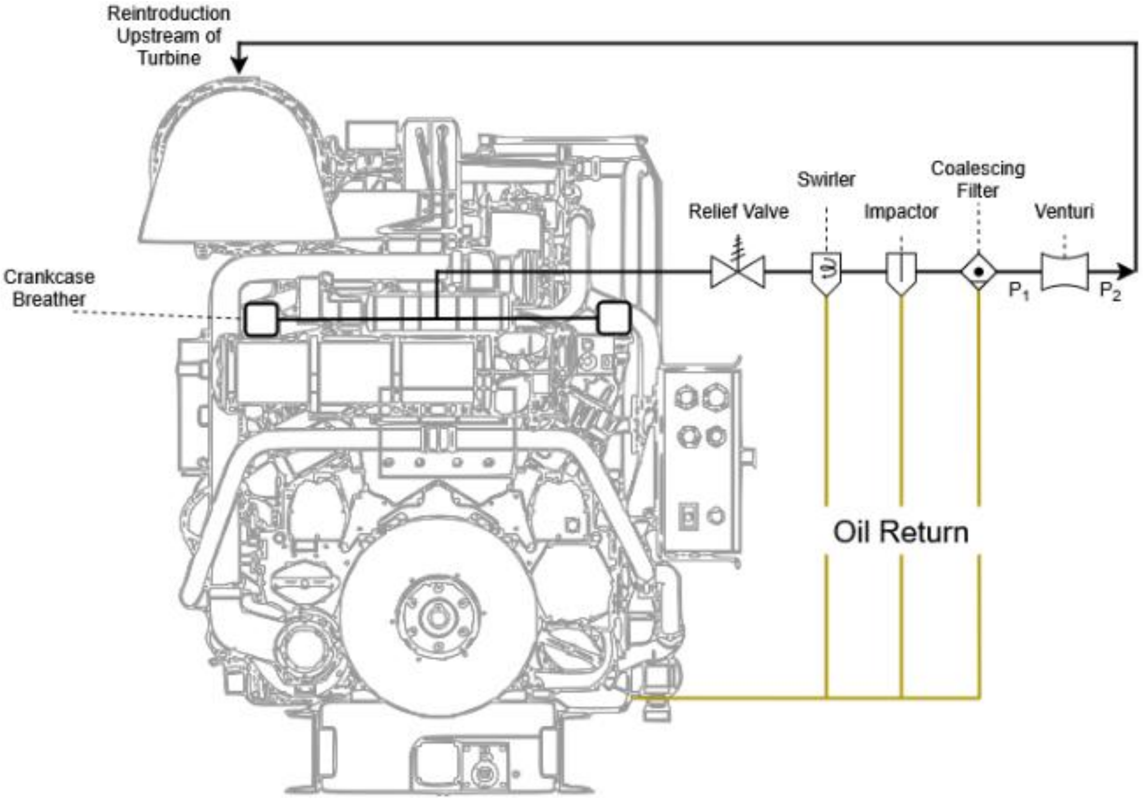


Figure 21: Illustration of P&ID diagram of closed crankcase vent system (CCV) installed for laboratory and field testing. Image reproduced from CSU crankcase vent gas recirculation. [41]

This testing setup, including pre-production hardware from Caterpillar, was installed on a field engine, as shown in Figure 22, to test the long-term effectiveness of a crankcase recirculation system.

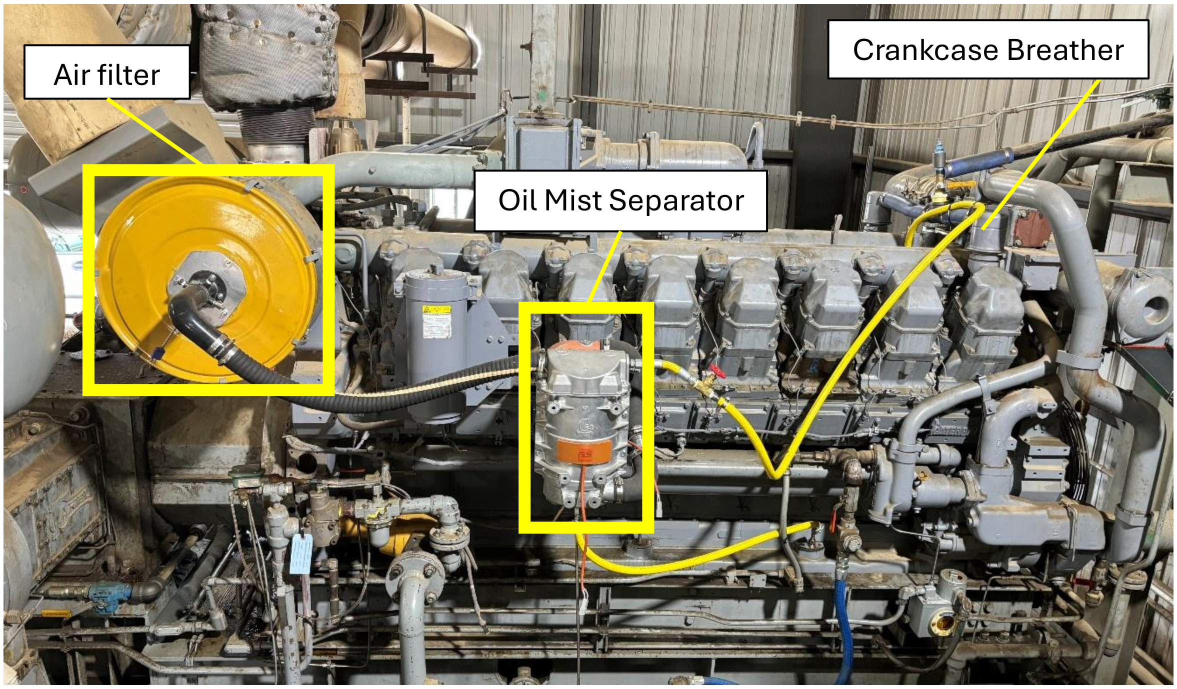


Figure 22: Photo of closed crankcase ventilation long duration field study test installation. Image taken from CSU crankcase vent gas recirculation, final CSU REMEDY report not yet published. [48]

This work found no effect on engine performance or damage to the engine from oil

2.5 Oil Filtration

A rod packing recirculation system is expected to encounter both process gas and vaporized compressor oil. The gas is routed for reuse within the process, but oil presents a problem for many of the components downstream of the capture system. Measurement devices such as resistance thermometers and flow meters can be damaged or measure incorrectly with the presence of significant liquid flow. Additionally, oil coats components within the air system, affecting flow. Finally, if oil is allowed to enter the engine cylinders, it may auto ignite and cause knock which can cause serious damage to the engine, aftertreatment systems, and field operations. Due to this, a rod packing recirculation system implemented on an engine must be able to handle and capture entrained oil.

For the purposes of this research, it is desired to disregard the effects of oil on rod packing recirculation. This simplifies the work and ensures that the project scope focuses on problems unique to gas recirculation, rather than filtration design. To justify this decision, evidence is presented below to two ends. First, that oil filtration systems can be constructed to reduce oil below engine manufacturer limits, and second, that high concentrations of oil reaching the air system do not disrupt engine operation.

In the case of most commercial systems, oil separation consists of two components. These are usually a coalescing filter and some form of pre-separation. The coalescing filter collects vapor in small gaps within the filtration element. The trapped vapor coalesces together, forming larger droplets until these are large enough to fall off of the element. As this filter consists of a tight matrix of fibers, droplets saturating the filter will increase pressure and may allow higher quantities of oil to be forced through. To avoid this condition, the pre-separation stage first removes larger slugs of oil from the system before the coalescing filter, which is capable of capturing vapor but inefficient at processing high volumes of liquid.

This pre-separation stage can take several forms. As described in Section 2.4.2, the system designed for previous CSU work on crankcase gas recirculation used a centrifugal swirler and an impactor as pre-separation. [47] These components are primarily used to remove larger droplets of oil which may rapidly saturate the coalescing filter. Alternatively, for fluid flow with higher quantities of smaller droplets, the commercialized Slipstream® rod packing vent gas capture system instead uses a seal pot. [49] This seal pot forces incoming gas to bubble through a liquid oil, which cools the gas and forces vapor to condense. These pre-separation options can be tailored to the application and would be selected for specific properties of rod packing vent gases.

After pre-separation, the gas passes through the primary filter element, typically a coalescing filter. These filters capture both particles and liquid. Solberg, a filter manufacturer, rates their filters at 99.97% capture efficiency for particles of size 0.3 micron. [50]

With a high efficiency filter, multi-stage separation, and application specific filtration, it is expected that a filtration system can remove oil from the system to a level at which engine operation is not affected.

The crankcase work presented in section 2.4 also provides some data for the operating state of the engine with oil present in the air system. The long duration field study on crankcase recirculation was conducted for one year and the filter was unable to be replaced for the full duration. During this time, the filtration efficiency decreased from the initial 99.5% oil removal efficiency to 71.5% oil removal efficiency as shown in Figure 23. This led to oil breakthrough reaching the engine. Despite this, no performance decrease or engine damage was detected.

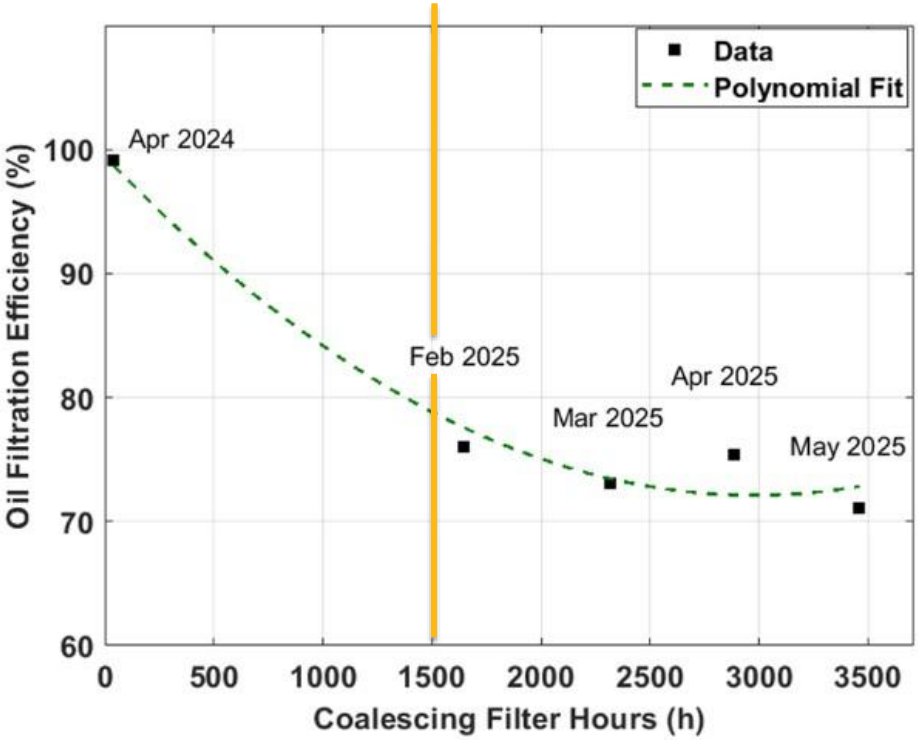


Figure 23: Coalescing filter efficiency as a function of time during a 1 year field study of closed crankcase vent recirculation. Image taken from CSU crankcase vent gas recirculation, final CSU REMEDY report not yet published. [48]

The initial maintenance timeframe for the coalescing filter was rated at 1500 hours. After this testing, the recommended threshold was changed to 1000 hours. Despite the decrease in filtration efficiency of the filtration element while operating significantly past its designed lifespan, this test has shown that the engine can operate normally with up to 29% oil vapor breakthrough. [48]

Due to both the efficiency of filtration which can be achieved, as well as the robustness of engine operation, oil concentration within rod packing gas will be disregarded for the rest of this rod packing recirculation testing. This is still a necessary component for a recirculation system but has been removed here to narrow project scope.

CHAPTER 3 – JUSTIFICATION OF WORK

3.1 Summary

This work is the first reported study to evaluate the effectiveness of rod packing recirculation as a solution to reduction of methane emissions, fuel savings, and continued safety and stability of the engine. The objectives of this work are

1. To design and test a surrogate rod packing recirculation system to evaluate the efficiency of inlet fumigation and effectiveness of fumigation to offset engine fuel.

2. To design and evaluate economic feasibility of the introduction of a rod packing recirculation system onto a field engine.

3. To evaluate the possible regulatory classification and requirements of such a system to enable operators to operate this technology while satisfying regulatory requirements and reducing overall emissions.

The execution of these three objectives will allow operators to implement rod packing recirculation systems with confidence that neither field operations nor their regulatory obligations will be negatively affected, thereby reducing methane emissions to the atmosphere and reducing fuel costs.

3.2 Gaps in Current Research

3.2.1 Efficiency of Rod Packing Recirculation Systems

Manufacturers offer vent-capture systems capable of containing and rerouting packing-vent gas, each with stated design limits for flow rate, gas composition, temperature, and filtration capacity. Under previous regulatory conditions it has been acceptable to integrate a vent capture system without rigorously documented capabilities. However, given advancing regulations, obtaining permits is increasingly difficult without thorough documentation of system efficiency. As OOOO requires a 95% route to process efficiency, it must be proven that these systems can deliver gas without leaks and with an uptime of at least 95%, including times such as engine startup.

Despite this emerging requirement, peer reviewed documentation has not established that these systems provide further capability than gas conveyance within operating envelopes. There is limited documented evidence that they provide benefit without adverse engine effects and provide sufficient efficiency to meet regulatory classification.

3.2.2 Efficacy of Engine Inlet Fumigation as a Solution to Offset Fuel Costs

Once the gas is delivered to the intake by the recirculation system, even if at an acceptable efficiency, it must be proven that the engine can make productive use of the gas. Industrial natural gas engines are typically controlled using an oxygen (lambda) sensor within the exhaust line which enables the engine to balance AFR by detecting oxygen left over from incomplete combustion. The engine controller is programmed to assume a base AFR for startup, during which it uses these sensors to compensate for unexpected combustion conditions, including gas composition. The controller then uses the fuel valve to increase or decrease fuel admission to balance combustion with the detected oxygen.

It is possible for the engine controller to be programmed in such a way that additional fuel introduction could be treated as an unexpected state. This could cause the engine control unit (ECU) to produce warnings or errors, which could either result in direct engine shutdown, or trigger another system to shut down the engine. Before recirculation can be implemented on engines, it is necessary to document that the engine controller will compensate for additional fuel addition without experiencing issues. This requirement was developed into justification 3.3.1, Validation of efficiency and safety of recirculation systems.

3.2.3 Engine Limits

In sufficiently extreme operating conditions, the engine control system will be unable to balance fuel delivery in a safe manner. With an integrated recirculation system, this is likely to take the form of excessive flow causing engine instability. Reaching a point at which a field engine can no longer compensate may result in unplanned downtime or engine damage. It is therefore important to know the engine limitations pertaining to fuel delivery from sources external to the engine fuel valve. In the case of a G3500 series engine, the fuel is premixed at a fuel drum before the turbocharger compressor which is located several feet forward of the cylinders on the air intake line. The lambda sensor is placed downstream within the exhaust. These placements delay sensing and control inputs to the engine. Given a rapid enough change, this may result in the controller detecting different conditions than are present in the engine cylinders and compensating incorrectly.

It is important to know both the engine and recirculation limits for gas flow in any condition which might be reached during operation before the system is implemented in the field. This is represented in justification 3.3.2, Determination of engine drop-in limits for intake gas fumigation.

3.3 Justification of Work

The overall objective of this research was to provide pipeline operators with third-party documentation regarding the effectiveness of methane recirculation technologies. The testing and analyses conducted in this project establish an independent verification of methane emissions reduction capabilities. This work seeks to deliver straightforward recommendations that balance emissions reduction, financial incentives, and regulatory compliance. The research provides pipeline operators with critical information needed to implement effective methane management practices on natural gas compressor packages.

3.3.1 Validation of efficiency and safety of recirculation systems

Recirculating rod-packing vent gas is only acceptable if the engine remains stable and controllable with the added fuel stream. This justification focuses on verifying steady and transient combustion stability, reliable air–fuel control, and the absence of unsafe behaviors (e.g., misfire, knock, or runaway).

3.3.2 Determination of engine drop-in limits for intake gas fumigation

Recirculation provides real benefit only when the fumigated gas can be burned to produce useful work without derating or efficiency loss. This justification defines the allowable fraction and operating envelope for adding vent gas to the intake, so the engine converts it to productive output rather than simply transporting emissions.

3.3.3 Evaluation of financial viability

Even if technically sound, implementation of a recirculation system will not occur unless it makes economic sense. This justification evaluates whether capital and installation costs, operating and maintenance burden, and uptime impacts yield acceptable lifecycle economics compared with alternatives.

3.3.4 Emissions classification

Adoption depends on the system fitting within applicable emissions regulations and permitting pathways. This justification confirms the configuration and operating mode meet regulatory definitions and limits so sites can obtain and retain permits using the recirculation solution.

3.4 Objectives

This work was funded by the Gas Machinery Research Council (GMRC) with the goal of providing relevant information for pipeline operators to implement closed packing vent recovery systems. "The Gas Machinery Research Council (GMRC) is a community of proactive natural gas companies dedicated to investigating technical issues within the rapidly evolving gas machinery industry and uncovering innovative solutions that improve reliability, efficiency, and cost-effectiveness of mechanical and fluid systems." [51]

There is substantial cost to installing a recirculation system on a field engine, including the capital expense, installation, and opportunity cost from the engine being offline during installation. System failure could also lead to regulatory or further operating concerns. Therefore, operators have significant incentive to install these devices only after concept validation.

This work is broken into three primary objectives. These objectives are: design of a surrogate rod packing recirculation system for lab testing, componentry selection for a field unit with an associated techno-economic analysis, and evaluation of emission regulations.

3.4.1 Surrogate Vent Gas Recirculation Study

To fill the justifications for this work proposed in 3.3.1, Validation of efficiency and safety of recirculation systems, and 3.3.2, Recirculating rod-packing vent gas is only acceptable if the engine remains stable and controllable with the added fuel stream. This justification focuses on verifying steady and transient combustion stability, reliable air–fuel control, and the absence of unsafe behaviors (e.g., misfire, knock, or runaway).

Determination of engine drop-in limits for intake gas fumigation, the first objective was the design and fabrication of a surrogate rod packing recirculation system for the G3516J owned by the Engines Lab at the CSU Powerhouse. This system was used to test engine response to fumigation of the air intake with fuel gas. All tests were conducted on an engine using the stock Caterpillar ADEM A3 controller. Depending on the engine control scheme and sensors, additional fuel added to the inlet may force the engine to run richer than designed. This could increase exhaust methane emissions and negate the purpose of the capture system. Additionally, under certain conditions, unexpected fuel could cause engine knock. The engine must be proven to operate safely and efficiently while gas is recirculated.

3.4.2 System Design and Techno-Economic Analysis

Justification 3.3.3, Evaluation of financial viability, was satisfied by the second objective, componentry selection and system design for a closed vent recirculation system. Vent gas capture systems are currently being considered as a technology in response to implemented and emissions regulations at federal and state levels. Economic feasibility was conducted via a techno-economic analysis. Emphasis is placed on recirculation systems and recompression systems, due to cost and capability, respectively. Given a shifting federal regulatory landscape, this work is conducted both with and without consideration of recent regulation, namely the Waste Emissions Charge introduced by the EPA. These must serve several functions and still prove economically viable for operators to consider adoption.

3.4.3 Evaluation of Regulatory Classification

For objective 3.3.4, Emissions classification, evaluation of the system under EPA emissions regulations is conducted. This work is supported by section 2.1 within the literature review. By previous EPA definitions, vent gas would be categorized as waste as it left the packing vents. Recirculation systems could only be classified as control systems from this point. This designation contains specific requirements which may complicate the use of or exclude rod packing recirculation systems. The alternative classification which is proposed by this work would be ‘route to process’. This classification has similar but distinct restrictions, which may be beneficial to a recirculation system. Emissions frameworks considered include the Waste Emissions Charge (WEC), 40 CFR Part 60 (Quad O), and Colorado’s Air Quality Control Commission Regulation 7. Providing a more open system classification will encourage the usage of recirculation technologies for emissions reduction.

CHAPTER 4 – METHODOLOGY

4.1 Surrogate Vent Gas Study

4.1.1 Description of Test

In order to satisfy objective 3.4.1, Surrogate Vent Gas Recirculation Study, testing of a recirculation system must be conducted on a natural gas compression engine. The engine selected was the CSU Energy Institute Caterpillar G3516J shown in Figure 24. This engine was donated by Western Midstream and formerly operated in the field as a natural gas compression engine. Caterpillar conducted a full 0-hour rebuild on the engine as a donation before installation in the lab.

Figure 24: Photo of Colorado State University Engines Energy Conversion Laboratory Caterpillar G3516J natural gas engine.

The engine does not have an installed natural gas compressor, so ducting true packing vent gas is infeasible. Surrogate testing also allows for the explicit definition of fumigation rates. Testing on an in-service compressor would limit flow rates to those experienced at the actual packing vents and could not necessarily supply the high flow rates desired for this testing.

In the field, packing vent gas comes directly from the compressor, which is acting on pipeline gas. The packing vent gas is therefore pipeline gas with some entrained oil vapor from the packing lubrication. The objectives listed both revolve around the engine's immediate response to gas flow and previous work has shown that engine operation is not degraded by the presence of oil in the air system [41]. Note, the design of the filtration system that would be required for a field installation is outside of the scope of this project. It is left to the responsibility of a company designing a recirculation system to ensure that only clean, dry gas reaches the engine intake [49].

With the assumption that the packing vent gas is identical in composition to the pipeline gas, and the recirculation system will sufficiently remove oil from the gas, this work was conducted using pipeline gas as a surrogate for the recirculated vent gas.

This gas, referred to as surrogate [vent] gas, was teed off from the engine's primary fuel line upstream of the engine's fuel control valve. The surrogate vent gas was separated from the engine fuel upstream of the engine fuel flow meter and control valve and sent through the test system, consisting of a regulator, flow meter, and control valve. The test system, shown as a diagram in Figure 25, directs the metered gas from the building fuel line into the engine intake between the fuel mixing drum and the turbocharger compressor.

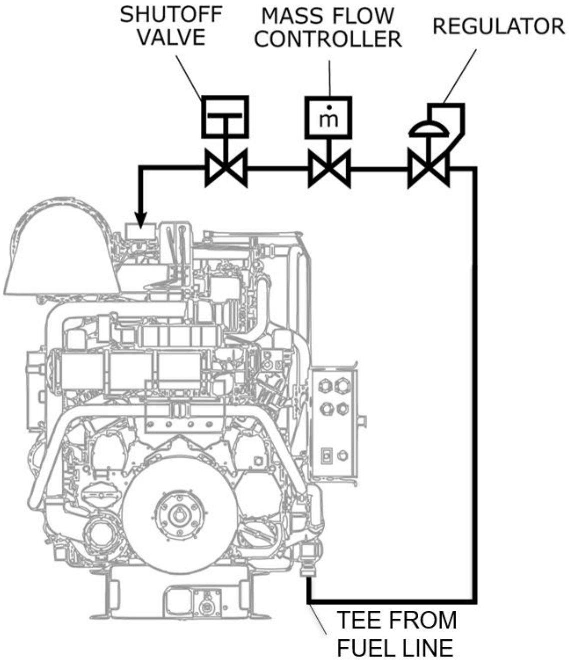


Figure 25: Illustration of P&ID diagram of surrogate gas recirculation system developed for this research.

The lab test setup is shown in Figure 25, Figure 26, and Figure 27, consisting of the flow control system shown in Figure 25 and insertion point directly after the fuel mixing drum in Figure 26. This gas is fumigated to the air intake. The reintroduction points into the elbow after the fuel mixing drum were selected in CSU's previous work on recirculation of engine crankcase gas as discussed in section 2.4. Following the success of this work, gas recirculation into the air intake elbows is duplicated here.

In commercial systems, this gas may be introduced upstream of the air filter. Figure 28 shows the two selector valves to route fuel between the engine inlets. On a true recirculation system, the gas must be routed from the compressor vents to the system itself, and then back to the engine inlet. This can require long piping runs and high install costs. To help reduce these costs to the operator, it may be beneficial to introduce recirculated gas closer to the compressor. Previous work conducted at CSU on crankcase vent gas recirculation reintroduced gas into only one of the two engine air intakes [41], allowing the system to connect to the air intake on the compressor end of the engine. This may be a solution to reduce installation complexity. The surrogate testing presented here however tests much higher flow rates, so it is possible that the aftercooler cannot mix this uneven fuel addition. This would result in one bank running with more fuel, leading to knocking or misfiring cylinders. Therefore, fumigation is independently tested with gas introduction into both air intakes evenly and into only one air intake. Flow rates are described below in section 4.1.3 Testing Regimes.

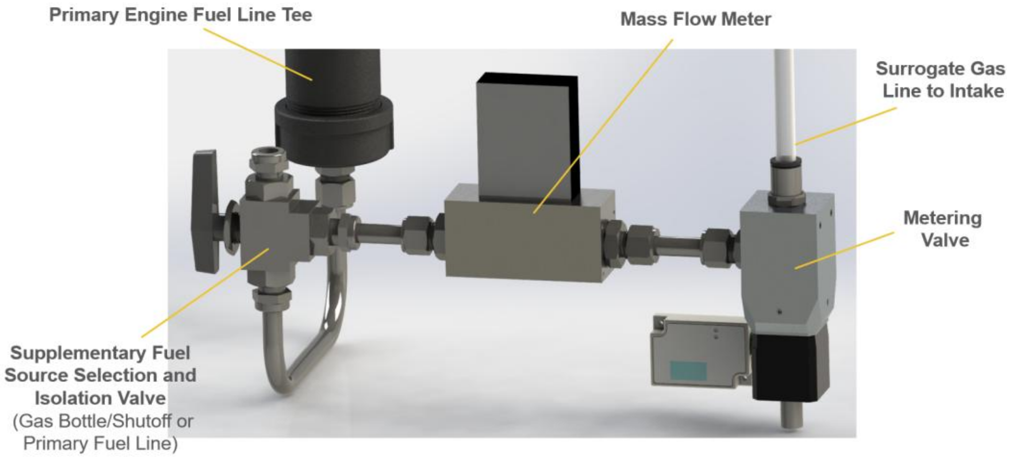


Figure 26: Surrogate gas recirculation system CAD model developed for this research.

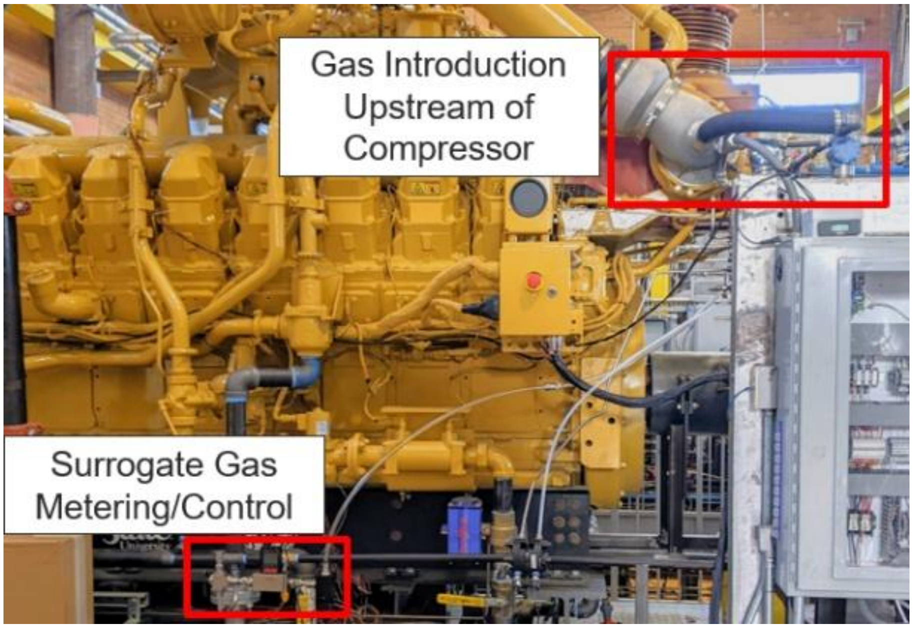


Figure 27: Photo highlighting location of metering components and fuel fumigation point within surrogate gas recirculation system mounted on engine. Developed for this research.

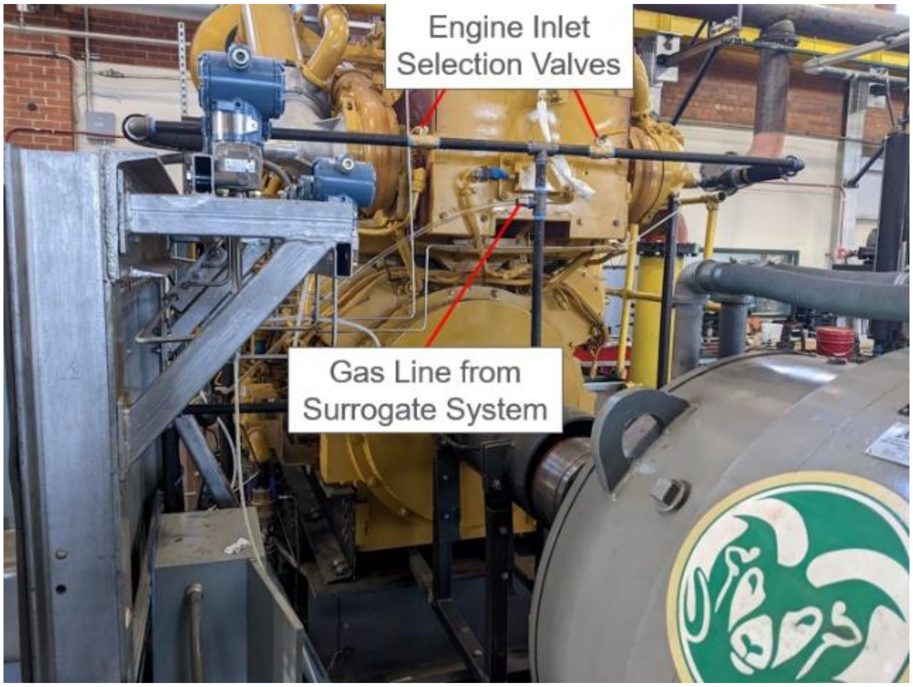


Figure 28: Photo highlighting surrogate gas recirculation system fuel selection points. Developed for this research.

4.1.2 Design Choices

Flow rates were selected to provide both a representative sample that a field engine connected to a compressor might experience, as well as extremes that should not be expected on a field engine. The minimum vent flow rate of packing is expected to be 0.1 SCFM at the time of installation. Packing replacement must occur at 2 SCFM per packing as per OOOOb [20]. A reciprocating compressor in natural gas service is expected to have between 2 and 6 throws. Therefore, expected leak rates from the compressor are considered in this report to be from 0.4 SCFM to 12 SCFM unless stated otherwise. Operators are generally only required to inspect packings on an annual basis for Greenhouse Gas Reporting Program (GHGRP) purposes. If a packing wears between annual surveys, it may exceed these limits before detection.

To ensure a factor of safety for field conditions and to meet budgetary constraints, the minimum desired flow range for these tests was set at 24 SCFM with an anticipated fuel pressure of 25 PSIG.

The flow metering device was an Alicat standard laminar differential pressure flow meter with a range to 1500 SLPM or 53 SCFM. Corresponding specifications are provided in Table V below. [52]

Table V: Specifications for M-1500SLPM mass flow meter. Data taken from Alicat Scientific. [52]

Specification	**Alicat M-1500SLPM**
Flow Accuracy	± 0.8% Reading ± 0.2% Full Scale
Flow Repeatability	± 0.2% Reading ± 0.02% Full Scale
Pressure Drop (PSIG)	~5.5

To provide the rangeability and precision required for flow conditions, an Enfield Technologies motorized needle valve was selected as the flow metering device. The specifications of this valve are provided below in Table VI. [53]

Table VI: Specifications for ENV-0825 Motorized Needle Valve. Data taken from Enfield Technologies. [53]

Specification	**Enfield Technologies ENV-0825**
Hysteresis (% Full Scale)	± 2
Linearity (% Full Scale)	± 10
Repeatability (% Full Scale)	± 0.1
Resolution (SLPM)	2.0
Response Time (Seconds)	2.5

The flow curve of the valve in air is given in Figure 29. The experimental setup was designed around 25 PSIG fuel delivered to the engine. As the valve was expected to see approximately 19 PSIG after pressure drop across the flow meter, the valve was rated for approximately 1040 SLPM flow. This is equal to approximately 36 SCFM. As both selected components were expected to flow more than 24 SCFM, the target was revised to 36 SCFM.

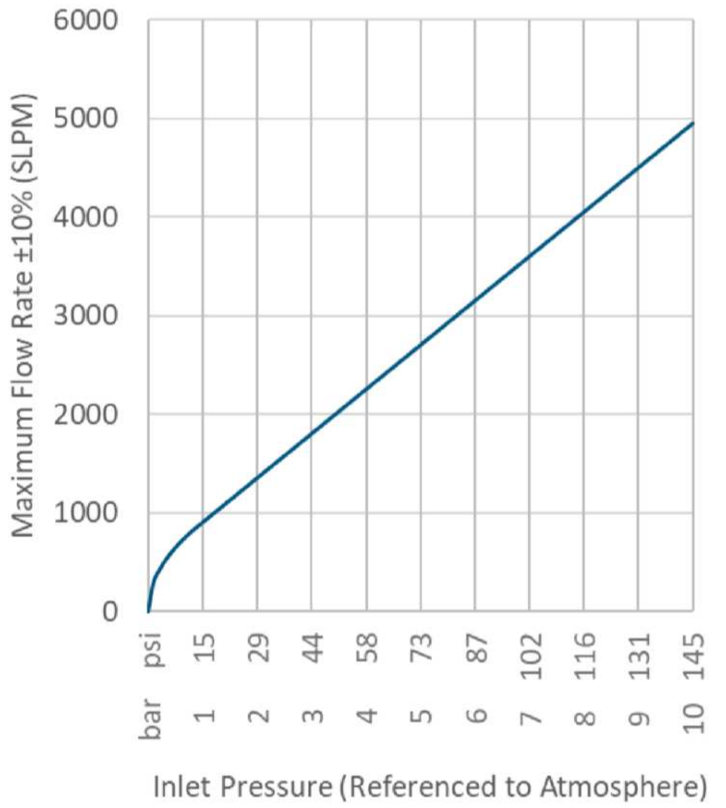


Figure 29: ENV-0825 motorized needle valve published flow curve in air. Figure taken from Enfield Technologies. [53]

Both devices were driven by NI hardware using LabVIEW and run in a closed loop control scheme. A PID controller was used to implement corrections and control flow using input from the flow meter and output signal to the valve. Given this, accuracy and repeatability effects from the valve were minimized and the primary contribution to inaccuracy was from the flow meter. This is given at ± 0.8% Reading and ± 0.2% Full Scale.

With a designed maximum flow rate of 24 SCFM, accuracy from the meter is approximately ± 0.3 SCFM. This is an error of 1%. At minimum steady state flow of 0.5 SCFM, accuracy is approximately ± 0.1 SCFM. This is an error of 20% but due to the purpose of this testing, accuracy on the low end of measurements is not of significant priority. It is far more important in this case to measure the effects of the high end of the flow limits. The minimum flow point of 0.5 SCFM was tested only to provide a very low entry point for testing to minimize adverse effects on engine performance. If any performance change was noted, it would likely be insufficient to damage the engine, and further tests could be modified.

Before engine testing, the flow meter and piping assembly was tested on a flow bench using plant air regulated to 25 PSIG. The maximum flow rate was determined to be approximately 23 SCFM. Given this limitation and concerns about indeterminate pressure in the engine fuel line, a secondary flow pathway was added in parallel. This pathway used an orifice flow meter and manual isolation valves. This meter was also placed on a flow bench to determine a flow curve as shown in Figure 30. At 24 PSIG inlet pressure, the system reached a flow of 25.5 SCFM flowing air.

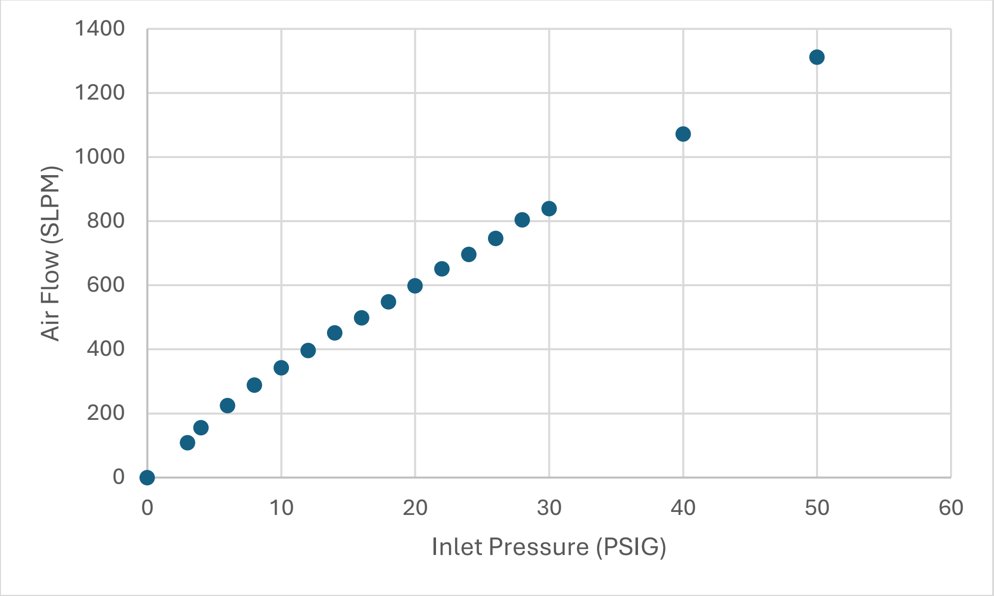


Figure 30: Plot showing results of orifice flow meter flow curve measured in air at 25 PSIG.

To reach the target of 36 SCFM, the orifice meter would be turned off while the automatic valve and control system ramped flow to the maximum of 23 SCFM. The orifice meter line was isolated by manual valves upstream and downstream of both meters. For higher flow rates, the automatic valve would be closed and the manual valves isolating the orifice meter opened. The automatic valve would then be allowed to resume control of the flow with an estimated 25.5 SCFM through the orifice meter and any further desired flow through the electronic valve.

4.1.3 Testing Regimes

There are a few different flow states expected for a recirculation system. The nuance of each of these conditions should be handled by the recirculation system itself, either slowing or blocking the release of fuel into the engine. However, the system will have some required response time or may fail entirely. It is therefore required that the engine be rated to handle not only the steady state flow, but also some level of transient. Three flow regimes were tested during surrogate recirculation tests: (1) gas fumigation at steady state, (2) slow transient introduction, and (3) rapid transient introduction.

4.1.3.1 Steady State

The most common condition for a recirculation system is a steady state condition with some quantity of vent gas flowing. As the packings wear across multiple years of their lifespan, the recirculation system will experience a slow increase in flow rate which is better described as steady state flow. During the steady state tests, it is easiest to see that the engine is compensating successfully for the additional fuel addition.

For this testing, experiments were designed to emulate a typical range of recirculated compressor vent flow. The test point 0.5 SCFM is a convenient measurement to represent the expected leak rate of a compressor with newly installed rod packing seals, while 2.0 SCFM represents the maximum leak rate for a single rod packing seal before replacement.

Test sweep flow rates are shown in Table VII. To test a range of conditions under which the engine itself could be operating, the engine was run in three configurations during steady-state gas fumigation. First, the engine was tested at half power and load. After confirming the engine was stable with fumigation at this state, the engine was brought up to full power, and a full range of fumigation flow rates was explored. Finally, the single inlet fumigation tests were run at 10 SCFM and 24 SCFM to stress test the engine.

Table VII: Volumetric flow rates for surrogate gas recirculation test sweep.

½ Rated Power	
0.5 SCFM	Minimum Expected Leak
2 SCFM	Maximum Expected Single Rod Leak
Rated Power	
2 SCFM	Maximum Expected Single Rod Leak
10 SCFM	
12 SCFM	Maximum Expected Leak
20 SCFM	
24 SCFM	2x Maximum Expected Leak
Single Inlet Fumigation	
10 SCFM	
24 SCFM	2x Maximum Expected Leak

4.1.3.2 Slow Transient

As the packings near wear limits, they begin to wear faster and more inconsistently, which will result in a faster transient, though likely still imperceptible. There is some delay on the control system so this data can be difficult to discern during transient tests. Slow transients allow inspection of engine response and emissions. Slow transient data was collected between steady state tests while the system was ramped between setpoints. The ramp rates are presented in Table VIII. The ramp rates were not defined ahead of testing and were chosen during operation to maintain stability in engine heuristics. These data points are conducted with the engine at rated power and fumigating both intakes.

Table VIII: Ramp rates for surrogate rod packing recirculation testing under slow transients.

Ramp Rate (SCFM/min)	**Ramp Start (SCFM)**	**Ramp End (SCFM)**	**Ramp Change (SCFM)**
-6	24	0	-24
0.98	0	2	2
2.15	20	24	4
2.9	10	12	2
3.2	2	10	8
3.2	12	20	8

4.1.3.3 Rapid Transient

Finally, in the event of a blowout, the system may receive a rapid pulse of gas or many as the piston continues acting on the gas. Rapid transients are the expected failure point of the engine, as changes in fuel delivery may outpace the engine's control loop too significantly for successful compensation, resulting in knock or stalling.

4.1.4 Sensor Timing Calibration

Data from the surrogate recirculation tests were collected on multiple different computer systems and using instruments at various points through the system. In order to account for these, some compensation factors are applied to the data to ensure that the data is properly aligned in time.

The computers used for data collection include internal clocks, but these can vary in accuracy and are only periodically corrected. To compensate for this, first the computers were re-synced to their time servers. This brought the devices within approximately 5 seconds of synchronization. Next, each computer visited https://time.is which returns the synchronization accuracy to the tenth of a second. This delta was recorded and applied later during data processing for alignment.

Physical hardware related to this test begins at a fuel valve upstream of the engine, includes the surrogate control system inline with the engine's main fuel valve, and continues until the FTIR and 5-gas meters placed within the engine exhaust line. This causes a delay from the introduction of fuel until the engine response, and then the exhaust measurements. To compensate, the surrogate fuel valve was pulsed once. During data processing, this pulse was tracked through the engine response and then to both the FTIR and 5-gas instruments. The delta was again collected and used for alignment.

4.1.5 Evaluation of Results

The Caterpillar Electronic Technician (CAT ET) system installed at the CSU Powerhouse is run in discrete 5-minute intervals, after which the operator must manually update log files and restart collection. This limits testing to 5-minute intervals and data is only collected during intentional segments. This limits the use of markers such as engine RPM or bank temperatures and instead encourages the use of an engine response indicator which is not captured by engine's onboard telemetry. The rapid transient testing for example occurred across a longer than 5-minute timeframe, after which the recording was not restarted so these instruments are not available.

4.1.5.1 Engine Performance Indicators

NO_x is used as the primary factor for evaluating engine response to surrogate fuel addition. There are a couple reasons for this choice, including that the 5-gas analyzer runs continuously and that NO_x is a point of current concern for new regulations introduced in Colorado Regulation 7. With the shifting federal regulations, state emissions reduction programs have become a significant forcing factor for the implementation of emissions reduction systems. Should the surrogate compressor vent gas be introduced, but the engine was unable to adjust the main fuel valve accordingly, the in-cylinder fuel/air mixture would be proportionally richer, burn hotter, and thereby produce more NOx.

CH_4 and O_2 in the engine exhaust are additional indicators which are used to demonstrate stable and complete combustion. Methane is widely targeted in emissions reduction efforts. A reduction in methane emissions is the primary intention for this work, and increasing methane slip through the engine is not desirable. Oxygen is the other component for engine combustion and is the direct measurement taken by the engine to ensure stable combustion.

4.1.5.2 Fuel Offset

To produce data demonstrating that the engine is successfully compensating for fumigation fuel input, two data points are needed. These are engine main fuel valve flow and engine surrogate vent gas flow. The engine fuel valve data exported from CAT ET only provides a position for the valve in percentage form, not a mass flow. Mass flow data is, however, collected from the building fuel flow, which measures the total fuel flow into the engine from both the surrogate and main fuel systems. Removing surrogate fuel flow from this flow provides the fuel flow into the engine through the main fuel valve.

4.2 Definition of subsystems

An operational recirculation system captures rod-packing vent gas and meters a controlled portion to the engine intake without compromising safety or engine stability. The system is organized into several subsystems which ensure reliable collection, conditioning, measurement, control, and redundant safety.

4.2.1.1 Gathering

The gathering subsystem ties the packing vents into a common line. It includes connections from each vent source, consisting primarily of the packing vents, distance piece vents and distance piece drains. Depending on operator preferences, it may also include ports for periodic measurement and thermocouples to take measurements close to the process. This subsystem is highly variable depending on engine-compressor packaging and may take the form of hard or soft lines which may be combined at the compressor or not until reaching the recirculation skid. It must be designed in such a way as to not provide a low point for oil settlement.

4.2.1.2 Oil Separation

Oil separation removes liquid and aerosols before the gas reaches meters, valves, or the engine. This subsystem typically consists of a knockout or coalescing device sized for expected flow. This must also include a destination for any collected oil sized sufficiently to capture throughout the duration of the maintenance period. Capture of oil and other fluids will protect downstream components, including flow metering equipment and delicate instrumentation. It also prevents oil carry-through to the intake which could damage components within the engine’s air system or disrupt cylinder combustion.

4.2.1.3 Measurement and Instrumentation

Measurement devices and instrumentation verify that operation stays within limits and provide quantification of recirculated flow. Practical points include vent connections, within the metering section, and at the engine intake, depending on packaging and desired measurements. Temperature measurements should be taken close to the vents to measure accurately. The flowmeter should be suitable for wet gas with a low pressure drop and may require straight upstream and downstream runs.

4.2.1.4 Control and metering

Control and metering deliver the commanded recirculation rate without disturbing the engine’s air-fuel control. A properly sized control valve and a simple local controller with bounded setpoints and reasonable rate limits are sufficient. The objective is smooth, stable metering that responds to operating changes without inducing intake pressure oscillations or transient enrichment/leaning. These devices should be placed far enough downstream from temperature or flow measurement devices to prevent valve response time from delaying safety shutoff actions.

4.2.1.5 Reintroduction

Engine intake integration and mixing introduce the recirculated stream at a location that preserves mixture uniformity and engine stability. A tie-in to the package air system, upstream of the engine intakes would be conventional, with basic mixing geometry (such as a tee or venturi injector) and a check device to prevent backflow, is generally adequate. Placement and line routing should encourage flow and mixing.

4.2.1.6 Safety Bypass

Finally, the safety bypass and vent subsystem ensures packing vent flow can always be exhausted from the compressor, regardless of operating state of the recirculation system. This dedicated pathway routes to the site's vent or flare and is designed such that flow can be immediately diverted during improper conditions. Pressure actuated and electronic valves are positioned for redundant operation to provide multiple mechanisms for gas bypass. This system is also required to include both alarm and flow measurement devices to detect gas being bypassed to atmosphere. [25]

4.3 Techno-Economic Analysis

A bill of materials was generated for the recirculation and recompression configurations to fulfill the subsystem requirements listed above.

The techno-economic analysis was conducted using a discounted cash-flow (DCF) model. “Discounted cash flow (DCF) is a financial model that calculates what an investment is worth today by projecting its future cash flows and adjusting them back to present value using a chosen discount rate.” [54] A DCF analysis compares the cost and rate of return of investing in a project, with the rate of return of investing in another option. Instead of investing in a recirculation system, a pipeline operator could invest in the stock market. Both options have a current cost and a slow rate of return. If it is more profitable to invest elsewhere and there are no other considerations, funding should not be spent on a project.

The discount cash flow formula is:

$$NPV = \sum_{i=0}^{n} \frac{CF_i}{(1+r)^i}$$

Where:

$$r = Discount\ rate$$

$$CF_i = Cashflow\ in\ year\ i$$

[54]

Analysis for this work was done with a 13% discount rate. To evaluate the recirculation and recompression systems defined later in Section 5.2.1., Capital expenses (CAPEX) were derived from the bill of materials (BOM) for that configuration, including parts and installation. Engineering time has been considered for the systems as 8-week and 10-week projects for recirculation and recompression, respectively. Profit margin and administrative overhead have been combined with a single factor of 20%. The resulting costs are in line with quotes received from industry for each system type. Where applicable, income reflected pipeline gas recovered and penalties avoided. Operational expenses (OPEX) were limited to operating power, system maintenance components, and maintenance personnel costs.

CHAPTER 5 – RESULTS

5.1 Surrogate Vent Gas Study

Compressor vent recirculation was simulated on CSU's G3516J laboratory engine using the system described in 4.1.1 and conditions described in 4.1.3.

5.1.1 Emissions

Figure 31 presents surrogate gas flowrate along with NOx emissions over a 1-hour test interval at rated power. NOx was used as an indicator for engine stability and reflects the capability of the engine to compensate for the addition of the auxiliary fuel.

Over the course of the hour, the flowrate of compressor vent surrogate was increased in discrete sections to reach each of the flow rates defined in 4.1.3. Notable increases to NO_x emissions were observed during transients (depicted by the shaded white regions in Figure 1) but quickly returned to ambient once the set point flowrate was reached. This behavior indicates that the engine, without modification, can rapidly and automatically compensate for the additional fuel by metering its primary fuel valve. This is made possible by the closed loop control scheme it employs using its exhaust lambda sensors.

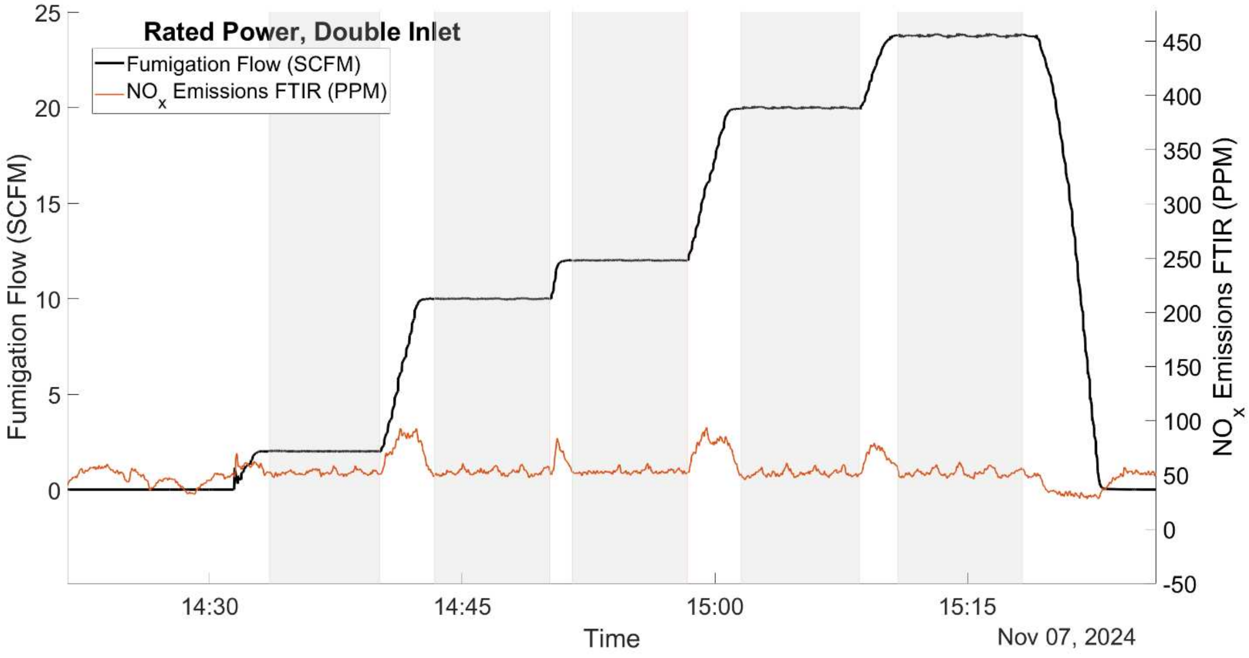


Figure 31: Results of engine exhaust NO$_x$ emissions and surrogate vent gas flow as a function of time. Steady state surrogate introduction highlighted in gray.

Figure 31 shows NO$_x$ emissions alongside the three test sweeps performed. There is an obvious increase in NO$_x$ emissions at each supplementary gas flow change. This increase is noticeably higher than the effect produced by increasing the engine rpm but stabilizes in all cases within approximately 40 seconds of the surrogate flow reaching steady state. After this point, the NO$_x$ emissions return to levels equal to the control.

In Figure 32, average exhaust NO$_x$ emissions are shown as a function of surrogate vent flow for three operating conditions: half rated power, full rated power, and single intake configuration. This data is measured using the lab installed MKS Instruments FTIR [55]. Across all three operating modes, no statistically significant increase in NO$_x$ emissions was observed when surrogate vent gas was introduced. This indicates that the recirculated gas does not adversely affect the combustion process or alter engine-out NO$_x$ levels in a way that would trigger emissions monitoring or exceed compliance thresholds. As a result, the recirculation system can be operated under these conditions without requiring recalibration of emissions controls or reporting protocols. These findings support the capability of surrogate vent gas recirculation to reduce methane emissions without causing significant changes to engine combustion.

The experimental data demonstrated that NO_x and mechanical performance remained unaffected by continuous steady-state recirculation of compressor rod-packing vent gases, apart from a direct offset in the engine's primary fuel consumption by the recirculated gas stream. Exhaust methane slip was a more complicated situation due to possible underlying engine conditions. This outcome represents the EPA's definition of "routed to a process" which specifies that emissions are recaptured and reincorporated into the facility's operation, effectively transforming what would otherwise be wasted emissions into a resource. The approach tested here satisfies this designation, as the recirculated methane replaces the original engine fuel. The collected gas is both serving a beneficial purpose and being consumed through a process similar to the original pipeline gas.

While the tested configuration satisfies the EPA’s criteria for emission control through demonstrated combustion and removal of methane, categorizing it as control is regarded as less desirable, due to the more restrictive requirements, including mandated measurement of combustion efficiency and continuous system monitoring. "Routed to a process" remains the preferable classification because it streamlines regulatory classification and maximizes economic benefit by reclaiming fuel. Vent gas recirculation in the form of route to process serves not only as an environmental compliance strategy but also provides a clear cost advantage, emphasizing its choice as the preferred category under the EPA's methane emission frameworks.

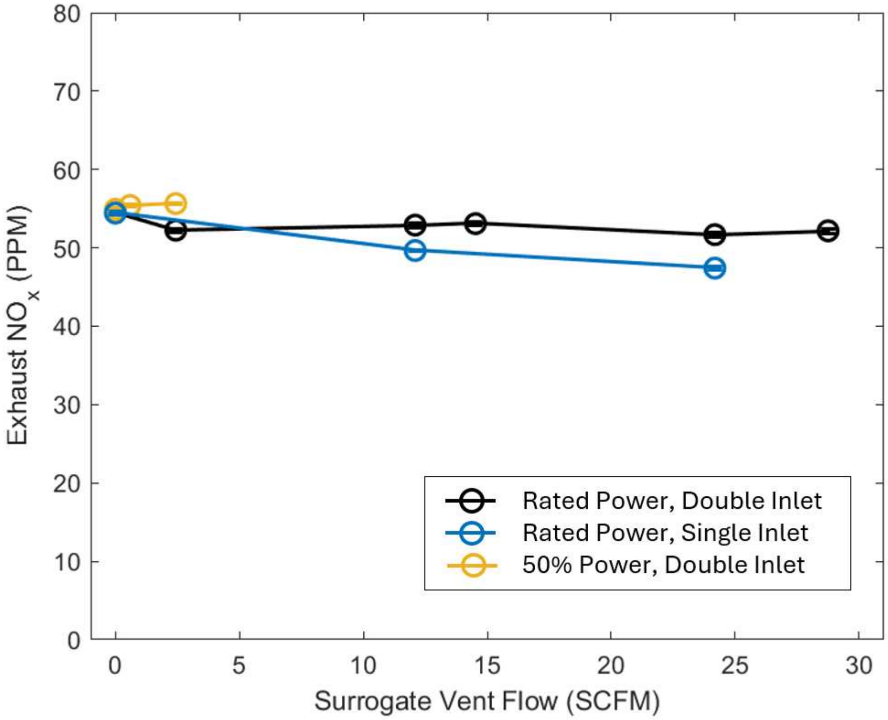


Figure 32: Average exhaust NO_x from G3516J as a function of surrogate vent gas fumigation flow.

The same process is used to generate Figure 33, which shows average exhaust methane emissions across each of the test states, again using lab FTIR equipment. Methane emissions are on average much more consistent than the NO_x emissions across the tests. Each variable test demonstrates strong correlation with the control data, indicating consistent engine behavior under all test scenarios. Although slight deviations are observed, the data points remain outside 95% confidence intervals primarily due to the narrow range of the confidence bands rather than meaningful statistical differences. While transient fluctuations are visible in the raw data, the average methane emissions across the tests align closely, emphasizing that brief peaks do not substantially influence overall performance. This outcome supports the conclusion that supplemental fumigation of vent gases into the engine intake has minimal impact on average methane emissions, providing evidence additional methane does not remain after the process and therefore the extra fuel being added to the engine is combusted efficiently.

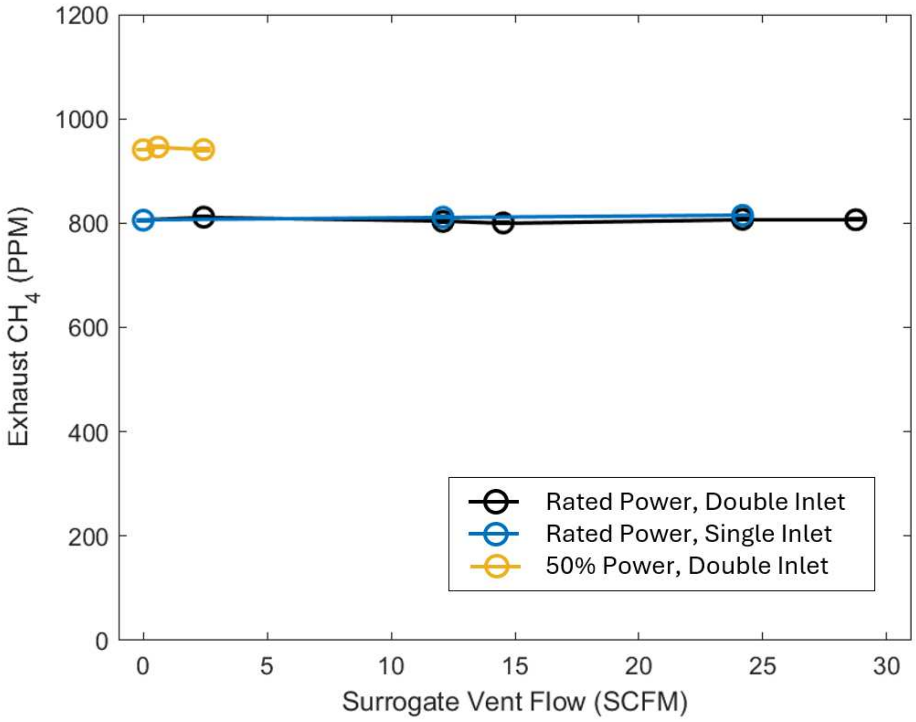


Figure 33: Average exhaust CH_4 slip through G3516J as a function of surrogate vent gas fumigation flow.

Finally, Figure 34 illustrates the average oxygen concentrations, recorded from the lab 5-gas monitor. The variable tests show strong agreement with the control data, demonstrating consistent engine performance. As with methane measurements, the variable test results fall slightly outside a 95% confidence interval due to the tight range on the intervals themselves, rather than significant performance differences.

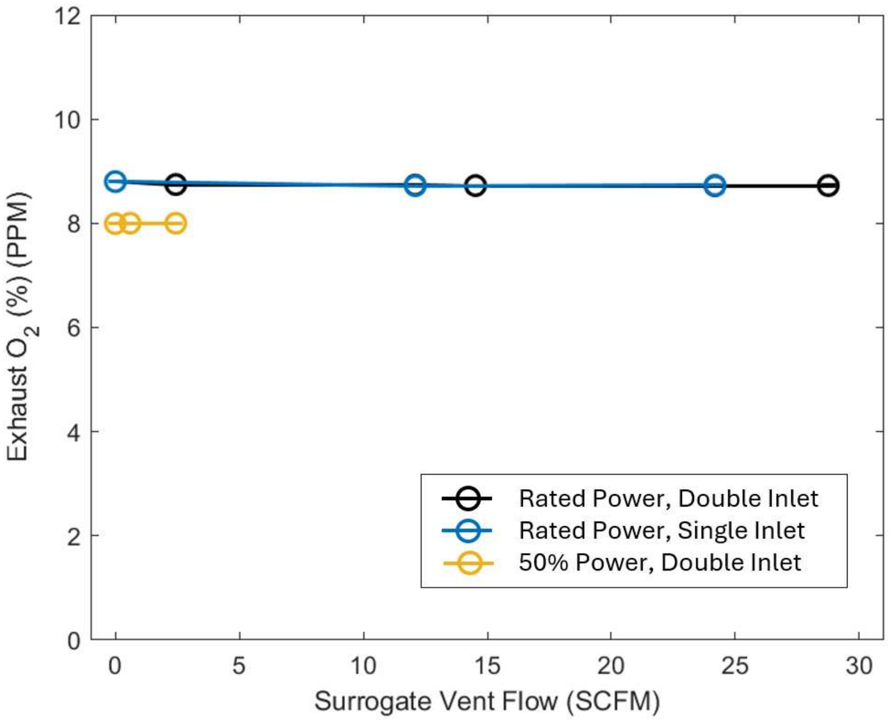


Figure 34: Average exhaust O_2 through G3516J as a function of surrogate vent gas fumigation flow.

The absence of any notable decrease in oxygen concentration, combined with the consistency of the methane slip rate in Figure 33 above, suggests that combustion is occurring normally. The engine's control system is correctly adjusting air-fuel ratios to compensate for the additional fuel supplied by recirculated vent gases. These findings validate the operation of the engine control loop and the route to process categorization desired for the system.

1.1.1. Fuel Offset

Figure 35 presents the relationship between volumetric flow rate of the surrogate vent gas and the engine's fuel consumption during the rated power tests. The first line, “Total Engine Fuel Consumption” represents the complete flow of gas into the engine, showing a consistent fuel consumption rate as the vent gas volume changes. The second, labeled "Surrogate Vent Gas Flow" shows flow of vent gas fumigated into the engine intake. The third line shows the fuel flow through the engine primary fuel valve. If the system is operating as expected, the fuel total fuel flow though the engine should remain constant regardless of the source of the fuel. This means that as the surrogate flow is ramped up, the engine fuel should reduce by an equivalent amount.

The primary fuel flow represented in Figure 35 is inversely proportional to the surrogate gas flow, demonstrating the fuel offset produced by recirculating vent gases.

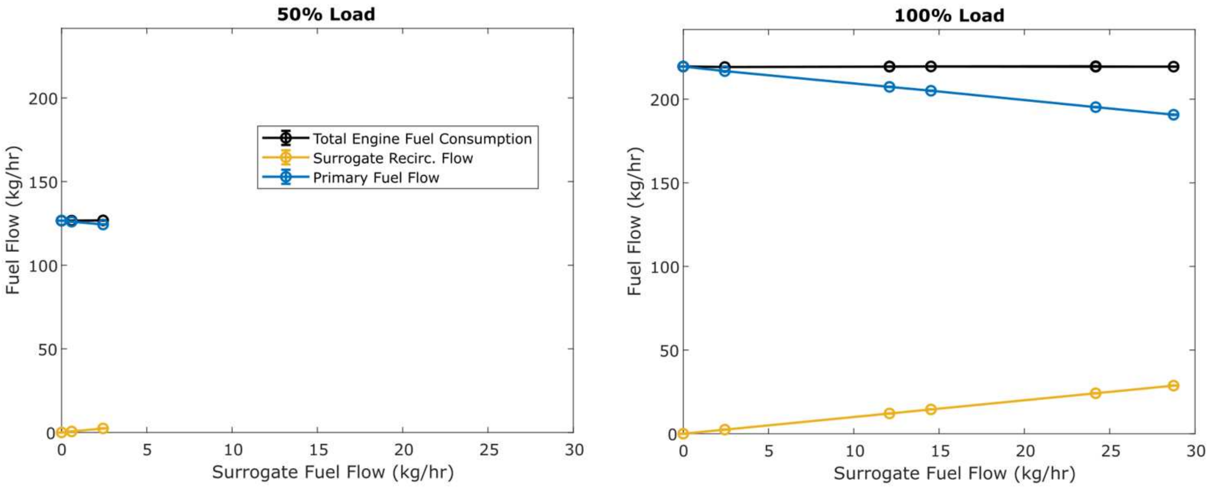


Figure 35: Observed fuel consumption as a function of surrogate vent gas flow during rated power fumigation testing into both engine inlets. Demonstrates fuel offset by surrogate fuel introduction.

1.1.2. Rapid Transient Testing

Figure 36 shows the results of rapid fuel transient testing. During this testing, the engine was subjected to short “burps” of fuel from the surrogate system. This figure shows several of these transients conducted under differing conditions. Fuel was rapidly increased to a set point and then reduced. The peaks generally show progressive increases in transient rate to determine NO_x release and engine stability limits. The first significant peak is an increase of 10 SCFM across 2 seconds, during which the NO_x levels used as a marker increase sharply, but as with previous transient tests, return to baseline levels when the system reaches steady state. The second peak is a ramp to 20 SCFM across 4 seconds. Despite showing a much more noticeable NO_x peak, the engine was again able to compensate and return to expected levels. Next, a sequence of peaks are present, ramping from 0 to 24 SCFM surrogate fuel flow across 4 seconds each. NO_x levels peak at this point but return to baseline after the fuel stabilizes, showing that the engine controller is still able to handle these transients. Finally, a single peak is present with no smaller peaks to provide ramping. This peak again reaches 24 SCFM within 4 seconds. This test caused detonation in two cylinders, and the engine safety system forced a shutdown. Given that the engine handled the previous peaks of the same magnitude, it is believed that the system already being in a transient state allows it to compensate for a larger change. After this shutdown, the engine was restarted and continued operation with no noticeable adverse effects. These results demonstrate the engine's ability to handle sudden spikes and drops in vent gas supply without significant performance or safety impacts. This helps to validate the operation of the fumigation process during packing blowout conditions before safety systems can divert flow.

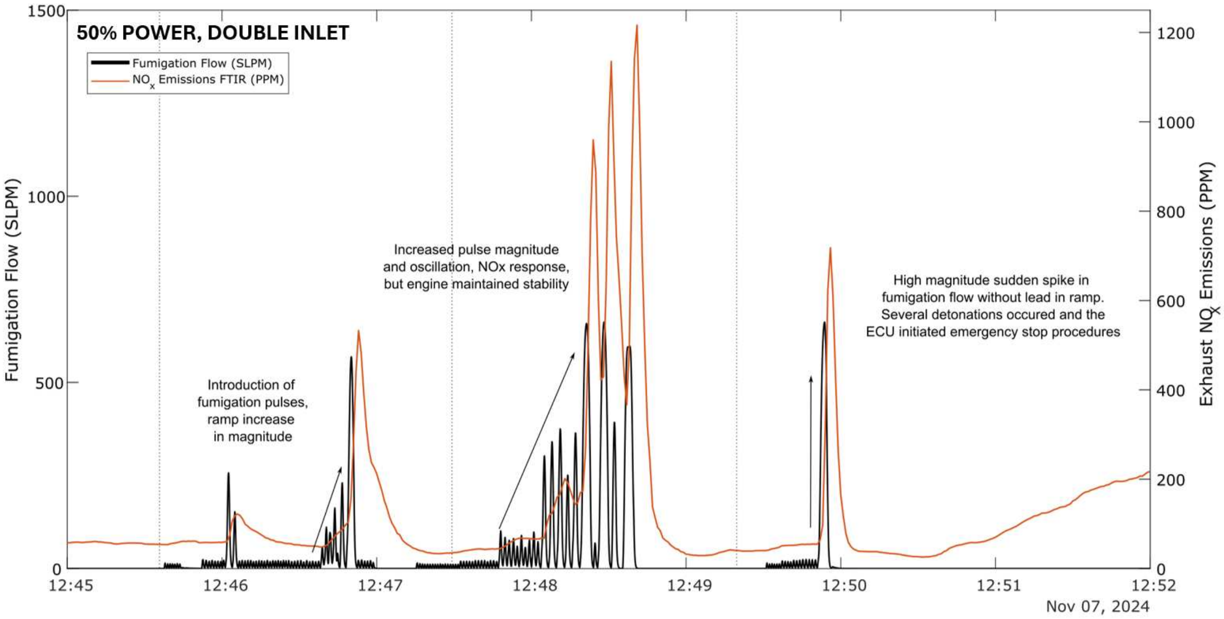


Figure 36: Observed engine exhaust NO$_x$ emissions as a function of surrogate vent gas flow during rapid transient fuel testing

5.2 Techno-Economic Analysis

A techno-economic analysis is conducted below, consisting of an analysis of system components and creation of a bill of materials (BOM), and then a discount cashflow calculation for system payback time.

5.2.1 System Configurations and Bill of Materials

Both the recirculation and recompression systems share a common design in their functional goal and core components. Each is designed to capture rod packing vent gas to prevent atmospheric release and direct this back to the system, eliminating methane emissions rather than venting or flaring. This overlap results in a very similar bill of materials for both. P&ID diagrams for each system are shown in Figure 37 and Figure 38, with the only significant change being the componentry in the final delivery mechanism. These systems are built around the subsystems defined in section 4.2.

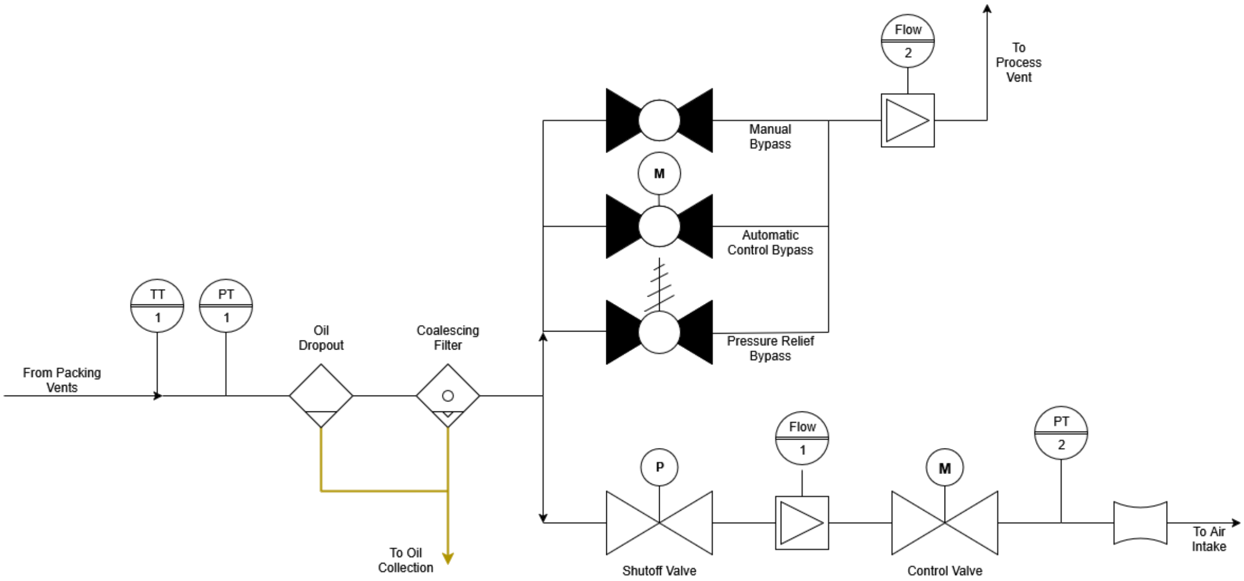


Figure 37: Illustration of P&ID for packing vent gas recirculation system used in this study.

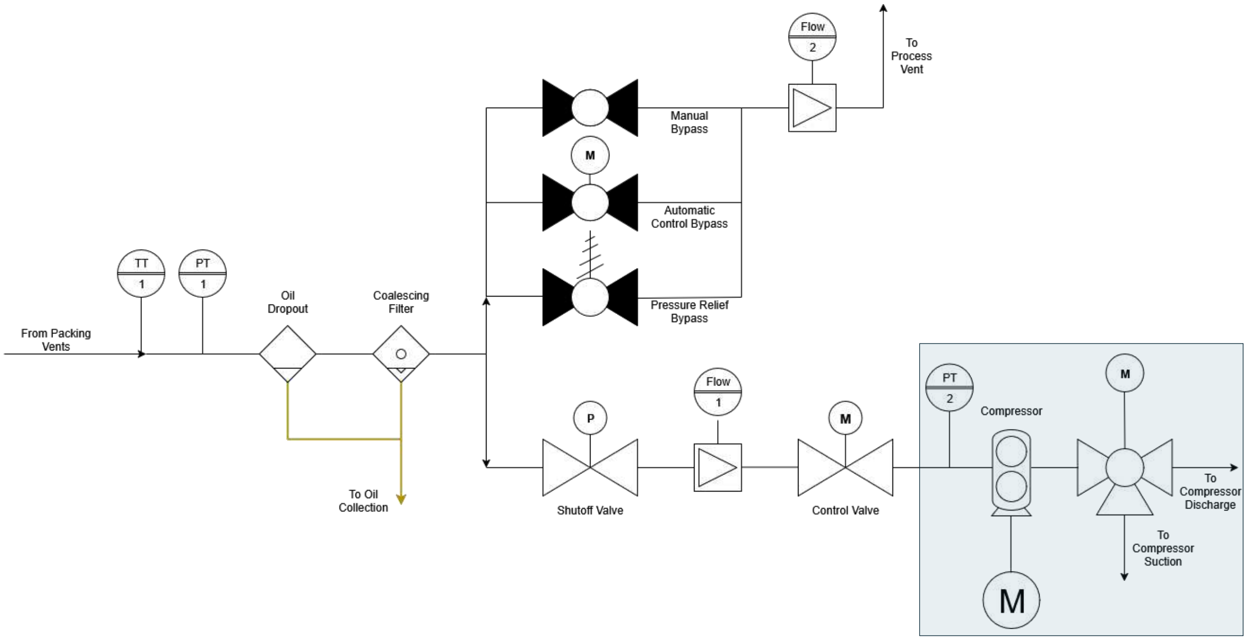


Figure 38: Illustration of P&ID for packing vent gas recompression system used in this study, functionally similar to recirculation system shown in Figure 37: Illustration of P&ID for packing vent gas recirculation syste, with added recompression subsystem.

Both systems principally serve to route gases along two pathways. The primary pathway consists of filtration, pressure regulation, and flow control, resulting in the gas reaching either the engine or pipeline to produce useful fuel. Each also incorporates a secondary pathway for emergency venting in the event of high backpressure or system failure. This line includes additional bypass valves, a remote valve for automatic bypass and backpressure valve for safety. Together, these options provide controlled recirculation under normal conditions and reliable venting to maintain engine safety in the event of a system fault or packing failure. Both pathways and systems incorporate pressure sensors and flow meters to ensure safe operating conditions and maintain flow within acceptable limits. These also provide operators with flow data which can be used to determine packing condition. Both recirculation and recompression systems are typically designed to tie directly into existing vent lines which provide the fuel from the vents and allow a pathway for the bypass system.

As of the writing of this report, the Waste Emissions Charge has been blocked from implementation. Given the magnitude of this charge, and likelihood of reimplementation, the DCF analysis has been performed separately both with and without the consideration of emissions penalties. These penalties introduce a significant forcing factor given their magnitude compared to that of the fuel cost alone.

Materials and installation required for a recirculation system are expected to have a capital cost of $59,000 as shown in Table IX.

Table IX: Example bill of materials for vent gas recirculation system. Emissions penalties are not included in yearly savings within BOM.

CAPEX				
Source	Part	Cost	Count	Total Cost
Plumbing				

McMaster-Carr	Pipe Fitting	$(79.05)	14	$(1,106.70)
McMaster-Carr	304 Tubing	$(165.09)	7	$(1,155.63)
McMaster-Carr	Tube Tee	$(219.94)	6	$(1,319.64)
McMaster-Carr	Steel Pipe	$(240.39)	1	$(240.39)
McMaster-Carr	Pipe Cap	$(14.00)	1	$(14.00)
McMaster-Carr	Stainless Hose	$(176.75)	1	$(176.75)
McMaster-Carr	Pipe Elbow	$(25.08)	3	$(75.24)
Vent				
Emerson	Back Pressure Regulator	$(2,500.00)	1	$(2,500.00)
Emerson	Actuated Bypass Valve	$(1,500.00)	1	$(1,500.00)
Emerson	Flow Meter	$(9,000.00)	1	$(9,000.00)
Recirculation				
Emerson	Actuated Valve	$(1,500.00)	1	$(1,500.00)
McMaster-Carr	Actuated Shutoff Valve	$(314.49)	1	$(314.49)
McMaster-Carr	Manual Isolation Valve	$(91.32)	2	$(182.64)
Rosemount	Pressure Transmitter	$(1,155.00)	2	$(2,310.00)
Solberg	Liquid Separator	$(1,930.00)	1	$(1,930.00)
Solberg	Coalescing Filter	$(131.00)	1	$(131.00)
Emerson	Flow Meter	$(9,000.00)	1	$(9,000.00)
Emerson	Temperature Transmitter	$(700.00)	1	$(700.00)
Allen-Bradley	PLC	$(900.00)	1	$(900.00)
Staff		Hourly Pay	Hours	Total Cost
Engineer		$(60.00)	320	$(19,200.00)
Technician		$(35.00)	160	$(5,600.00)
Welder		$(30.00)	16	$(480.00)
Total CAPEX				$(59,336.48)
OPEX				
Source	Part	Cost	Count	Total Cost
Maintenance				
Solberg	Coalescing Filter Element	$(131.00)	1	$(131.00)
Chevron	Valve actuator oil	$(20.00)	1	$(20.00)
McMaster-Carr	Valve actuator O-ring	$(3.00)	2	$(6.00)
Staff		Hourly Pay	Hours	Total Cost
Technician		$(35.00)	5	$(175.00)
Total Yearly OPEX				$(332.00)
Income				

Source	Savings	(Unit)		Total Savings
CNG Savings	2.5	$/MSCF		$7,900.00
Emissions Penalties	1500	$/ton		$95,370.00
Total Yearly Savings				$7,900.00

Despite significant overlaps in design, the recompression system requires additional hardware to reintroduce gas at a higher pressure. The proposed recompression system includes a rotary screw compressor to boost the pressure of the captured gas, enabling reinjection into the pipeline or other high-pressure locations. This compressor is paired with a variable frequency drive (VFD) to optimize power for flow rate and load conditions. These additions increase both capital expenditure due to the higher equipment cost and operational expenses due to power consumption and maintenance needs. The manufacturing and installation cost of the compression system is expected to be $123,000 as shown in Table X.

Table X: Example bill of materials for vent gas active recompression system. Emissions penalties marked in red text, not included in yearly savings BOM.

CAPEX				
Source	Part	Cost	Count	Total Cost
Plumbing				
McMaster-Carr	Pipe Fitting	$(79.05)	14	$(1,106.70)
McMaster-Carr	304 Tubing	$(165.09)	8	$(1,320.72)
McMaster-Carr	Tube Tee	$(219.94)	6	$(1,319.64)
McMaster-Carr	Steel Pipe	$(240.39)	1	$(240.39)
McMaster-Carr	Pipe Cap	$(14.00)	1	$(14.00)
McMaster-Carr	Stainless Hose	$(176.75)	1	$(176.75)
McMaster-Carr	Pipe Elbow	$(25.08)	3	$(75.24)
Vent				
Emerson	Back Pressure Regulator	$(2,500.00)	1	$(2,500.00)
Emerson	Actuated Bypass Valve	$(1,500.00)	1	$(1,500.00)
Emerson	Flow Meter	$(9,000.00)	1	$(9,000.00)
Recompression				

Emerson	Actuated Valve	$(1,500.00)	1	$(1,500.00)
McMaster-Carr	Actuated Shutoff Valve	$(314.49)	1	$(314.49)
McMaster-Carr	Manual Isolation Valve	$(91.32)	2	$(182.64)
Rosemount	Pressure Transmitter	$(1,155.00)	2	$(2,310.00)
Solberg	Liquid Separator	$(1,930.00)	1	$(1,930.00)
Solberg	Coalescing Filter	$(131.00)	1	$(131.00)
Emerson	Flow Meter	$(9,000.00)	1	$(9,000.00)
Emerson	Temperature Transmitter	$(700.00)	1	$(700.00)
Allen-Bradley	PLC	$(900.00)	1	$(900.00)
Atlas-Copco	Compressor	$(34,489.50)	1	$(34,489.50)
Schneider Electric	VFD	$(2,404.37)	1	$(2,404.37)
McMaster-Carr	Diverter Valve	$(729.88)	1	$(729.88)
Staff		Hourly Pay	Hours	Total Cost
Engineer		$(60.00)	400	$(24,000.00)
Technician		$(35.00)	160	$(5,600.00)
Welder		$(30.00)	40	$(1,200.00)
Total CAPEX				$(123,174.38)
Ongoing				
Source	Part	Cost	Count	Total Cost
Maintenance				
Solberg	Coalescing Filter Element	$(131.00)	2	$(262.00)
Chevron	Valve actuator oil	$(20.00)	1	$(20.00)
McMaster-Carr	Valve actuator O-ring	$(3.00)	3	$(9.00)
Ingersoll	Compressor maintenance kit	$(181.99)	1	$(181.99)
Staff		Hourly Pay	Hours	Total Cost
Technician		$(35.00)	10	$(350.00)
Energy		Yearly Cost		Total Cost
City of Fort Collins	Electricity	$(1,522.00)	1	$(1,522.00)
Total Yearly OPEX				$(2,344.99)
Income				
Source	Savings	(Unit)		Total Savings
CNG Savings	2.5	$/MSCF		$7,900.00
Emissions Penalties	1500	$/ton		$95,370.00
Total Yearly Savings				$7,900.00

5.2.2 Discount Cashflow Analysis

Four discount cashflow analyses are presented below. Both recirculation and recompression systems are considered, with and without the Waste Emissions Charge.

A discount cashflow analysis for each of the four system configurations is presented below. Fuel sale price with or without emissions penalties account for yearly inlays and outlays include system capital expenses and yearly maintenance. A hurdle rate of 13% is used for this analysis and the system lifetime is expected to be 10 years.

Without emissions penalties, the 10-year NPV of the recirculation system is $(18,271). Using the values presented in the recirculation bill of materials above, the system will not pay for itself within 10 years. A plot of both yearly expenses and revenue, as well as the system NPV, is shown in Figure 39.

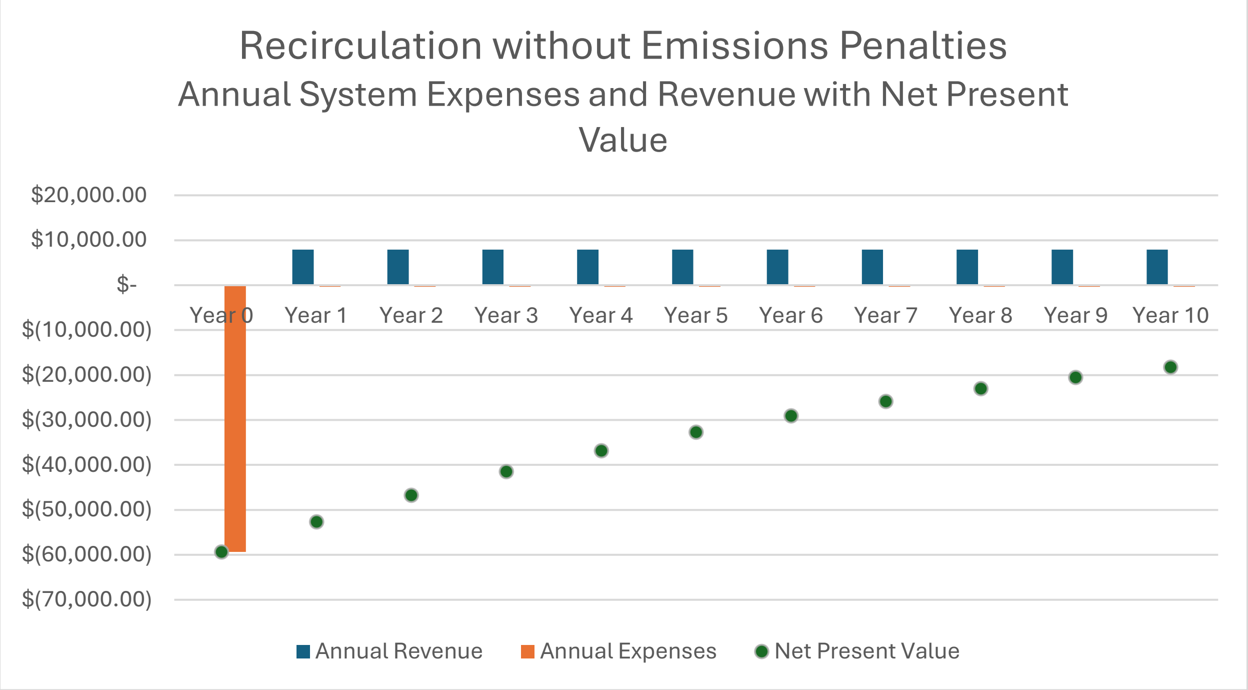


Figure 39: Annual system expenses and revenue with net profit trend for recirculation system. No consideration of emissions penalties.

With emissions penalties considered, shown in Figure 40, the recirculation system's low cost is significantly less than the potential penalties for even a single year. Therefore, the system breaks even within the first year. For the rest of the system lifetime, the maintenance cost is negligible, and the consistent fuel and emissions savings continue to provide a return on investment.

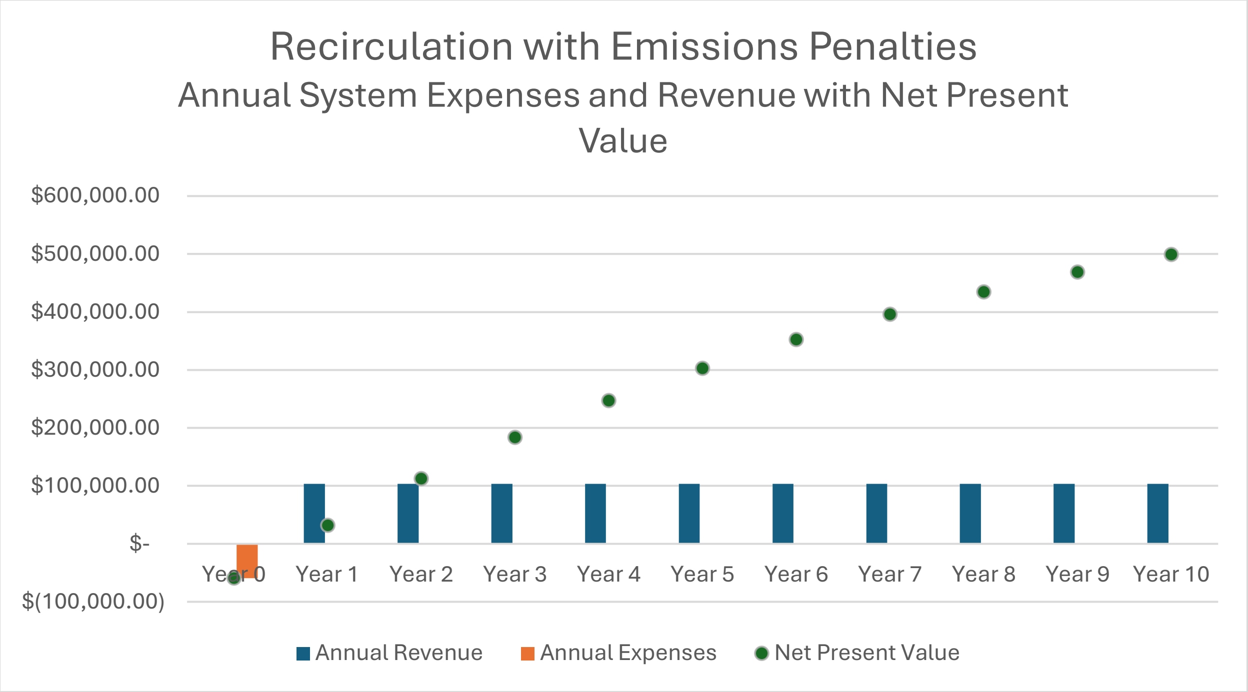


Figure 40: Annual system expenses and revenue with net profit trend for recirculation system. Emissions penalties considered.

The high cost of the active recompression system, requiring the addition of a compressor and control system, shown in Table X, add significantly to the system cost. In addition, the added compressor requires power and over doubles the ongoing costs, resulting in it failing to have a positive 10-year NPV when methane penalties are not considered, as shown in Figure 41. A recompression system, however, has the capability to capture gas from blowdowns, which can range widely in volume, or from pressurized holds, during which the rod packings contract away from the rod and can leak at rates 50 times higher than during operation [56]. Pressurized holds are better treated using other methods, such as static seals, but a recompression system could be considered to reduce emissions in these conditions, albeit at the cost of energy for the compressor.

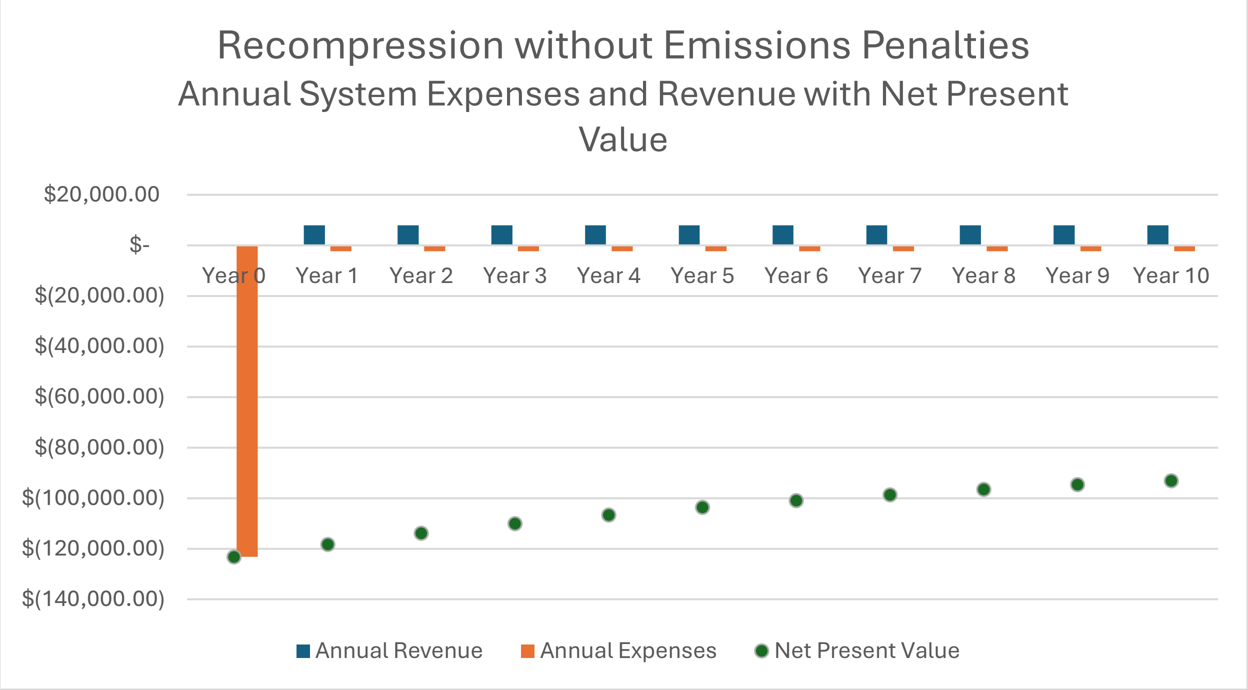


Figure 41: Annual system expenses and revenue with net profit trend for active recompression system. No consideration of emissions penalties.

As with the recirculation system, the capital expenses of the recompression system are quickly outweighed by emissions penalties. Therefore, the recompression system also breaks even during the second year of operation and produces a profit for the rest of the system lifetime. This is shown in Figure 42.

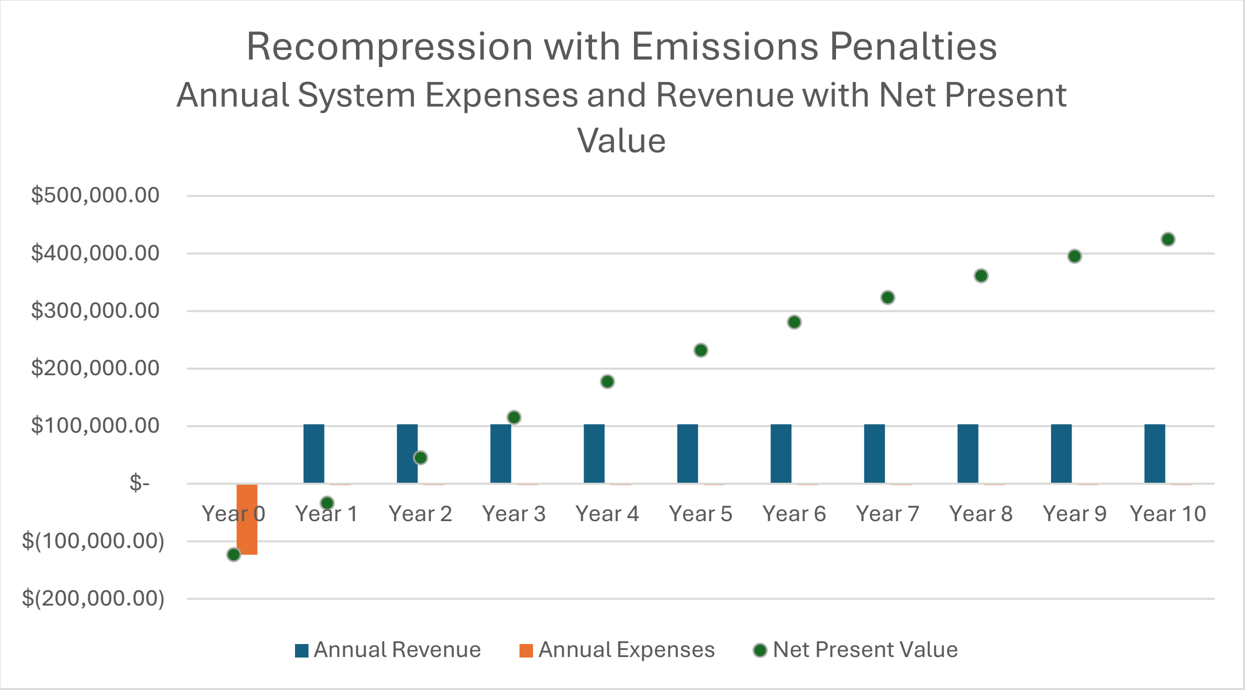


Figure 42: Annual system expenses and revenue with net profit trend for active recompression system. Emissions penalties considered.

5.3 Regulatory Considerations

5.3.1 Waste Emissions Charge

In March 2025, the Waste Emissions Charge (WEC) introduced by the Inflation Reduction Act was prohibited from taking effect under the Congressional Review Act. [57] The analysis presented herein was prepared prior to these decisions and relies heavily on the WEC penalties that were expected to come into effect this year. The ebb and flow of the federal regulatory landscape is inevitable, and though recent deregulation has put many at ease, efforts to hedge against future emission reduction policies are likely wise. Future emission-based penalties introduce a significant forcing factor for the adoption of capture/reuse systems compared to that of the fuel savings alone, a fact that is likely to once again become relevant in the coming decade.

Considering a site which has reached the 0.05% transmitted gas leakage threshold – the upper limit of permitted leakage under WEC before fines are imposed – the cost of fuel gas is significantly lower than the cost of emissions penalties for the WEC. Using $2.5 per MSCF as fuel cost to the pipeline operator [58] and normalizing this cost per metric ton to align with the $1,500 per metric ton emissions cost [57], the fuel cost is $124 per metric ton as shown in Listing B4 in the appendix. Accounting for only these direct costs from loss of pipeline gas, the summed charge for the operator is $1624 per metric ton in lost gas revenue and emissions charges. Gas cost accounts for 7.6% of this to the operator and possibly less depending on payment agreements. Therefore, the direct financial benefit of this system is reduced by the remaining 92.4% without consideration of the WEC.

5.3.2 Section OOOO

Under NSPS Subpart OOOO, a closed-vent system (CVS) used as a route-to-process must be designed and operated to:

(i) capture and convey all vented gas to a process for productive use in a manner similar to the original gas. In this case the engine intake, which is a use of some of the original gas;

(ii) maintain no detectable emissions using sealed, properly sized piping with no open-ended lines;

(iii) control or monitor any bypass so inadvertent venting cannot occur;

(iv) undergo initial and periodic inspection with prompt repair of discovered leaks; and

(v) retain records documenting design, inspections, and repairs. [25]

The testing here shows that the engine productively uses the recirculated rod-packing gas as fuel in the same manner as the original fuel supply: air-fuel-ratio control remained stable, NO_x stayed within baseline variability, and no combustion or operability penalties were observed. During steady-state recirculation, the engine exhibited no adverse effects on performance, NO_x, or AFR, and smooth transients (tie-ins and modest load changes) likewise produced no issues. Because these steady and smoothly transient conditions constitute >95% of normal operation, minimizing downtime shifts the remaining uncertainty from fundamental feasibility to commercial system integration and long-term operation; no outstanding theoretical questions remain regarding the viability of recirculation.

CHAPTER 6 – CONCLUSION

6.1 Conclusion

The project objectives defined in section 3.4 are design and testing of a surrogate vent gas recirculation system, system design and techno-economic analysis for a rod packing recirculation system, and regulatory classification of a rod packing recirculation system.

6.1.1 Surrogate Vent Gas Recirculation Study

The goal for the surrogate vent gas recirculation system was to evaluate the efficiency of rod packing recirculation systems, efficacy of engine inlet fumigation as a solution to offset fuel costs, and determine engine drop-in limits for intake fumigation. This work has shown that surrogate rod packing fumigation offsets fuel required by the engine and combusts the external fuel cleanly to produce power without affecting combustion byproducts. Engine limits for maintaining stable operation under transient fuel introduction were determined to be -6/+3 SCFM/min. An absolute limit to transient fumigation was found at a 24 SCFM pulse across 4 seconds, after which the engine was forced to shut down.

During steady fumigation conditions, the engine remained stable, and the control system compensated for the steady addition of fuel. In a lab setting, closed-loop fuel control incorporated the extra flow and held commanded setpoints. The engine controller maintains air–fuel ratios and speed at their targets. When the engine experienced both test-induced transients and incidental disturbances, it compensated effectively, maintaining control over the air–fuel ratio and therefore power across the expected recirculation operating envelope. As a result, the surrogate recirculation system operated without measurable adverse impact on performance, and a production system configured similarly is expected to do so as well.

In parallel, the fuel system's response and the absence of changes in regulated emissions indicate that recirculated vent gas is being put to productive use rather than simply passed through the engine and exhausted. The added flow reduced the net fuel required from the engine fuel valve while maintaining comparable exhaust-emissions behavior, implying that the captured stream is combusted effectively rather than vented. Taken together, these observations support the central objective of routing rod-packing vent gas to a productive end-use while preserving engine performance and compliance characteristics.

6.1.2 System Design and Techno-Economic Analysis

The system design and techno-economic analysis objective determined that a rod packing vent gas recirculation system is not economically feasible at the current time considering only existing federal regulation. However, at either the state level, or considering the possible reintroduction of the Waste Emissions Charge, these systems can become both profitable and necessary. Under the waste emissions charge, a recirculation system could have a 10-year NPV of approximately $500,000.

Capital costs are likely to be dominated by engineering time and implementation on retrofit installations. Economies of scale from standardized designs and repeatable installation work will reduce costs on packages with recirculation integrated from day one. Policy trends, however, continue to move toward explicit methane fees and tighter standards; if a fee comparable to the WEC is implemented, the value proposition improves and can approach typical hurdle rates assumed by operators. Regardless of near-term pricing, companies may elect to deploy these systems to satisfy internal emissions targets or respond to investor expectations. These factors were outside the economic scope here but may influence adoption decisions.

6.1.3 Evaluation of Regulatory Classification

Finally, the evaluation of regulatory classification is an important consideration before adoption of rod packing recirculation. The system must be shown to fit within existing regulatory frameworks. This work has shown that these systems can meet all OOOO requirements for route to process systems.

Regulatory momentum is shifting toward deeper methane control at the state level. Even if national incentives fluctuate, state-level economics and compliance drivers may still justify projects, particularly in Colorado, Pennsylvania, and California, where methane-control frameworks, inspection frequency, and enforcement emphasis are advancing ahead of federal implementation. In such jurisdictions, route-to-process classification aligns with existing closed-vent provisions and streamlines monitoring and reporting practices.

For deployment strategy, it is strategically simpler and cheaper to incorporate recirculation capability into new sites and major overhauls starting now rather than executing one-off retrofits later. These systems require space, power, and panel capacity. Beyond footprint, power, and panel capacity, practical layout decisions include specifying compatible connections, designing clear tie-in points, and arranging a direct, minimal-length flow path from the rod-packing vents through the recirculation skid and then to the engine air intake. Early implementation of the recirculation system simplifies operator training and makes data collection and communications easier to implement, improving long-term reliability and maintainability.

While laboratory and system-integration results are encouraging, further field testing is required to verify robustness and to quantify sustained emissions reductions and emissions capture effectiveness under real operating variability. Priority future work includes validation of performance across multiple engine models and load ranges and long-duration operation to quantify maintenance needs and fouling/oil-carryover effects. Completing this field program will establish a field-proven solution and the operation materials required for broader adoption.

6.2 Continued Gaps in Literature

Although commercial interest in recirculating compressor vent gas has accelerated, evidence of field performance under operating conditions remains sparse. Our prior year's work on a laboratory surrogate is valuable for fundamental implementation of the technology but has significant shortcomings as an analogue to field implementation. These tests used clean, downstream gas with a controlled composition and minimal entrained oil, water, or solids. While this approach isolated results to the engine controller and simplified filtration, it does not represent variability expected on field engines.

Gathering and midstream assets can differ substantially in methane fraction, heavier hydrocarbons, diluents, and sulfur species, all of which may reduce the effectiveness of a deployed system. These systems include several components which may be affected by sour gas composition or oil entrainment. Oil build-up may alter coalescer performance, pressure drop, fouling rates, and engine intake health over time. Robust understanding of these compositional effects, especially under high-oil, high-C_2+ conditions, has not been documented with third-party data.

6.2.1 Oil Entrainment and Filtration Efficiency

Neither existing literature nor this work have presented data on oil characteristics under realistic compressor duty. Characterization of oil droplet size distributions, concentrations, and variability in rod-packing vents across operating states is important for the design and integration of rod packing recirculation systems. Without comprehensive oil measurements, filter design is unlikely to capture necessary oil and breakthrough may occur.

6.2.2 Engine Response to Fuel Constituents

This work established initial drop-in limits for a natural gas engine, finding no limits even at flow extremes on clean, dry midstream gas on a single engine type. The limit for rapid transients was established. These limits are however expected to vary across combustion conditions (rich-/lean-burn; two-/four-stroke), fuel composition, fuel system, and engine manufacturer. The resulting effects from recirculation on a wide range of engine styles require further documentation to optimize recirculation systems for each engine type. These limits are expected to change if oil carryover or heavy hydrocarbon constituents are non-negligible.

6.2.3 Recirculation System Reliability

Long-term reliability, safety, and compliance with regulatory classification remain poorly documented. Independent documentation of recirculation system response during varied failure modes including overpressure, excessive flow, and coalescer saturation is not available. The system must maintain 95% uptime and delivery efficiency, failing which, site permitting using these systems will not be available. Further validation that existing safety systems are sufficient to protect the engine and fit within emissions regulations during unexpected conditions is necessary.

6.2.4 Extended Economic Analysis

Further techno-economic analyses that include financial burden due to system design and commercialization, maintenance, downtime, and fuel offset considering differing pipeline contracts would allow more nuanced operator decision-making.

6.3 Future Work - Packing Vent Recirculation Long Duration Field Trial

6.3.1 Field Trial Description and Objectives

This field trial will install a commercial rod-packing vent-gas recirculation skid on an operating compressor package. A Spartan Controls SlipStream® system will serve as the primary recirculation platform, providing telemetry on vent-gas flow and system uptime while CSU independently validates key measurements. The study will run under normal package operating conditions.

- Validate SlipStream® telemetry for flow rate and uptime with independent CSU measurements.
- Expand on a low-cost flow monitoring solution by quantifying the relationship between measured vent flow and packing-vent temperature and other conditions including external temperature and packing vent pressure.
- Demonstrate ≥95% system uptime and capture efficiency to support classification as route to process.
- Evaluate durability risks by inspecting air-intake components (filters, turbocharger, intercooler/ducting) for oil deposition.

6.3.2 Methodology

A Spartan Controls SlipStream® skid will be installed on a field compressor, providing primary measurement for vent-gas flow and uptime, while CSU instrumentation performs redundant measurements for validation. Diagrams of the Slipstream® system are shown in Figure 43 and Figure 44. This system includes built-in safety systems and instrumentation to enable field validation of capture efficiency.

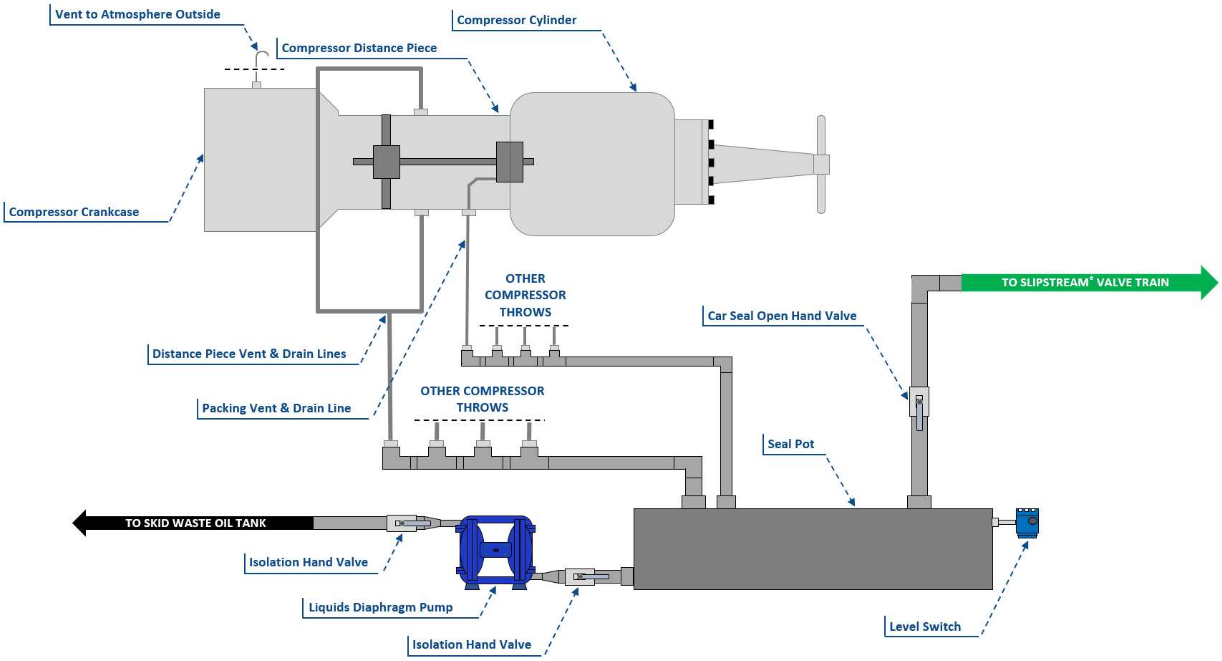


Figure 43: Slipstream® gathering and oil removal systems. Image provided by Spartan Controls.

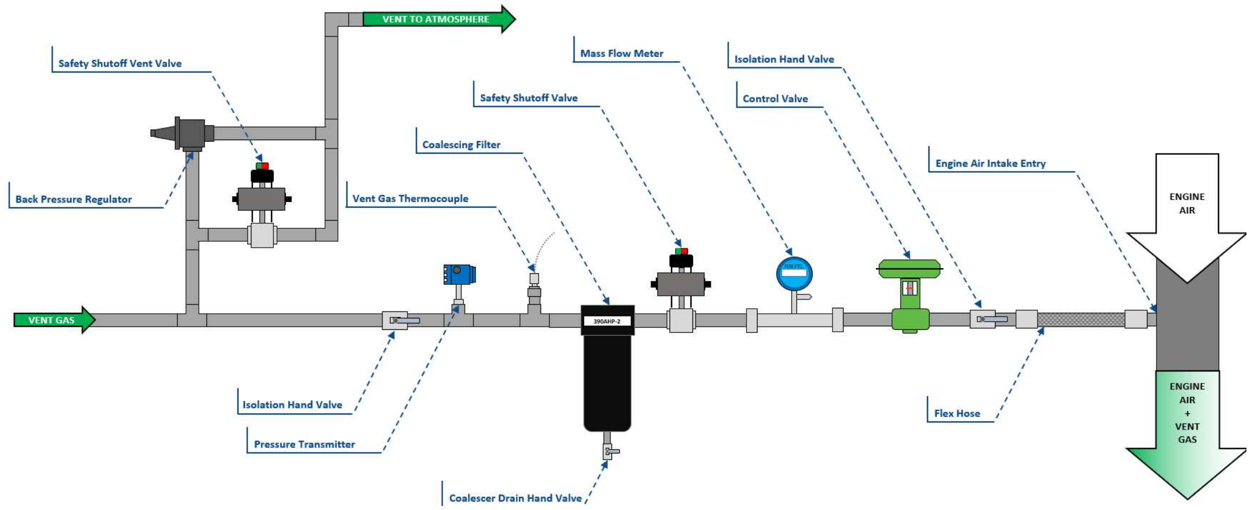


Figure 44: Slipstream® valve train. Image provided by Spartan Controls.

Continuous data collection will log vent-gas pressure, temperature, and flow and periodic sampling will quantify oil concentration upstream and downstream of the filter to assess coalescer efficiency. To help operators implement cost-effective monitoring, thermocouples will be mounted on packing vent lines and their measurements correlated with simultaneously measured vent flow, external temperature, and compression. This will produce a correlation table which will allow operators to accurately estimate flow using lower cost monitoring equipment than flow meter instrumentation. During planned engine downtime, the air-intake path, including air filters, turbochargers, and the engine aftercooler, will be disassembled and inspected for oil deposition.

In order to remain within the project budget, the data collection system was originally designed to measure all four vent lines with orifice meters as shown in Figure 45. These orifice meters would be calibrated by a flow meter inline with one of the orifice meters as shown in Figure 45.

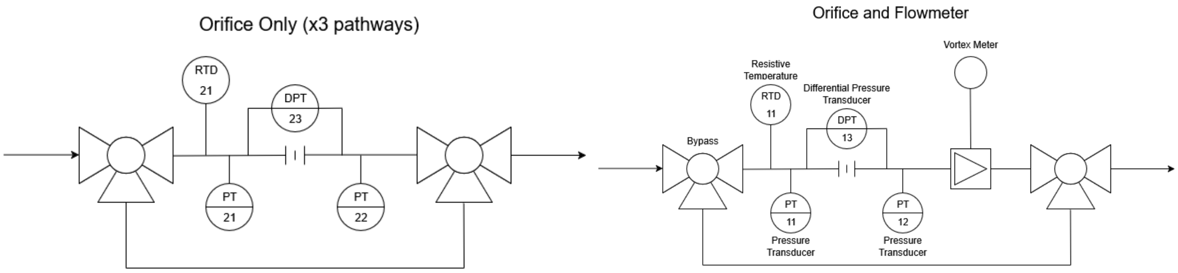


Figure 45 (a): Orifice meter only configuration for measurement of packing vent conditions. (b): Orifice meter inline with flow meter configuration for measurement and calibration of packing vent conditions

This is not an ideal solution. There are no orifice meters commercially available at the size required to provide proper data collection for a packing flow. Therefore, this would require the manufacture and assembly of bespoke orifice meters. As well, there is expected to be significant oil flow through these meters, so an oil drain or bypass would be crucial. Producing an orifice meter with a drain at this scale will be made difficult by oil surface tension. The oil may be able to flow directly through the flow meter if it is placed at a steep enough angle, but this is complicated by the requirement for the entire gathering system to flow downhill and a short distance between the packing vents and the floor.

If the system can be made cost permissible, it would be ideal to redesign this system using direct flow meter measurements for each packing vent. The estimated cost for this change is approximately $5,000 if using blowby meters or $20,000 if using packing vent meters. This change would result in lower error, more direct traceability to certified measurements, and simpler assembly and installation.

6.3.3 Expected Results

It is expected that agreement will be observed between SlipStream® telemetry and CSU measurements, establishing confidence in automated flow and uptime reporting. The correlation work will produce a quantified relationship between packing-vent thermocouple temperatures and true vent flow, enabling operators to track changes in leak rate using inexpensive sensors instead of dedicated meters on every line. The system uptime of at least 95% will be documented, demonstrating that vent gas is consistently routed to the engine intake and supporting route-to-process treatment. Periodic measurements will confirm sufficient oil removal efficiency and intake inspections are expected to link any observed oil deposition to measured downstream oil concentrations and maintenance intervals, informing filtration sizing and service schedules.

6.3.4 Conclusion

This field trial will provide validated performance data, confirm high uptime, and deliver a low-cost monitoring solution for operators. Together with filtration efficiency measurements and air system inspections, the results will address key durability concerns and support regulatory classification as route to process, reducing methane emissions while offering guidance for operators and maintainers.

6.4 Future Work - Colorado State University Methane Emissions Reduction Program Study

6.4.1 Field Trial Description and Objectives

This work is funded by the U.S. Department of Energy's Methane Emission Reduction Program (MERP), a national initiative to accelerate field deployment of technologies that cut methane from natural-gas engine–compressor systems. Our MERP project will integrate four complementary technologies on CAT G3516-series engines to drive engine methane emissions to ≤0.5% of the methane delivered to the engine. To ensure results are generalizable, the full system will be installed at three geographically separated field sites. Each G3516 location was chosen to span distinct fuel-gas compositions and duty conditions. Before field deployment, the combined package will be validated on the CSU G3516J laboratory engine to confirm co-functionality. The overall MERP plan is organized into four tasks: Task 1 (Project Management & Planning) runs throughout the effort and includes commercialization planning and TEA; Task 2 (Community Benefits Plan) proceeds alongside Task 1 and delivers workforce development and stakeholder engagement; Task 3 (Laboratory Workplan) follows to integrate and verify subsystems on the lab G3516; and Task 4 (Field Deployment Plan) installs and operates the full solution at the three field G3516s for long-duration validation.

6.4.2 Methodology

Four technologies will be integrated together into a comprehensive methane emissions reduction solution. These will be tested together in a lab setting and then deployed at three field sites and evaluated for engine performance and methane emissions over one year. The technologies are as follows.

6.4.2.1 Low-crevice-volume pistons (PRL package)

Piston heads which reduce top-land crevice volume and optimize ring/liner geometry directly lower unburned hydrocarbon (methane) trapped in quench regions, cutting engine slip. Prior studies on similar hardware show strong sensitivity of THC to crevice size, especially at lean conditions.

6.4.2.2 Closed crankcase ventilation (CCV)

A CCV system captures blow-by gas and coalesces oil before routing gases to the intake, eliminating a persistent methane source. The CCV configuration is already at an advanced TRL from prior field testing and will be included in the integrated system to verify operation in conjunction with the other technologies.

6.4.2.3 Exhaust methane destruction

We will evaluate oxidation catalysts in combination with sulfur guard beds and thermal management options (e.g., recuperator preheat or a small duct burner) to overcome deactivation at low exhaust temperatures and high sulfur levels. Early TEA results indicate that recuperative oxidation and duct-burner assisted oxidation are among the most promising cost/performance concepts, with conventional oxidation plus guard bed also competitive depending on fuel and duty.

6.4.2.4 Rod-packing vent-gas recirculation

A commercial SlipStream® system produced by Spartan Controls and discussed in section 6.3, collects vent gas from the compressor distance piece, captures entrained oil, and meters the stream to the engine intake. Lab testing will confirm stable control of recirculated vent gas and characterize over-pressure behavior; field deployments will verify high uptime and filtration performance various field gas compositions.

6.4.3 Expected Results

This project will produce a practical operator manual aimed at company engineers and field technicians containing implementation guidance with focus on the following sections.

The first point is site screening & design selection. These systems each have specific space and operating requirements which may not be possible in all cases. Determining both how and when to install these components is important to streamline adoption for operators.

Instrumentation and controls are an important component to implementation of methane reduction components. Many operators interested in installation will be doing so to satisfy regulatory requirements, several of which require measurement of gases. Required instrumentation for both safety and system evaluation will be documented.

Finally, the documents will include technician SOPs written specifically for installation of the components and system startup.

In short, the manual is designed to let operators implement, verify, and sustain the integrated technologies on field G3516s across the country, providing concrete steps for selecting hardware, implementing systems, validating performance, and maintaining reliability under varied gas compositions and loads.

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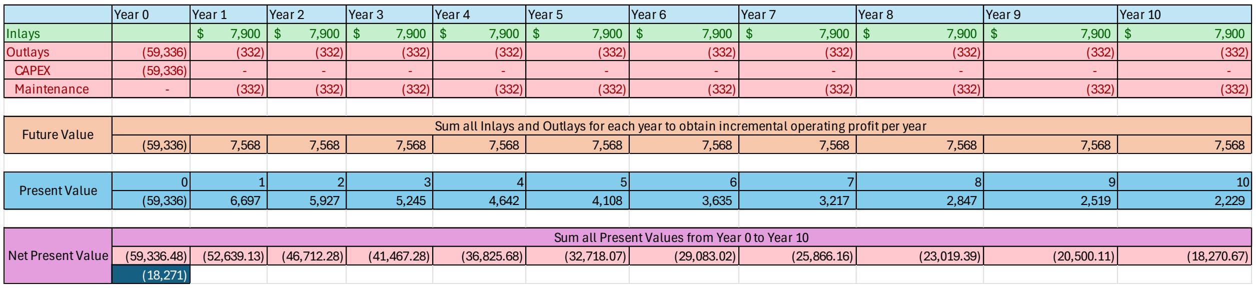
APPENDIX

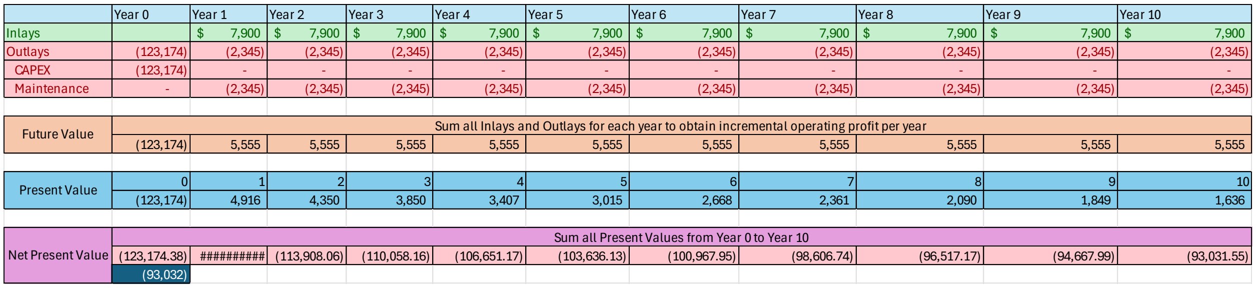
Appendix A - DCF Analysis

Listing A1. Table XI: Discounted cash flow (DCF) analysis for recirculation system. No consideration of emissions penalties.



	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Inlays		$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900
Outlays	(59,336)	(332)	(332)	(332)	(332)	(332)	(332)	(332)	(332)	(332)	(332)
CAPEX	(59,336)	-	-	-	-	-	-	-	-	-	-
Maintenance	-	(332)	(332)	(332)	(332)	(332)	(332)	(332)	(332)	(332)	(332)
Future Value	Sum all Inlays and Outlays for each year to obtain incremental operating profit per year										
	(59,336)	7,568	7,568	7,568	7,568	7,568	7,568	7,568	7,568	7,568	7,568
Present Value	0	1	2	3	4	5	6	7	8	9	10
	(59,336)	6,697	5,927	5,245	4,642	4,108	3,635	3,217	2,847	2,519	2,229
Net Present Value	Sum all Present Values from Year 0 to Year 10										
	(59,336.48)	(52,639.13)	(46,712.28)	(41,467.28)	(36,825.68)	(32,718.07)	(29,083.02)	(25,866.16)	(23,019.39)	(20,500.11)	(18,270.67)
	(18,271)										

Listing A2. Table XII: DCF analysis for active recompression system. No consideration of emissions penalties.



	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Inlays		$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900	$ 7,900
Outlays	(123,174)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)
CAPEX	(123,174)	-	-	-	-	-	-	-	-	-	-
Maintenance	-	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)	(2,345)
Future Value	Sum all Inlays and Outlays for each year to obtain incremental operating profit per year										
	(123,174)	5,555	5,555	5,555	5,555	5,555	5,555	5,555	5,555	5,555	5,555
Present Value	0	1	2	3	4	5	6	7	8	9	10
	(123,174)	4,916	4,350	3,850	3,407	3,015	2,668	2,361	2,090	1,849	1,636
Net Present Value	Sum all Present Values from Year 0 to Year 10										
	(123,174.38)	##########	(113,908.06)	(110,058.16)	(106,651.17)	(103,636.13)	(100,967.95)	(98,606.74)	(96,517.17)	(94,667.99)	(93,031.55)
	(93,032)										

Appendix B - Code Listing

Listing B1. Matlab script to calculate vent gas flow rate and cost given compressor conditions. Additionally calculates external power cost in Fort Collins, Colorado [59] to operate a recompression system on provided gas flow rate. Ariel JGJ considered. [60], [61] Natural gas density from Colorado State University Energy Institute gas chromatography and Unitrove calculator [62] Horsepower requirement equation from Engineer's Edge [63]

```
clc
clear
close all

compression_stages =  3;
throw_leakage = 1;
compressor_throws = 6;
suction_pressure = 25; % psia
compression_ratio = 3;
fuel_penalty = true;
emissions_penalty = false;
rod_diameter = 1.5; % in
k = 1.27; % Natural gas

compressor_efficiency = .8;
compressor_stroke = 3.5; % JGJ
compressor_bore = 3.875; % https://naturalgasequip.com/product/compressor-2/
fuel_density = 712/35.3146; % g/ft3 STP
fuel_cost = 2.5/1000; % $/scf
emissions_cost = 1500; % $/Mg
```

Vents

```
leakage_volumetric = throw_leakage * compressor_throws
horsepower = (144*compression_stages*suction_pressure*leakage_volumetric*k/(33000*(k-1))) * ((compression_ratio)^((k-1)/(compression_stages*k))-1)/compressor_efficiency

compressor_leakage_fuel_cost = fuel_cost * leakage_volumetric; % $/min
compressor_leakage_emissions_cost = leakage_volumetric * fuel_density / 1e6 * emissions_cost; % $/min

compressor_yearly_leakage_cost = (compressor_leakage_emissions_cost*emissions_penalty+compressor_leakage_fuel_cost*fuel_penalty)*60*24*365.25 % $/yr
```

Blowdown

```
compressor_volume = (pi*(compressor_bore/2)^2*compressor_stroke*2 - pi*(rod_diameter/2)^2*compressor_stroke)*compressor_throws; % in^3
discharge_pressure = suction_pressure * compression_ratio * compression_stages % psia
compressor_average_pressure = (suction_pressure+discharge_pressure)/2 % psia

standard_compressor_volume = compressor_volume*compressor_average_pressure/14.7/144; % scf

blowdown_fuel_cost = fuel_cost * standard_compressor_volume; % $
blowdown_emissions_cost = standard_compressor_volume * fuel_density / 1e6 * emissions_cost; % $

blowdown_cost = blowdown_emissions_cost*emissions_penalty + blowdown_fuel_cost % $
```

Standby

Electricity

Rates for 2025, Fort Collins, Colorado

```
summer = 4/12 % months/year
nonsummer = 1 - summer % months/year

energy_charge_summer = 0.0527; % $/kWhr
energy_charge_nonsummer = 0.0527; % $/kWhr

demand_charge_over750 = 7.78; % $/kWhr

coincident_peak_summer = 16.92; % $/kWhr
```

Listing B2. Table XIII: Script B1 results [60] [61] [62] [59] [63]

blowdown_cost	0.067644
blowdown_emissions_cost	0.818292
blowdown_fuel_cost	0.067644
coincident_peak_nonsummer	14.07
coincident_peak_summer	16.92
compression_ratio	3
compression_stages	3
compressor_average_pressure	125
compressor_bore	3.875
compressor_efficiency	0.8
compressor_leakage_emissions_cost	0.181455
compressor_leakage_fuel_cost	0.015
compressor_stroke	3.5
compressor_throws	6
compressor_volume	458.2062
compressor_yearly_leakage_cost	7889.4
demand_charge_over750	7.78
discharge_pressure	225
electricity_cost	484.6004
electricity_cost_kW	190.7173
electricity_cost_kWh	293.8831
emissions_cost	1500
emissions_penalty	false
energy_charge_nonsummer	0.0527
energy_charge_summer	0.0527
fuel_cost	0.0025
fuel_density	20.16163
fuel_penalty	true
horsepower	0.934781
k	1.27
kW	0.697066
leakage_volumetric	6
nonsummer	0.666667
rod_diameter	1.5
standard_compressor_volume	27.05772
suction_pressure	25

Listing B3. Table XIV: CSU gas chromatograph normalized average fuel concentration during lab testing

N2	CH4	CO2	ethane	propane	i-butane	n-butane	i-pentane	n-pentane	hexane
0.001983	88.4421	0.354754	10.61655	0.368104	0.040331	0.042832	0.044845	0.045045	0.043452

Listing B3. MATLAB Script to calculate gas cost to compressor operator per metric ton

```
clc
clear
close all
```

Constants

```
cost_MSCF = 2.5; % $/MSCF
fuel_density = 20.1616; % g/ft3 STP = 0.713 kg/m3
```

Calculation

```
cost_metric_ton = cost_MSCF / fuel_density * 1000 % $/metric ton
```

[62]

Listing B4. Table XV: Script B3 results

cost_MSCF	2.5
cost_metric_ton	123.9981
fuel_density	20.1616