MEMBRANE TECHNOLOGY: A METHOD OF GAS SEPARATION

by

Skylar Addicks

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MEMBRANE TECHNOLOGY: A METHOD OF GAS SEPARATION

Project Approved:

Supervising Professor: Walt Williamson, Ph.D.

Department of Engineering

Robert Bittle, Ph.D.

Department of Engineering

Kim Janzen

Outside Consultant

ABSTRACT

In the Oil and Gas Industry many pieces of equipment in the production field are fueled by the natural gas that is either produced on a well pad facility site or from a nearby gas pipeline. The problem with using directly produced natural gas as fuel is that, typically, it is very rich, or abundant in heavier hydrocarbons. The leaner the fuel, meaning fuel consisting of lighter hydrocarbons such as methane and ethane, burn better and have several benefits which are discussed later in this report. There are various methods of conditioning fuel which aim to reduce the fuel's energy content and increase its molecular percent in methane and ethane. This allows for the engine to burn off a cleaner fuel. In this particular test, the MTR FuelSep® system will be used as the method of fuel conditioning. The MTR FuelSep® system functions with the use of membranes, and this experiment was designed to validate its function, characterize its performance map, determine if it is economical to use, and discover any other benefits such as emission reduction. After gathering over 44 hours of testing data, a performance map was created which associated the differential pressure across the membrane with its performance index as well as its rate of return. Additionally, emission testing was conducted which shows the MTR FuelSep® system significantly reduces the content of CO and NOx in the compressor engine exhaust. Throughout this report more information will be provided on membrane technology, the design procedures, the results of the testing, and discussion of the unit's performance as well as performance in the future.

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INTRODUCTION

Membrane Technology Background Information

The key to the FuelSep® recovery process is an organic-selective composite membrane that permeates condensable vapors, such as C_{3+} hydrocarbons, aromatics, and water vapor, while rejecting non-condensable gases, such as methane, ethane, nitrogen, and hydrogen. MTR can achieve efficient separations by exploiting differences in permeability through MTR's robust, high-flux polymeric membrane. This is a relatively new technology, first commercialized in 1990.

The membrane consists of a very thin, highly selective, rubbery top layer and a tough, relatively open micro-porous support layer (see Fig.1). The top layer performs the separation; the porous support layer provides mechanical strength. A non-woven fabric serves as the backing material for membrane structure.

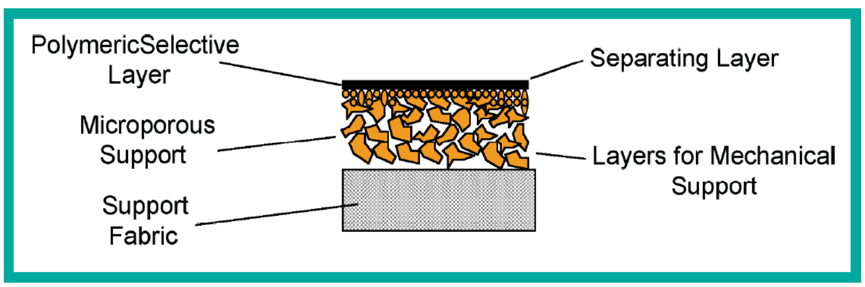

Figure 1: Microscopic View of Membrane Layers

For use in FuelSep® Processes, MTR incorporates membrane into spiral-wound membrane modules. These modules contain membrane envelopes wound around a central collection pipe. Mesh spacer materials create channels through which the feed gas and permeate vapors travel. As a feed gas stream containing organic vapor passes across the membrane surface, the organic fraction passes preferentially though the membrane and enters the permeate channel. The permeate vapor spirals inward through the permeate channel to the central collection pipe.

To provide the driving force for permeation, a pressure difference is maintained across the membrane between the feed and the permeate stream. The pressure difference is obtained by compressing the feed stream and having two back pressure regulators on the residue and permeate outlet streams. The pressure difference directly affects the rate at which nitrogen and organic vapor permeate the membrane. The larger the pressure difference the greater the flux through the membrane, resulting in a reduction in the number of membrane modules needed to perform a desired separation.

The membrane modules consist of densely packed sandwich of membrane and spacers in a spiral wound configuration around a central permeate pipe (observe Fig. 2).

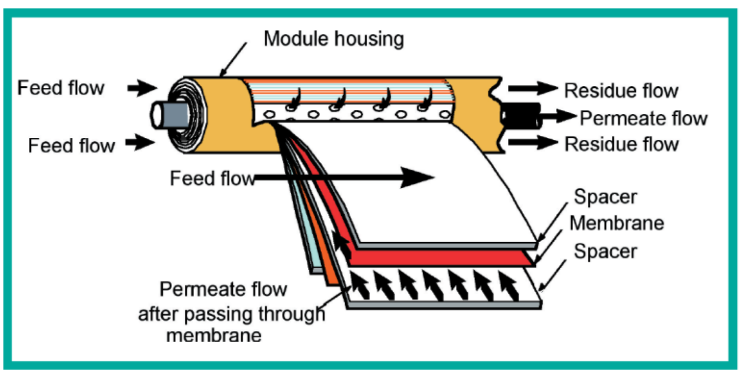

Figure 2: Side View of Membrane Function

<u>Other Membrane Designs</u>

Another type of membrane that could also perform fuel gas conditioning is the hollow fiber module consisting of rigid, glassy polymers. (Shown in Figure 3 below). For all membrane separations, the driving force is the differential pressure between the inlet feed and the permeate side of the membrane. In rigid, glassy polymers the dominant factor determining membrane selectivity is the ratio of the gas diffusion coefficients, which is highly dependent on molecular size. Thus, glassy polymer membranes typically permeate the smaller molecules, methane and ethane, and reject the larger molecules, propane, butane, and higher hydrocarbons. For the rubbery polymer membranes like the one being tested, the dominant factor for membrane diffusion is the ratio of the gas solubilities, which reflects the ratio of the condensability of the components making it a reverse selective behavior.

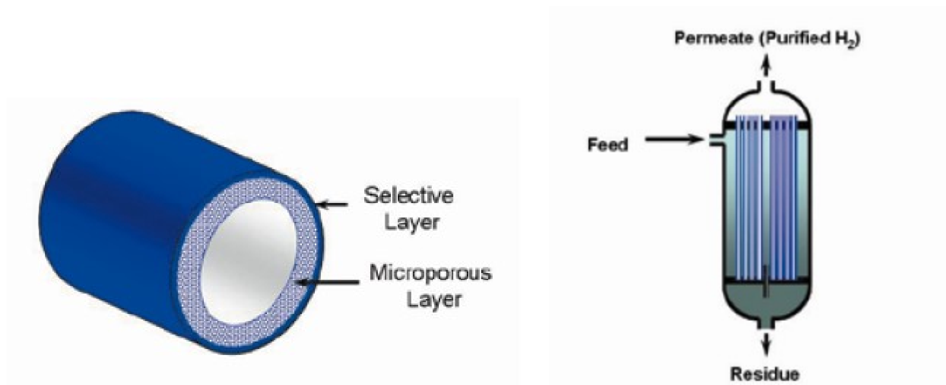

Figure 3: Hollow Fiber Module Cross Section (on left) and Side View (on right)

<u>Fuel Gas Conditioning through FuelSep®</u>

Natural gas is commonly used in the field as a fuel source for gas engines and turbines in the gas processing industry. Frequently, raw natural gas is the only fuel available to operate compressor stations with in remote locations and on offshore platforms. The gas has a high heating value, high hydrocarbon dew point, and low octane number, which can cause operating problems. In gas engines, the rich fuel may pre-detonate which can severely damage the internals of the firing chamber. Also, the condensation of hydrocarbons (due to day-night temperature variations) may damage combustion chambers in gas engines and gas turbines, increasing maintenance cost and downtime. Since the engines drive and turbines drive other machinery, any disruption in their operation will reduce production resulting in significant revenue loss. To increase the reliability and reduce unscheduled downtime of such key equipment, fuel conditioning through membrane technology is a simple way to solve this problem. The conditioned fuel gas is significantly depleted in the higher hydrocarbons, is completely dehydrated, and still retains the heating value needed to drive a compressor.

Other Applications of Membrane Technology

Membrane technology is an umbrella term referring to the mechanical separation processes of gaseous or liquid streams with the use of membranes. Although it is a relatively young technology, it proves to have many benefits to a variety of industries. Membrane systems can be found in water treatment using reverse osmosis, in waste water purification because of ultra and microfiltration that can be achieved with membranes, filtration in the food industry, for medical applications such as artificial kidneys and lungs, as fuel cells, in gas separation processes, and these are just a few examples. One of the reasons this technology is becoming more useful is because membranes use less energy than other separation processes, and typically have no moving parts.

Design of MTR FuelSep® Unit

The MTR FuelSep® system sits on a skid that is approximately 5 ft. wide, 7 ft. tall, and 23 ft. long, seen in Figure 4. No operator attention is required and since the system has no moving parts, maintenance expenses are minimal. The expected membrane life is from 3 to 5 years. There are three main parts to the makeup of this unit. The separator, the filter coalescer, and the membrane modules. The filter coalescer is located in the region farthest left in Figure 4. The separator is to the right of the filter coalescer, and the membrane modules are housed in the longest portion of the membrane on the right side of the system. The residue exits out the bottom of the unit while the permeate exits out the end.

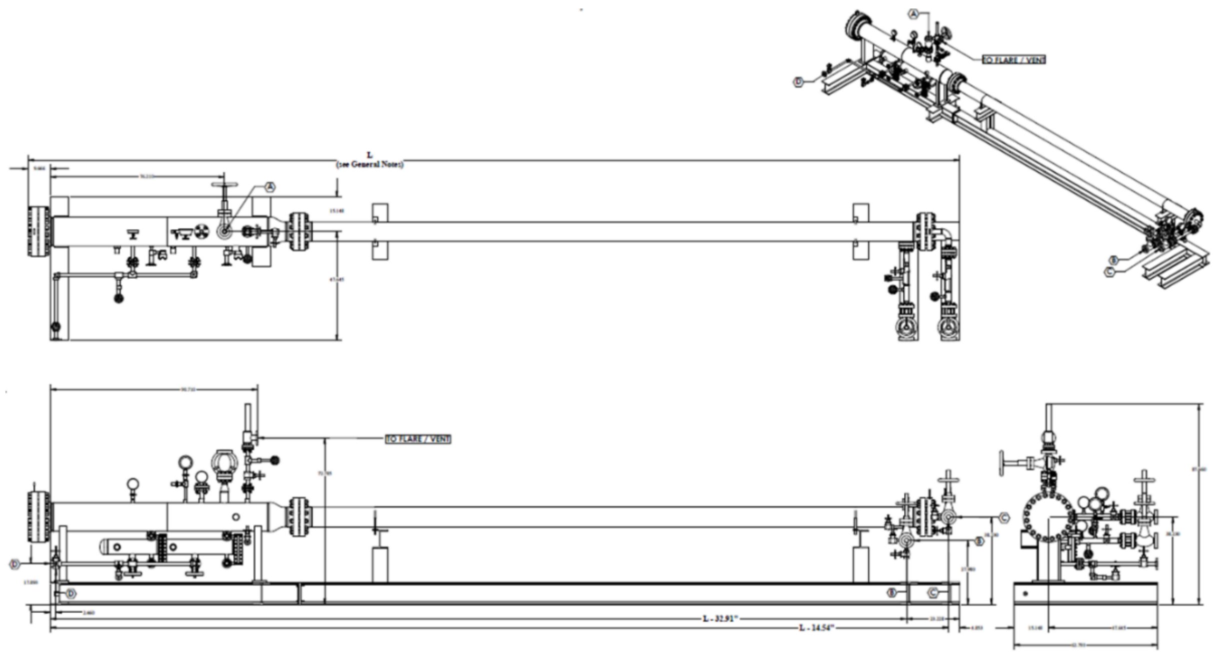

Figure 4: Outline of MTR FuelSep® System

<u>Process Description</u>

The purpose of this membrane is to generate a conditioned fuel gas, as well as recover hydrocarbons from the nitrogen/hydrocarbon gas stream in order to provide lower energy content gas streams for fuel gas.

The feed gas mixture enters the membrane vessels through the inlet ports and then enters the feed spacer material in the membrane modules as it flow through the feed spacer material, the gas mixture is in contact with the ultrathin separation layer. Part of the H_2S and hydrocarbons permeate the separation layer and flow via the micro-porous support layer and the woven material, to the permeate spacer material. The amount of gas that permeates is determined by the flowrate or residence time in the feed spacer material in the membrane modules. This is controlled by the pressure on the permeate line. The permeate gas flows through the spacer material to a central permeate collection pipe of each membrane module. This gas then flows out the permeate connection to the permeate piping.

The non-permeated gas- with H_2S and heavy hydrocarbon portions mostly removed at this point is collected as residue from the membrane module insert and flow out of the membrane module housing through the residue nozzle to the residue piping where it is sent to the fuel gas line.

The membrane module inserts are fitted with U-cup seals to avoid gas flow between the membrane module insert and the membrane module pressure vessel, which would allow a bypass around the membrane module insert. The membrane module pressure vessels are closed with a flange on each end, one of which has a permeate outlet port in the center of it.

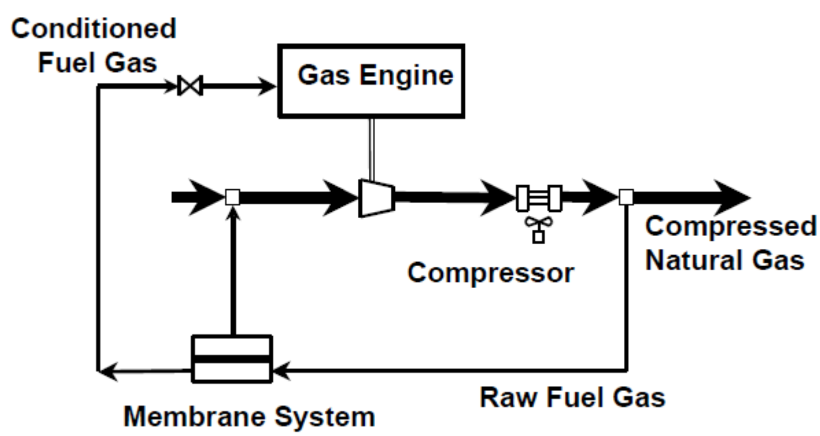

Figure 5: Flow Diagram of Membrane Unit at Well Pad Facility

The inlet to the membrane is taken as a slip-stream from the HP discharge at approximately 700 psig and is throttled to a significantly lower pressure (~430 psig) before entering the membrane. The inlet gas first enters a 2-stage integrated filter coalescer which removes any liquid condensates/aerosols formed and the clean gas enters the membrane vessels. The membrane vessels split the inlet into two streams:

1. The membranes preferentially permeate the heavy hydrocarbons, and the resulting permeate stream which is enriched in the heavy hydrocarbons, will be recycled back to the suction header of the compressor at 85 to 100 psig.
2. The residue gas stream will be conditioned gas with a lower LHV of less than 1000 BTU/SCF. The residue gas will be throttled further down in pressure and routed to the fuel header.

Purpose of Performance Testing

The goal of the MTR FuelSep® is to improve the quality of the fuel gas by removing the heavy hydrocarbon content. Therefore, the purpose of this testing is to determine whether the MTR unit performs as specified, how sensitive is the unit to performance parameters, and what is the optimal operating conditions of this unit.

METHODS AND MATERIALS

Manufacturer System Specification

The membrane module unit consists of one 8” membrane module pressure vessel and the 8” membrane module inserts. The module pressure vessel is design to hold three membrane module inserts, but currently the module only holds two membrane module inserts. The membrane module pressure vessels is a cylindrical tube, which is machined on the inside to a fine tolerance. The roughness of the machined surface is of critical importance with respect to the seal of the membrane modules via the U-cup seals. The membrane has a 2” outlet nozzle for the permeate gas (end of vessel) and reside gas (bottom of vessel) streams.

Table 1: Description of Major Parts	
Membrane Module Inserts: VMI-1, VMI-2	2x8" High-Pressure Membrane Module Inserts Manufacturer: MTR Serial No: 6665, 6666
Membrane Module Pressure Vessel: M-101	7.60" I.D. Membrane Module Pressure Vessel Design Pressure: 1213 psig Design Temperature: 150°F MDMT: 0°F at 1213 psig Material: Carbon Steel Manufacturer: Progressive Recovery, Inc. (Dupo, IL.) Dwg. No: AB71 – 8" 600# FLAT MEMBRANE SECTION and AB71 – 8" 600# FLAT VESSEL ASSEMBLY Codes: ASME Sect. VIII Div. 1
Filter Vessel: F-1	12" SCH80 Shell Filter Vessel Design Pressure: 1213 psig Design Temperature: 150 °F MDMT: 0°F at 1213 psig Material: Carbon Steel Manufacturer: Progressive Recovery, Inc. (Dupo, IL.) Dwg. No: AB71 – 8" 600# FLAT FILTER SECTION and AB71 – 8" 600# FLAT VESSEL ASSEMBLY Codes: ASME Sect. VIII Div. 1
Piping	ASME B31.3 Design Pressure: 1213 psig Design Temperature: 150 °F
Flanges	ANSI CL 600

Manufacturer Process Connections

The Fuel Gas Conditioning Unit is designed as a complete unit. The following process connections are required to make the unit operational:

1. Design and prepare anchoring locations and surface.
2. Allow enough space on the membrane module pressure vessel permeate head side of the skid (at least 50 inches) to remove and re-install membrane module inserts.

3. Anchor the skid to anchor locations.
4. Connect NOZZLE A to the feed gas line.
5. Connect NOZZLE B to the residue outlet line.
6. Connect NOZZLE C to the permeate outlet line.
7. Connect NOZZLE D to the liquid dump drain line.
8. Connect the flare/vent header to the PSV-193 blowdown line.
9. Perform a leak test with nitrogen prior to start-up according to normal plant operating procedures.

It is very important to carry out leak testing in a way that will not damage the module inserts. Never allow the permeate-side pressure to exceed the feed/residue- side pressure. Never expose the membrane modules to liquid, and do not "shock" the modules with a sudden pressure increase.

Manufacturer General Rules

The MTR FuelSep® membrane modules are robust and simple in construction. However, they are vulnerable to damage in the following ways:

Permeate Over-Pressure

Never allow the permeate-side pressure to exceed the feed/residue side pressure. The membrane module inserts are designed to be pressurized from the feed/residue side only. Over-pressure or back-flow in the central permeate tube can cause physical damage to the membranes. The membrane/spacer layers may separate, creating flow by-pass channels. The net result will be reduced separation efficiency. Spring-loaded check valves are permanently installed on the permeate tube lines to avoid such a scenario.

Liquid Contact

Never allow organic liquids to come into contact with the membrane module inserts. Organic liquids will cause swelling of the membrane and spacers, thus reducing feed flow and increasing the feed/residue differential pressure. Also, organic liquids may be absorbed into the membrane itself, effectively “blinding” it.

Pressure Shock and Flow Surges

Sudden and dramatic changes in pressure and flow rates inside the module pressure vessels should be avoided. Do not “shock” the modules with a sudden pressure rise. Although prototype modules have survived pressure cycling tests without damage, it is good practice to avoid pressure shocks. A pressure rise of 29-43.5 psi per minute is acceptable. When starting up the system, the feed inlet control valve must control the gas flow increase to the modules. The feed gas volume flow to the modules during start-up should increase at the same rate as the pressure.

Maximum Differential Pressure Feed to Reside

The maximum differential pressure from the feed inlet port to the residue outlet port of one membrane module pressure vessel with on membrane insert should not exceed 5 psi.

Maximum Operating Temperature

The maximum operating temperature for the module inserts is 140°F. For optimal performance, the inserts should not be operated at more than 100°F.

Oil Vapor

Oil vapor in concentrations of more than 1 ppm (wt) should not be introduced into the membrane module inserts.

HCL

The maximum HCL content in the feed stream should not exceed 1 ppm (wt).

Instrumentation Guide

The FuelSep ® unit is held on a single skid. All controls are operated pneumatically via instrument air. The instruments below in Table 2 are the variables to consider.

Table 2: Instruments Used

Tag. No.	Description	Function
XV-110	Control Valve	Opens when pressure on membrane residue outlet line reaches 350 psig, closes when under 350 psig. PV-110A senses pressure and sends signal. SR-110C is a supply gas pressure regulator; it regulates the instrument gas line down to a pressure of 20-35 psig. This setup is located on the main feed line.
PSV-193	Pressure Relief Valve	Set to relieve pressure on inlet gas line and protect the filter pressure vessel F-1 and membrane pressure vessel M-101 when the pressure exceeds 1213 psig. It is a Fire Safe type relief valve and is located on the flare/vent line.
LS-593	Liquid Level Switch	When liquid level rises enough within the filtration stage chamber of the two-stage filter vessel and it is switched “on”, it sends a pneumatic signal to the on/off liquid dump valve XV-511 to open up and dump the liquids. It is located on the section of the bottle chamber attached to the filtration stage of the two-stage filter vessel F-1.
LS-594	Liquid Level Switch	When liquid level rises enough within the knockout stage chamber of the two-stage filter vessel and it is switched “on”, it sends a pneumatic signal to the on/off liquid dump valve XV-512 to open up and dump the liquids. It is located on the section of the bottle chamber attached to the knockout stage of the two-stage filter vessel F-1.
XV-511	On/Off Liquid Dump Valve	It will open when the fluid accumulated within the filtration stage chamber of the two-stage filter vessel F-1 rises to the level which will switch the liquid level switch LS-593 on. It is located on the filter vessel liquid dump line.
XV-512	On/Off Liquid Dump Valve	It will open when the fluid accumulated within the knockout stage chamber of the two-stage filter vessel F-1 rises to the level which will switch the liquid level switch LS-594 on. It is located on the filter vessel liquid dump line.
LG-590	Liquid Level Gage	Indicates the fluid level accumulated within the filtration stage chamber of the two-stage filter vessel F-1, and provides a visual indication of the level. It is location on the section of the bottle chamber attached to the filtration stage of the filter vessel F-1.
LG-591	Liquid Level Gage	Indicates the fluid level accumulated within the knockout stage chamber of the two-stage filter vessel F-1, and provides a visual indication of the level. It is location on the section of the bottle chamber attached to the knockout stage of the filter vessel F-1.

TI-291	Temperature Indicating Gage	Indicates temperature on the membrane module pressure vessel residue outlet line.
PI-292	Pressure Indicating Gage	Indicates pressure on the membrane module pressure vessel residue outlet line.
TI-391	Temperature Indicating Gage	Indicates temperature on the membrane module pressure vessel permeate outlet line.
PI-392	Pressure Indicating Gage	Indicates pressure on the membrane module pressure vessel permeate outlet line.
PI-595	Pressure Indicating Gage	Indicates pressure on the combo (filter and membrane) vessel and is located on the knockout stage of the vessel.
TI-597	Temperature Indicating Gage	Indicates temperature on the combo (filter and membrane) vessel and is location on the knockout stage of the vessel.
DPI-598	Differential Pressure Indicating Gage	Indicates the pressure difference between the knockout stage chamber and the filtration stage chamber of the filter vessel section, and has a pressure tap within each of these chambers.
Emerson ROC 800 RTU	Series Remote Operations Controller	It is the device that collects all of the field data and transmits it to the online data gathering system, Cygnet. It also has a digital display screen that allows for the viewing of data in the field.
MVS 205	Multi-Variable Sensor	Provides static pressure, differential pressure, and process temperature inputs to a Remote Operations Controller (ROC).
Daniels Simplex Meter Runs	Flowrate Measurement	This is a standard 2” diameter meter run. It is the method in which the flow rates are measured for the inlet, residue, and permeate streams.

PROCEDURES

Preparation for Start-Up Procedure

1. All process pipes and electrical connections should be connected to the skid properly.
2. Make sure all of the following manual valves are **CLOSED**:
    a. Drain/Purge Valves:
        i. Four x ¾” gate valves (V-160, V-272, V-372, V-572)
    b. Sample Port Valves:
        i. Three X ¾” gate valves (V-270, V-370, V-570)
    c. MTR Skid Isolation Valves
        i. One x 2” gate valve (V-700) on the main feed line @ TP-A

ii. One x 2” gate valve (V-200) on the membrane reside line @ TP-B

iii. One x 2” gate valve (V-300) on the rich gas line @ TP-C

iv. One x 1” gate valve (V-500) on the filter drain line @TP-D

3. Make sure all of the following manual valves are **OPEN**:

   a. Instrument Gauge Valves:

      i. Six x ½” gate valves (V-240, V-241, V-340, V-544, V-545, V-546)

      ii. Four x ¾” gate valves (V-540, V-541, V-542, V-543)

   b. Isolation Valves:

      i. One x 1” gate valve (V-143) in front of PSV-193 (lock open)

Start Up Procedure of FuelSep® System

1. Begin supplying the feed gas to the system through tie-point A, and slowly open V-700. Slowly open the F-1 condensate drain outlet line isolation valve V-500 at tie-point D. this will gradually pressurize the system and prevent any shocking to the membrane module inserts.
2. When the system pressure reaches approximately 200 psig (PI-392) slowly open the permeate purge line valve V-370.
3. Slowly open V-200 at tie-point B.
4. XV-110 should begin to open slowly as the pressure begins to build up throughout the system and approach the “on” set pressure of 450 psig; PV-110A is sensing the pressure on the reside line, via V-241. Once the pressure

throughout the system begins to equalize, the opening action of XV-110 will level off.

5. Slowly open V-300 at nozzle C. Slowly close V-370.
6. Observe PI-292/PI-392 and TI-291/TI-391. Verify that all lines are at their normal operating conditions.

Skid Purge Procedure

1. Begin supplying the purge gas to the system through tie-point A, and slowly open V-700. This will gradually introduce the purge gas into the system and prevent any shocking to the membrane module inserts.
2. Open V-370 simultaneously on the permeate line.
3. When the system pressure rises to 100 psig (PI-392), close V-700 to shut in the supply of the purge gas to the system.
4. The system will be purged through V-370.
5. Slowly open V-270 to purge from the residue line.
6. Manually open dumb valves XV-511 and XV-512. Simultaneously open drain valve V-572 on the liquid drain line.
7. System will slowly bleed through V-270, V-370, and V-572 and the pressure will drop to atmospheric.
8. Close V-270, V-370, and V-572.
9. System is now purged and the pressure inside the system is now at atmospheric pressure.

Shut Down Procedure of FuelSep® System

1. Slowly close the main feed isolation valve V-700 at tie-point A

2. Slowly close the membrane module pressure vessel residue outlet line isolation valve V-200 at nozzle B.
3. At this point, there is no more incoming flow through the inlet at tie-point A, and the remaining gas trapped within the membrane system will eventually be forced to escape through the permeate line. Observe the pressure indicating gauges PI-292, PI-392. The pressure should equalize throughout the system to the permeate pressure of 20 psig.
4. Slowly close the membrane module pressure vessel permeate outlet (rich gas) isolation valve V-300 at nozzle C.
5. To relieve the remaining pressure on the system, open the permeate purge valve V-370. This will allow a blowdown of the remaining pressure without causing any back-pressurization of the membrane module elements in the vessel. Once all the pressure has been bled out of the system (as confirmed by zero-readings on all pressure gauges) close V-370.
6. Close the F-1 condensate drain outlet line isolation valve V-500 at tie point D.

Phase I: Testing for Function of FuelSep® System

MTR provided a single-point operating condition of the MTR unit given the well pad operating conditions and gas composition of the compressor discharge shown in Table 3. The important streams to note are the inlet stream, the residue gas heading to the engines fuel gas system, and the permeate gas heading to the suction header of the compressor station. The Heat and Material Balance table below summarizes the estimated system performance. Also, below is a diagram (Fig. 6) outlining the integration of the MTR FuelSep® system with the compressor at the well pad facility.

Table 3: Operating Conditions at Well-Pad Facility	
Injection Total Flow	2400 MSCFD
Likely Total Max Flow Handling Capacity	3200 MSCFD (One 3508 Compressor)
Fuel Rate	90 MSCFD
Suction Pressure on Gas Lift	25 psig
Discharge Pressure on Gas Lift	700 psig
Sales Line Pressure	85 to 100 psig
Gas Composition	Shown below

Table 4: Heat and Material Balance (Model Prediction)			
Stream Name	**Inlet**	**Residue (Fuel)**	**Permeate (To Gathering)**
Stream No.	**22**	**3**	**5**
Overall			
Molar Flow [lbmol/h]	30.1285	9.8823	20.2462
Mass flow [lb/h]	663.246	186.2934	476.9530
Temperature [°F]	100.8	74.5	87.7
Pressure [psia]	415	414	95
Vapor Mole Fraction	1.000	1.000	1.000
STD Specific Gravity	0.760	0.651	0.813
Heating Values (60°F)			
Gross BTU/lbmol	4.354E+005	3.908E+005	4.572E+005
Net BTU/lbmol	3.947E+005	3.529E+005	4.151+005
Average Mol Wt.	22.0139	18.8513	23.5576
Actual Vol. [MMCFD]	0.0097	0.0031	0.0294
STD Liquid GPD	5118.8936	1574.6980	3544.1951
STD Vapor 60°F MMSCFD	0.2744	0.0900	0.1844
Vapor Only			
Molar Flow [lbmol/h]	30.1285	9.8823	20.2462
Mass Flow [lb/h]	663.2463	186.2934	476.9530
STD Vapor 60°F MMSCFD	0.2744	0.0900	0.1844
Component Mole %			
Carbon Dioxide	6.284190	3.189610	7.794665
Hydrogen Sulfide	0.000000	0.000000	0.000000
Nitrogen	1.502597	3.069078	0.737993
Methane	75.891155	86.247981	70.835942
Ethane	8.674885	4.943058	10.496403

Propane	4.737492	1.907245	6.118945
I-Butane	0.3706999	0.089459	0.507973
N-Butane	1.278298	0.308487	1.751667
I-Pentane	0.291999	0.063511	0.403525
N-Pentane	0.351299	0.071061	0.488085
N-Hexane	0.617199	0.110491	0.864524
N-Heptane	0.000000	0.000000	0.00000
Water	0.000189	0.000015	0.000273

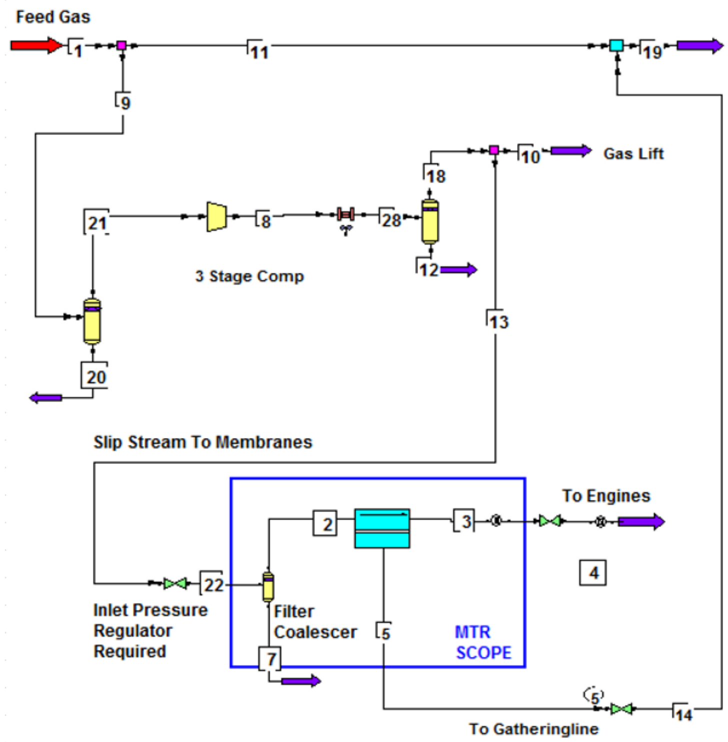

Figure 6: Model of Membrane Performance at Well Pad Facility

The first phase in the performance testing of the MTR unit is to operate it at the given optimal operating conditions and compare the G.C. of the residue and permeate outlet lines to the model provided by MTR. The following procedure outlines how this will be done. Note: the G.C. cycles every 5 minutes and always record time of operation of the MTR unit.

1. Insure that XV-110 is set to open at 350 psig and regulate the following pressure control valves: PR-710 to 430 psig, PR-200 set to lowest possible

pressure, roughly 70 psig, and the PR 310 to 100 psig. Record the fuel gas line pressure and the raw gas line pressure. Follow the procedures outlined above for initiating start-up and start-up of the unit.

2. Record the G.C., temperature (TI 597, TI 391, TI 291), and flow rates of the residue, permeate, and inlet streams through Cygnet. Confirm that the pressures are set to as specified in Step 1 (PI 595, PI 392, PI 292). Record the fuel gas line pressure and the raw gas line pressure.
3. Compare the experimental G.C.s and flow rates to the model prediction.
4. Determine the performance index.

Phase II: Optimizing Performance Test of FuelSep® System

The purpose of the second phase of performance testing is to generate a performance map that shows the ideal operation range of the MTR unit. Hopefully, the performance map will demonstrate at what conditions the unit will meet the fuel consumption rate of a given compressor and have the leanest residue composition possible. Note: GC cycles every 5 minutes and always record time of operation of the MTR unit.

1. Insure that XV-110 is set to open at 350 psig and regulate the following pressure control valves: PR-710 to 430 psig, PR-200 set to lowest possible pressure, roughly 70 psig, and PR 310 to 100 psig. Record the fuel gas line pressure and the raw gas line pressure. Follow the procedures outlined above for initiating start-up and start-up of the unit if unit is not on already. Allow time for the unit to reach a steady state.

2. Record the initial G.C., temperature (TI 597, TI 391, TI 291), and flow rates of the residue, permeate, and inlet gas streams through Cygnet. Confirm pressures are set to as specified in Step 1 (PI 595, PI 392, PI 292).
3. Reset PR-710 to 475 psig located on the inlet gas stream. Record the G.C., flow rates, temperature (TI 597, TI 391, TI 291), and pressures (PI 595, PI 392, PI 292) of the residue, permeate, and inlet gas streams once a steady state has been reached and the G.C. has cycled.
4. Repeat step 3 but vary the PR-710 setting in increments of 25 psig. Can increase or decrease.
5. Determine the performance index for each variation in inlet pressure.
6. Reset PR-710 to the normal operating pressure of 430 psig.
7. Reset PR 310 to 95 psig located on the permeate gas stream. Record the G.C., flow rates, temperature (TI 597, TI 391, TI 291), and pressures (PI 595, PI 392, PI 292) of the residue, permeate, and inlet gas streams once a steady state has been reached and the G.C. has cycled.
8. Repeat step 6 but vary the PR 310 setting in increments of 5 psig. Can increase or decrease.
9. Determine the performance index for each variation in permeate pressure.
10. Record the fuel gas line pressure and the raw gas line pressure.

Phase III: Testing for Upsets of FuelSep® System

Once it is clear that the MTR unit is operational, it is important to understand how it interacts with the system surrounding it when there are upsets. Ideally, the compressors should not quit running in the event of a membrane malfunction. Instead, the compressors should start pulling directly from the suction header gas line for fuel when the MTR quits supplying residue gas. The following procedure will test this scenario and confirm no effect on the compressor. Additionally, there needs to be an understanding of what happens to the membrane itself if the residue outlet valve or permeate outlet valve is shut during operation. The following procedure will test this scenario as well.

1. Insure that XV-110 is set to open at 350 psig and regulate the following pressure control valves: PR-710 to 430 psig, PR-200 set to lowest possible pressure, roughly 70 psig, and the PR 310 to 100 psig. Record the fuel gas line pressure and the raw gas line pressure. Follow the procedures outlined above for initiating start-up and start-up of the unit if unit is not on already. Allow time for the unit to reach a steady state.
2. Record the initial G.C., temperature (TI 597, TI 391, TI 291), and flow rates of the residue, permeate, and inlet gas streams through Cygnet. Confirm the pressures are set to as specified in Step 1 (PI 595, PI 392, PI 292).
3. Slowly shut the V-300 valve located on the permeate gas line.
4. Record the G.C., temperature (TI 597, TI 391, TI 291), and flow rates of the residue and inlet gas streams through Cygnet.
5. Compare the outcome to that outlined in the PHA.
6. If the MTR unit shut down, consult the start-up procedures to turn the unit on again and allow it to come to a steady state before continuing through this procedure.
7. If the unit did not shut down, slowly re-open V-300 and allow time for the unit to reach steady state.

8. Record the initial G.C., temperature (TI 597, TI 391, TI 291), and flow rate of the residue, permeate, and inlet gas streams through Cygnet. Confirm that the pressures are set to as specified in Step 1 (PI 595, PI 392, PI 292).
9. Slowly shut the V-200 valve located on the residue gas line.
10. Record the G.C., temperature (TI 597, TI 391, TI 291), and flow rates of the permeate and inlet gas streams through Cygnet. Record the fuel gas line pressure and the raw gas line pressure.
11. Compare the outcome to that outlined in the PHA.
12. If the compressor shut down, follow the shutdown procedures of the MTR Unit and call the foreman in order to restart the compressors.
13. If the compressor did not shut down, slowly reopen V-200 and allow the unit to regain steady state.
14. Record the G.C. and flow rates of the residue, permeate, and inlet gas streams through Cygnet.

Phase IV: Emissions Testing

Once an ideal point of operation of the membrane unit has been established, it will be beneficial to see the effect of the fuel composition change on the compressor. Therefore an emissions test will be performed on the compressor while operating with rich fuel gas and while operating with the lean fuel gas produced by the membrane. The emissions testing will need to be completed by an authorized person.

1. Set up an appointment with an authorized person for emissions testing.
2. Have the authorized person emission test the compressor for 20 minutes while running with rich fuel.

3. Follow the start-up procedure in order to turn on the membrane to feed the compressor lean gas. Shut off the feed of the rich fuel gas to the compressor. This will insure that the compressor is solely running off of a lean gas supply. The operating point of the membrane should be the point that has been proven to provide the leanest supply of fuel gas.
4. Have the authorized person emission test the compressor for 20 minutes while running with lean fuel.
5. Collect the data presented by both test and compare the results.

RESULTS

Phase I, Testing for Function, was conducted on the first day of operation, June 11th, 2014. The MTR unit was started by the procedures outlined by the manufacturer and was set to operate at an inlet pressure of 415 psig, a permeate pressure of 70 psig, and a fuel line pressure of 75 psig. The fuel regulator on the compressor skid was set for 60 psig. The MTR unit ran without issue, but the compressor did shut down because the fuel line pressure was not high enough. No data was recorded on this day because it was just a trial run to see how well the membrane system started and interacted with the compressor before further testing was conducted. Phase II, Optimizing Performance, occurred over several testing days and it outline below.

Table 5: Membrane Optimization Data

Test Date	Inlet Pressure Ranges [psig]	Fuel Consumption Rates [MCF]	Commentary
6/16/2014	360-510	73-95	XV-512 dumped 4 times off separator. Condensation on line off of separator; New spring on PR-200; Temperature drop across PR-200 is 10 to 19°F
6/18/2014	384-472	94-99	Condensation line off of separator was disconnected because it was leaking gas;

			differential pressure and flow rates were oscillating; XV-512 dumped twice off of separator;
6/23/2014	385-540	110-281	Oscillations continued even after a tee off fuel line was opened to allow for greater fuel consumption rates; Stopped testing early due to oscillations.
6/25/2014	407-701	100-245	Moved downstream sensor for PR-710 to try and decrease oscillations. PR-710 still oscillating in spurts. XV-512 dumped three times; Temperature drop across PR-200 was 24 to 35°F.
6/30/2014	364-665	99-218	PR-710 pilot valve replaced which significantly reduced oscillations; XV-512 dumped once; Temperature drop across PR-200 was 28 to 34°F.
7/1/2014	525-615	144-168	Fuel consumption rate focused to roughly 150 MCF; Temperature drop across PR-200 was 21 degrees; Fuel consumption rate was not steady; Pressure change was slow at 515 psig and fast at 580 psig.
7/7/2014	399-620	106-192	Fuel consumption rate was not steady; Pressure change fast at 500 psig and slow at 400 psig; No oscillations occurred at 585 psig and 600 psig.

Phase III, Testing for Upsets, occurred on June 14th, 2014 when the membrane system was being prepared for overnight run time. While the membrane system as well as the compressor were running, the fuel line to the compressor was closed. At that time the PSV went off. Therefore, in the event that the fuel line is shut gas will be released into the atmosphere uncontrollably. Unfortunately, the portion of testing that closed the permeate line during operation was not conducted for fear of damaging the membrane.

Phase IV, Emissions Testing, was scheduled for June 23rd, 2014. The results from that test are shown below.

Table 6: Emissions Testing Data		
Component	**Percent Difference Control vs. Test**	**Gain or Reduction**
%O2	6.54%	Gain
ppm CO	-21.52%	Reduction
ppm NO	-82.87%	Reduction
ppm NO2	-43.03%	Reduction
ppm NOx	-60.70%	Reduction

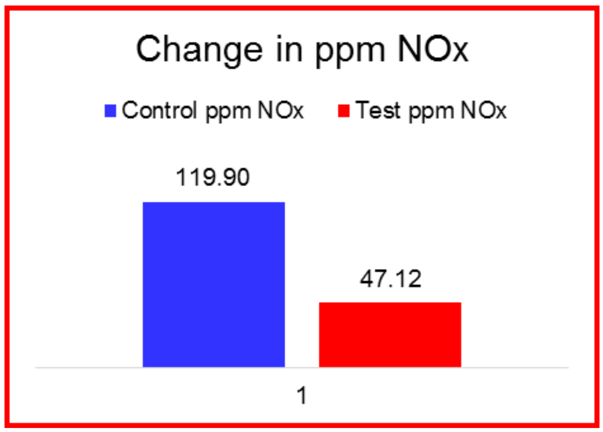

Figure 7: Nitrogen Oxide Emissions Reduction

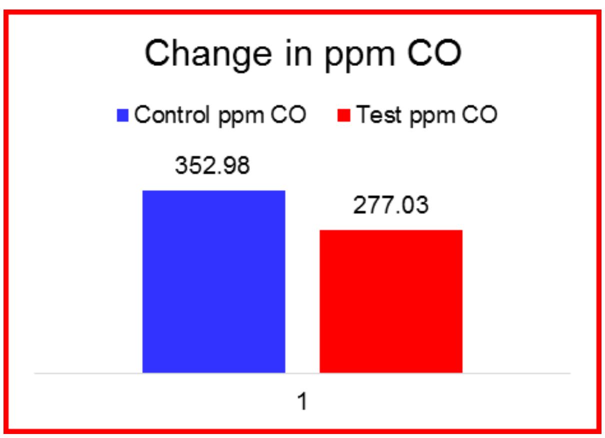

Figure 8: Carbon Monoxide Emissions Reduction

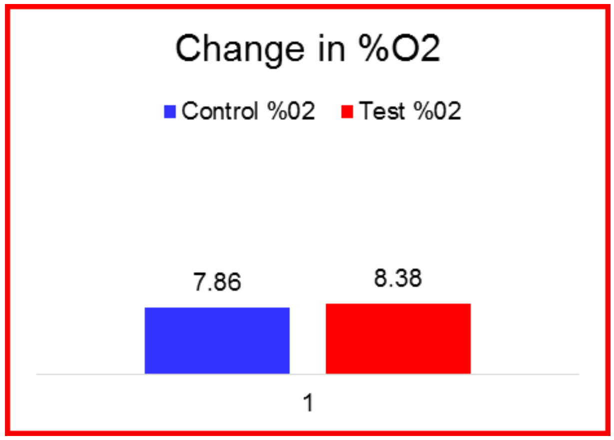

Figure 9: Oxygen Emissions Reduction

Performance Index

The performance index is the means in which the data can be analyzed to determine the optimal performance of the MTR unit as well as how sensitive it is to changes in operating parameters. The performance index is a measure of membrane efficiency and is based on the model predictions of the perfect division between permeate and residue gas streams (i.e. the gas compositions) as well as the operating inlet and outlet pressures. The ultimate goal is to have the permeate gas line as rich as possible and the residue as lean as possible. When either one infiltrates the other, there is less efficiency. Equation 1 is the way in which to calculate the performance index:

$$P.I. = 1 - \left[\frac{ResidueBTU/MCF - 1000}{10} * 0.09\right] - \left[\frac{100 - Residue\ Mol\ \%}{20} * 0.15\right] \quad (1)$$

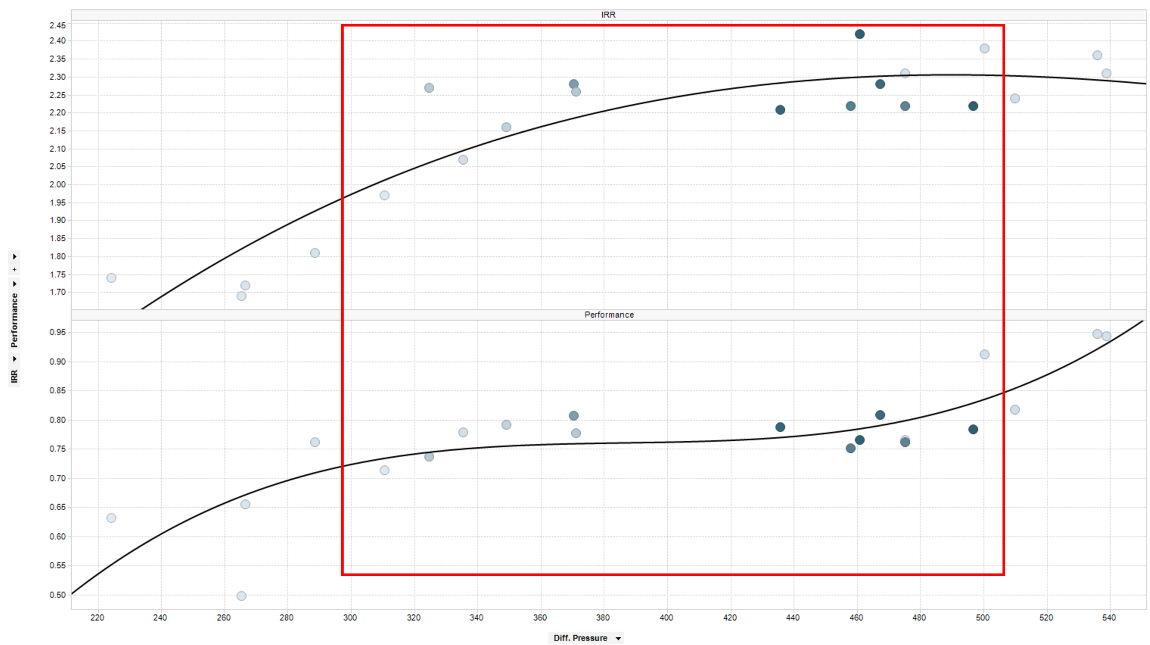

Figure 10: Internal Rate of Return and Performance versus Performance Index

DISCUSSION

The most important analysis are the performance index and the Internal Rate of Return, or IRR. Performance was calculated through consideration of the residue stream using a sum of products method outline above while the IRR was calculated with the permeate stream composition using an economics worksheet. The reason each of these values are calculated differently is because on one hand this unit ought to be measured on how well it produces a lean fuel going to the compressor while simultaneously producing the richest stream possible to the sales gas gathering system. Therefore, the permeate stream (rich gas) is what adds value and is used in economics because of the recovery of natural gas liquids, or NGL's, that are currently being burnt; and, performance is based just on how lean the fuel is to the compressor. It is the combination of these two values which will result in the best possible operating condition for the unit. Figure 10 shows that as differential pressure increases so does performance and IRR. However, at some point the IRR reaches its maximum and flat lines. In the median differential pressure values there is a flat line as well for performance at various flow rates. The performance then continues to increase, but only for high differentials with low fuel consumption rates. Therefore, the best operating range is outlined by the red box.

Not only is the membrane system consistently giving a lower BTU/MCF content for the compressor fuel, but also reducing the compressor's emissions by 60% in NOx and 21% in CO. This is a very important realization to this system because it is a viable option to a compressor that has issues meeting environmental regulations. It is hard to prove that the unit would be economical for the sole purpose of emissions, but it is clear that there are intangible benefits to it. As a side note, this emissions test was done on a compressor that is a lean burn system and did not have a catalyst. A catalyst is a material that helps compressor reduce their emissions. It would be interesting to run an emissions test on a compressor that is not a lean burn, and one that has a catalyst. The expectation would be that the non-lean burn compressor would have a greater emission reduction that the lean burn compressor, and an extended life period on the catalyst.

Assumptions Made

During testing, inevitably there will be assumptions made. For this particular experiment, the assumptions include that no membrane degradation occurred while testing, the unit had no inherent flaws, the inlet gas stream had a consistent gas composition, there was a steady flow into the membrane inlet from the compressor, instrumentation was calibrated and within tolerance, and all systems were set up correctly as designed.

Economics

Economic analysis was completed on each data point. There are two angles of approach when evaluating the economics of the membrane system, the first being fuel savings. If the MTR unit were to run permanently, then the compressor will be running off of leaner gas; therefore, the fuel cost charged to that well pad should be reduced because the membrane is producing cheaper fuel gas than the fuel gas coming straight from the well. Basically, the idea is that by having cheaper fuel costs, the lease operating expense, LOE, should be reduced. Unfortunately, this does not show much promise. From the economics analysis, the fuel savings would really only be roughly $12,000 a year assuming a fuel consumption of 100MCF/day. This will not cover the cost of the unit. Additionally, accounting allocates fuel on a MCF basis.

The second angle would be adding value back to the well because the membrane is recovering NGL's that would have normally been burnt by the compressor as fuel. By tracking how much the membrane is recovering and the composition of that stream, there would be a way to allocate the NGL's back to the well pad site. By adding more produced value to the well this should also reduce LOE. The economic spreadsheet used for determining IRR is the view point of earning revenue through NGL recovery. Net membrane revenue includes transportation and fractionation cost, a rough estimate of membrane operation and maintenance cost, cost of compression as well as natural gas plant recovery rates. If the gas were going to plant not company owned, then additional reductions would need to be made in the net membrane revenue calculation. Any sort of royalties were not accounted for, as well as membrane degradation over time before it were to be replaced. The overall rate of return was greater than 100%.

Qualitative Benefits

Qualitative benefits include less emissions, longer lasting catalyst, less deposits on valves for the compressor, which combine to decrease compressor maintenance cost. More natural gas liquids maybe recovered at the plant if more units were implemented. Also, head life on the compressor will be longer due to less fatigue due to burning a rich fuel.

Plans for Long Term Installation

Before the membrane unit would be left for unattended, long term operation, a couple of safety features would need to be added to increase user confidence. The first would be a high differential pressure switch on the coalescing filter. In the event that the coalescing filter reaches a high differential pressure and no longer is doing its job, there would need to be a way to shut down the membrane's operation to insure that the membrane modules downstream of the coalescing filter would not be contaminated. The membrane modules cost much more to replace than just the coalescing filter. Also, the separator section of the membrane would need to have a high level shut down switch on it as well. The liquids that ultimately build up in the separator section of the membrane system would need to be prevented from reaching the membrane modules, so a high level switch will make sure that will not happen. In addition to safety features, if the membrane unit were to operate under normal conditions it would not have all of the instrumentation that is currently on it. The membrane would probably only need to have a fuel meter. Therefore, there would need to be a quarterly gas analysis that would confirm the unit is operating as expected, and to monitor the water content in the fuel stream. Any kind of gas stream with too much water could have freezing problems during the winter. In the event that it seems economical to put a feedback loop on the membrane, it could be done by actuating the inlet regulator to match the fuel consumption rate. Finally, the allocation back to the well would need to be evaluated and the economics of the unit would need to be refined once maintenance and operation cost of the membrane are better understood.

CONCLUSION

The MTR FuelSep® System effectively creates a lean fuel to the compressor. It proves to be economical and functional at a variety of differential pressures and fuel consumption rates. The empirically based performance map for the unit gives an idea as to what differential pressure will result in the fuel consumption rate needed to maximize performance. Additionally, the membrane (because it is providing a better fuel) is reducing the compressor emissions and extending the head life by leaving less deposits on the valves and fittings. Overall, this unit seems to do its job and do it well. This unit would be further beneficial to areas such as San Antonio and Midland where the fuel gas being burnt has a much higher concentration in heavier hydrocarbons than was seen in this test.

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