Quarterly Research Performance Progress Report

Federal Agency to which the report is submitted	Office of Fossil Energy
FOA Name	Environmentally-Prudent Unconventional Resource Development
FOA Number	DE-FOA-0001076
Nature of the Report	Research Performance Progress Report (RPPR)
Award Number	DE-FE0024314
Award Type	Cooperative Agreement
Name, Title, Email Address, and Phone Number for the Prime Recipient	**Technical Contact (Principal Investigator):** Melissa Poerner, P.E., Senior Research Engineer, melissa.poerner@swri.org, 210-522-6046 **Business Contact:** Jennifer Bigler, Associate Specialist, jennifer.bigler@swri.org, 210-522-3179
Prime Recipient Name and Address	Southwest Research Institute 6220 Culebra Road, San Antonio, TX 78238-5166
Prime Recipient type	Not for profit organization
Project Title	**TA2 Development and Field Testing Novel Natural Gas Surface Process Equipment for Replacement of Water as Primary Hydraulic Fracturing Fluid**
Principal Investigator(s)	Melissa Poerner, P.E., Klaus Brun, Ph.D., and Kevin Hoopes – *SwRI* **Subcontractor and Co-funding Partner**: Sandeep Verma, Ph.D. – *Schlumberger*
Prime Recipient's DUNS number	00-793-6842
Date of the Report	April 30, 2015
Period Covered by the Report	January 1, 2015 – March 31, 2015
Reporting Frequency	Quarterly
Signature of Principal Investigator:	Melissa Poerner Melissa Poerner, P.E.

TABLE OF CONTENTS

1 INTRODUCTION

Southwest Research Institute® (SwRI®) and Schlumberger Technology Corporation (SLB) are working to jointly develop a novel, optimized, and lightweight modular process for natural gas to replace water as a low cost fracturing medium with a low environmental impact. Hydraulic fracturing is used to increase oil and natural gas production by injecting high-pressure fluid, primarily water, into a rock formation, which fractures the rock and releases trapped oil and natural gas. This method was developed to increase yield and make feasible production areas that would not otherwise be viable for large-scale oil and natural gas extraction using traditional drilling technologies.

Since the fracturing fluid is composed of approximately 90% water, one of the principal drawbacks to hydraulic fracturing is its excessive water use and associated large environmental footprint. Each application of fracturing consumes between three and seven million gallons of water. During the fracturing process, some of the fracturing fluid is permanently lost and the portion that is recovered is contaminated by both fracturing chemicals and dissolved solids from the formation. The recovered water or flow back, represents a significant environmental challenge, as it must be treated before it can be reintroduced into the natural water system. Although there is some recycling for future fracturing, the majority of the flow back water is hauled from the well site to a treatment facility or to an injection well for permanent underground disposal.

To mitigate these issues, an optimized, lightweight, and modular surface process using natural gas will be developed and field tested to replace water as a cost-effective and environmentally-clean fracturing fluid. Using natural gas will result in a near zero consumption process, since the gas that is injected as a fracturing fluid will be mixed with the formation gas and extracted as if it were from the formation itself. This eliminates the collection, waste, and treatment of large amounts of water and reduces the environmental impact of transporting and storing the fracturing fluid.

There are two major steps involved in utilizing natural gas as the primary fracturing medium: (i) increasing the supply pressure of natural gas to wellhead pressures suitable for fracturing and (ii) mixing the required chemicals and proppant that are needed for the fracturing process at these elevated pressures. The second step (natural gas-proppant mixing at elevated pressures) still requires technology advancements, but has previously been demonstrated in the field by SLB. However, the first step (a compact on-site unit for generating high-pressure natural gas (supercritical methane (sCH_4)) at costs feasible for fracturing) has not been developed and is currently not commercially available. The inherent compressibility of natural gas results in significantly more energy being required to compress the gas than is required for pumping water or other incompressible liquids to the very high pressure required for downhole injection.

This project aims to develop a novel, hybrid method to overcome this challenge. Several processes will be evaluated to identify the optimal process for producing high-pressure natural gas (sCH_4). Initial calculations have shown a substantial reduction in the total topside process energy requirements if a low-yield Liquefied Natural Gas (LNG) expansion, instead of a refrigeration production process, is utilized and treatment is limited to removal of only the minimal amount of impurities. The project will develop, optimize, and test this process both in the lab and in the field.

The project work will be performed in three sequential phases. The first phase will start with a thorough thermodynamic, economic, and environmental analysis of potential concepts, as well as detailed design. This will allow the selected thermodynamic pathway to be optimized for the intended application. The second phase will consist of the assembly and testing of a reduced-scale model in a SwRI laboratory to measure the overall efficiency and cost savings of the developed process. The third and final phase will be an onsite demonstration conducted in close partnership with SLB. This will allow the real world benefits of the technology to be demonstrated and quantified.

This report covers the work completed in this budget quarter. The project goals and accomplishments related to those goals are discussed. Details related to any products developed in the quarter are outlined. Information on the project participants and collaborative organizations is listed and the impact of the work done during this quarter is reviewed. Any issues related to the project are outlined and lastly, the current budget is reviewed.

2 ACCOMPLISHMENTS

2.1 *Project Goals*

The primary objective of this project is to develop and field test a novel approach to use readily available wellhead (produced) natural gas as the primary fracturing fluid. This includes development, validation, and demonstration of affordable non-water-based and non CO_2-based stimulation technologies, which can be used instead of, or in tandem with, water-based hydraulic fracturing fluids to reduce water usage and the volume of flow back fluids. The process will use natural gas at wellhead supply conditions and produce a fluid at conditions needed for injection.

The project work is split into three budget periods. Each budget period consist of one year. The milestones for each budget period are outlined in Table 2-9. This table includes an update on the status of that milestone in relation to the initial project plan. Explanations for deviations from the initial project plan are included.

2.2 *Accomplishments*

In the past quarter, the project team began the technical work for the project. A kickoff meeting was held with SwRI and SLB at the SLB facility in Houston, TX during the first quarter to discuss initial concepts and define the boundary conditions for the process. During the second quarter, the team started to work on the models of the various thermodynamic cycles. This included the direct compression, pre-compression, pre-cooled, and direct refrigeration cycles. In parallel to the cycle analyses, availability of commercially available equipment was explored. This helped the project team to include realistic equipment designs in the cycle models. Lastly, the team also defined the metrics for evaluating the various thermodynamic cycles. These metrics will be used to select the top three cycles for more detailed thermodynamic and techno-economic analyses.

2.2.1 Boundary Conditions and Assumptions

Boundary conditions were defined for the thermodynamic analyses that reflect reasonable and realistic operating conditions that may exist in fracturing with high-pressure natural gas (sCH_4). The first step in defining the inlet boundary conditions was to consider the source of the natural gas. It was estimated that approximately 35 bbl/min of natural gas at 10,000 psia and 80°F would be needed to apply fracturing treatment to a gas field. Assuming pure methane, this equates to 128 MMSCFD. A typical well produces a maximum of 10 MMSCFD at the beginning of its production life. Since this wellhead gas flow is ten times lower than that needed for the fracturing process, the gas must come from either multiple wellheads or a central gas processing facility.

Transporting liquefied or pressurized natural gas by vehicles to the site was not considered due to the heavy traffic that this would create. Also, the amount of gas needed would require an unrealistic number of vehicles for transport. The most practical solution would be to use gas from a nearby processing plant, where the gas from all the local wells is collected. This would also allow processed or “cleaned up” gas to be used. This eliminates the need for the mobile process to include gas clean-up equipment.

After the gas source was defined, the inlet boundary conditions were determined. The pressure of the produced natural gas from the processing facility ranges from 500 to 1,000 psia. In the analyses, a natural gas pressure of 500 psia was used. This represents the most conservative inlet condition for design of the mobile system. The inlet gas temperature was set to 80°F.

The system outlet conditions were defined based on the fracturing process requirements. SLB advised the project team that the outlet stream needed to be at 10,000 psia and +/- 20°F of ambient. The flow rate was set to a maximum value of 35 bbl/min. At the outlet process stream conditions, this equates to 61.7 lbm/s. Some reservoirs may require lower flow rates for fracturing; therefore, in the future, it is planned to extend the analyses to include flow rates of 3.5 and 14 bbl/min. For simplicity, methane is used as the process gas for the initial analyses. A more realistic gas composition will be considered in future detailed analyses. Table 2-1 summarizes the boundary conditions for the thermodynamic cycles.

Table 2-1. Boundary Conditions for Thermodynamic Cycle Analyses

Parameter	Value
Inlet Temperature	80°F
Inlet Pressure	500 psia
Outlet pressure	10,000 psia
Fluid	Methane (REFPROP for EOS calculations)
Outlet volume flow	35 bbl/min
Mass flow (based outlet process conditions)	61.7 lbm/s

2.2.2 Thermodynamic Cycle Analysis

Several thermodynamic cycles are being considered for the production of high-pressure natural gas (sCH_4) for the fracturing process. The cycles under consideration include:

- Direct compression
- Pre-compression
- Pre-cooled (single- and two-stage refrigeration)
- Direct refrigeration (with a nitrogen refrigerant or mixed refrigerant)

During the second quarter of this project, all of these cycles were investigated to some extent. Three of these cycles that had a substantial amount of work completed are discussed below. In the future work of this project, all of these cycles will be analyzed on a high level. Then the top three cycles will be selected for detailed analysis.

2.2.2.1 Direct Compression

The most straightforward pathway from supply to injection conditions is through direct compression of methane using intercooling. This process is shown on a pressure-enthalpy (P-h) diagram for methane as the red line in Figure 2-1 and schematically in Figure 2-2. Figure 2-2 shows this cycle being implemented using three stages while Figure 2-1 shows five stages of intercooling. The main advantage to the direct compression approach is that it is relatively straightforward to implement, as it does not require separate refrigeration loops or other flow components apart from the compression stages and intercoolers.

In order to analyze this process, a simple model was built that incorporated multistage intercooled compression. The real operation of the compression stages was modeled as isentropic with a specified compressor isentropic efficiency. The boundary conditions are outlined in Table 2-1.

Using the boundary conditions outlined in Table 2-1 and Table 2-2, the total compression power was calculated to be 20.0 MW.

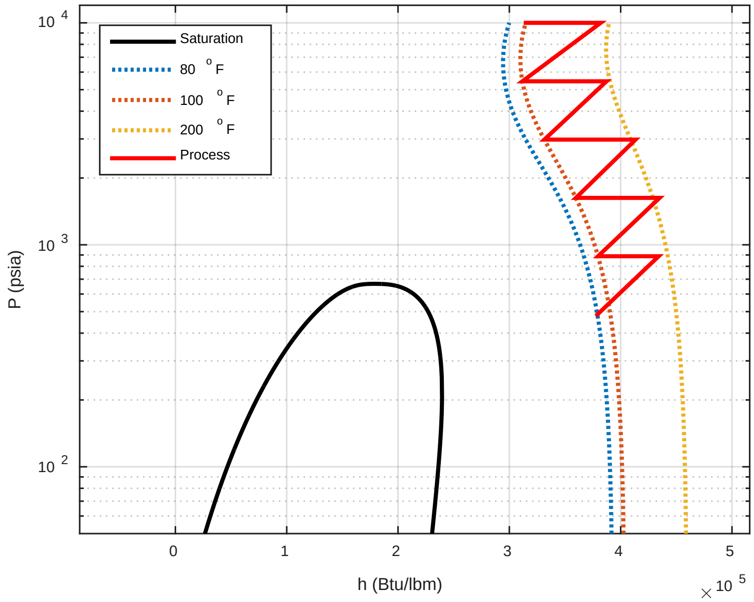


Figure 2-1. Direct Compression Process Illustrated on a P-h Diagram using Five Stages

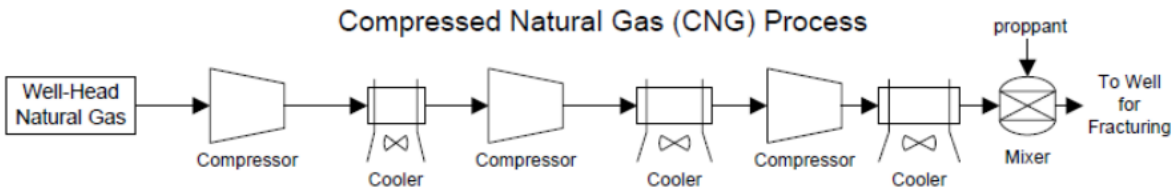


Figure 2-2. Schematic of Direct Compression Process

Table 2-2. Additional Boundary Conditions for Direct Compression Cycle

Parameter	Value
Intercooling Temperature	100°F
Compressor Isentropic efficiency	75%
Stages	3 (All with equal pressure ratio)

Required cooling power

Apart from compression power, power will also be needed to cool the flow in the intercoolers. This power will take the form of a fan to blow atmospheric air over a heat exchanger or a fan that powers an evaporative cooling tower.

In order to estimate the power required for dry air cooling, which is preferable to a water-based method, several air cooled heat exchanger manufacturers were reviewed. A plot of fan power versus heat exchanged was created along with a linear fit to the data. This fit was then used as the basis to extrapolate the cooling power required for the direct compression method. This plot, along with linear fit, is shown in Figure 2-3. It can be shown in this figure that roughly 6% of the computed heat removal is needed in the form of fan power. Using this relationship, since the direct compression process will require rejecting 24 MW, it would require an additional 1.44 MW of power for dry air cooling. Further analysis and research will be done to quantify the performance of water-based cooling as well as footprint requirements for both methods.

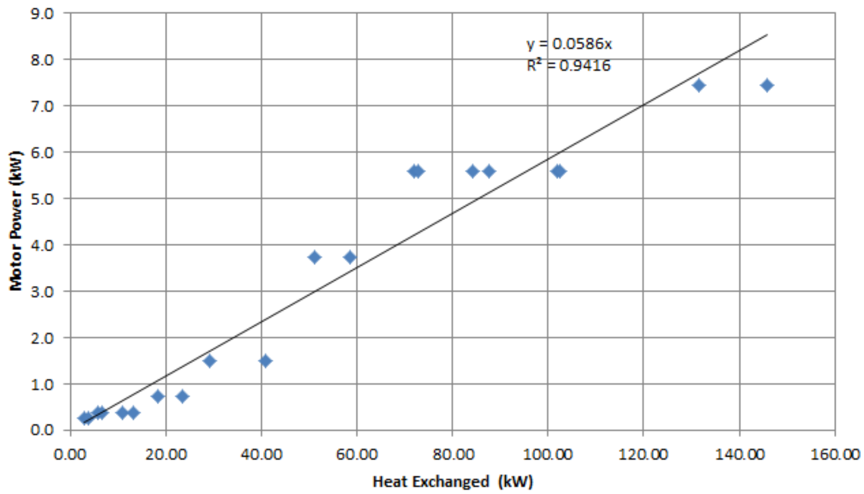


Figure 2-3. Heat Exchanged versus Fan Power along with Linear Fit

Effect of variable inlet pressure

The effect of variable inlet pressure was also investigated. Figure 2-4 shows the total compression work required for the above process and a function of inlet pressure. These simulations used five intercooled stages as well as the other values listed in Table 2-1.

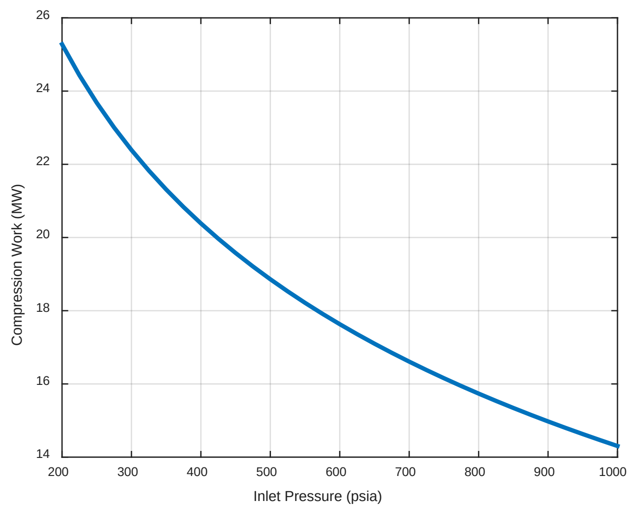


Figure 2-4. Effect of Variable Inlet Pressure

Effect of Variable Stage Count

The effect of varying stage count was also investigated. Using the boundary conditions outlined in Table 2-1 the number of stages was varied from three to twelve. Figure 2-5 was generated to show the compression power as a function of the number of intercooled stages. There is a clear trend that the compression work decreases with an increase in the number of compression stages. However, with more stages, the compressor will likely be more expensive and have a larger footprint.

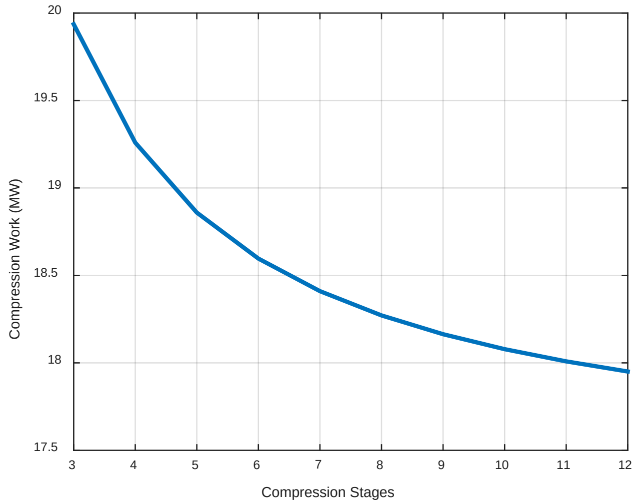


Figure 2-5. Effect of Variable Stage Count

Effect of using a real natural gas mixture

The direct compression cycle was evaluated with several different gas mixtures representative of those found in gas wells. The power required for compression with these different compositions did not deviate more than 2% from the baseline case using pure methane.

Comparison metrics

Table 2-3 lists the comparison metrics for the direct compression cycle. These metrics will be used in the thermodynamic cycle selection, which is discussed later in this report.

Table 2-3. Design Metrics for Direct Compression

Parameter	Value
Total Power Required	20 MW
Compressor Power	20 MW
Pump Power	0
Expander Power	0
Specific Power	305 Btu/lbm
Heat Rejected	24 MW
Number of Compressors	1
Number of Expanders	0
Number of Pumps	0
Number of Heat Exchangers	0
Number of Coolers	3
Total Equipment Count	4

2.2.2.2 Pre-Cooled Cycle

The pre-cooled cycle is shown schematically in Figure 2-6 with annotated pressures and temperatures shown in Figure 2-7 and Figure 2-8, respectively. This process starts with the same flow conditions as were considered in the direct compression cycle but instead of using direct compression, it uses a recycle loop with an expander to cool the process stream prior to pumping.

The combined stream is first passed through a three-passage heat exchanger, which reduces the temperature to -75°F. The combined stream is then separated into the recycle and process streams with 78% of the flow being recycled. The recycle stream is expanded to 80 psia, which further reduces the temperature to -212°F. This stream then passes through the two-passage heat exchanger with the process stream. This cools the process stream to -168°F, which is in the subcooled liquid region. The process stream is then throttled to 250 psia to meet the inlet pressure conditions required for cryogenic pumping. It is then pumped to 10,000 psia and as its temperature is still below ambient temperature, it is passed through the three-passage heat exchanger to provide cooling to the process stream.

Meanwhile, the expander outlet (stream 8) provides the refrigeration to cool the natural gas stream in the three-passage heat exchanger. This stream is warmed through two stages of the heat exchanger and is then compressed by an intercooled recycle compressor to inlet temperature and pressure conditions. It is then mixed with the incoming process natural gas stream.

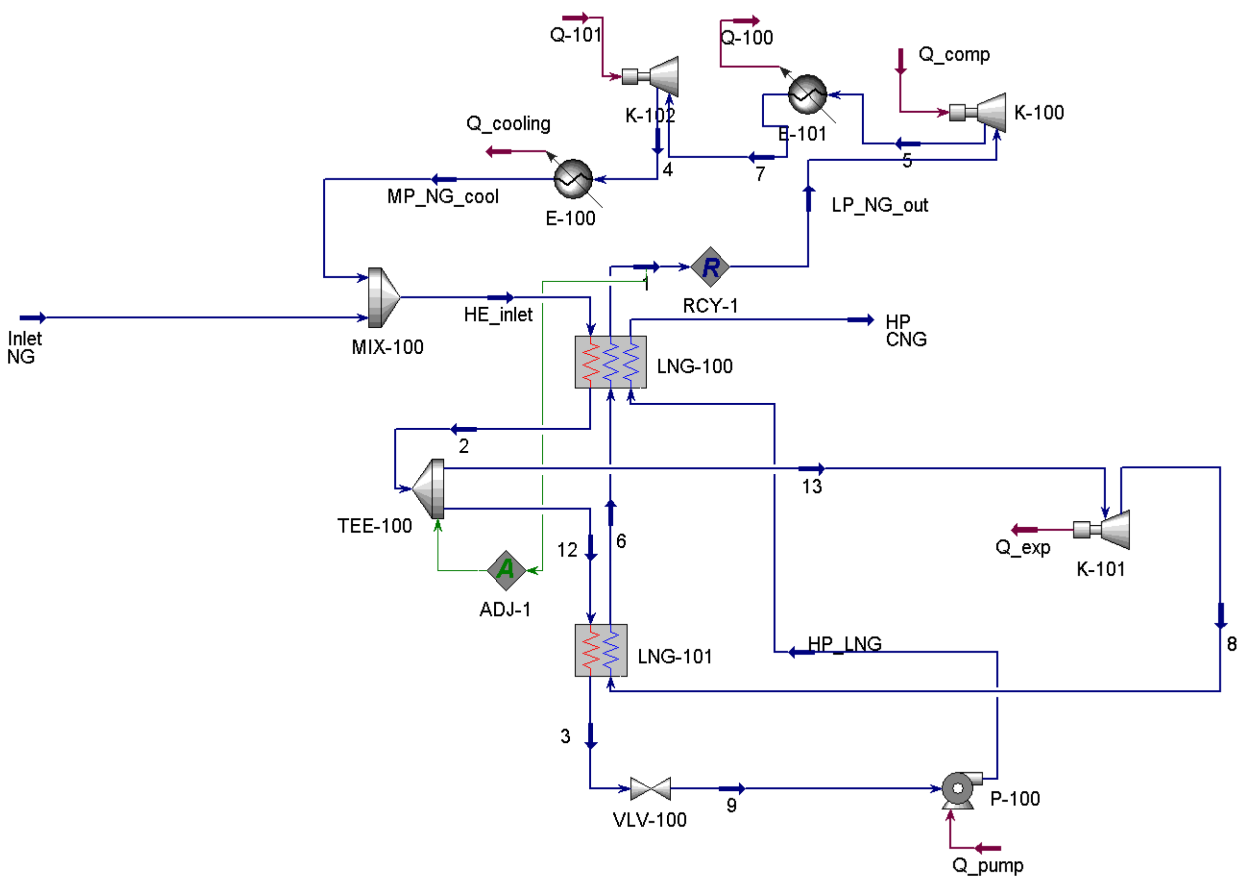


Figure 2-6. Pre-cooled Cycle Diagram

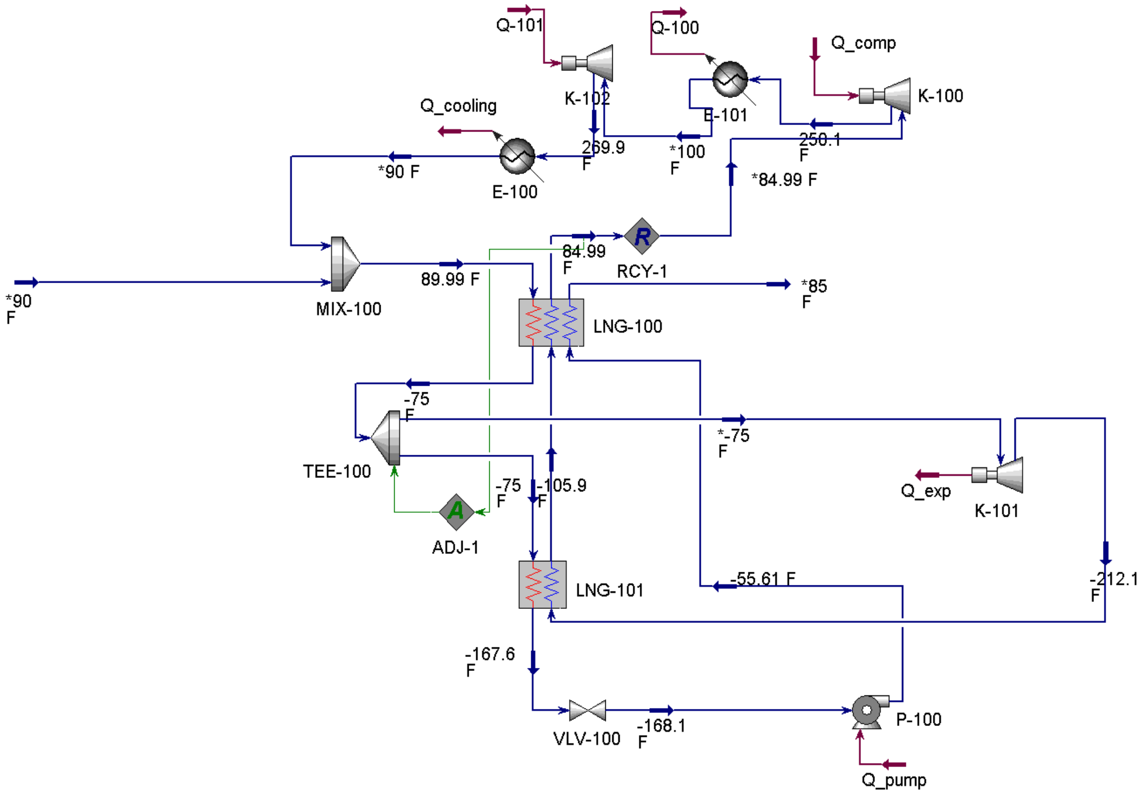


Figure 2-7. Pre-cooled Cycle Diagram with Annotated Temperatures

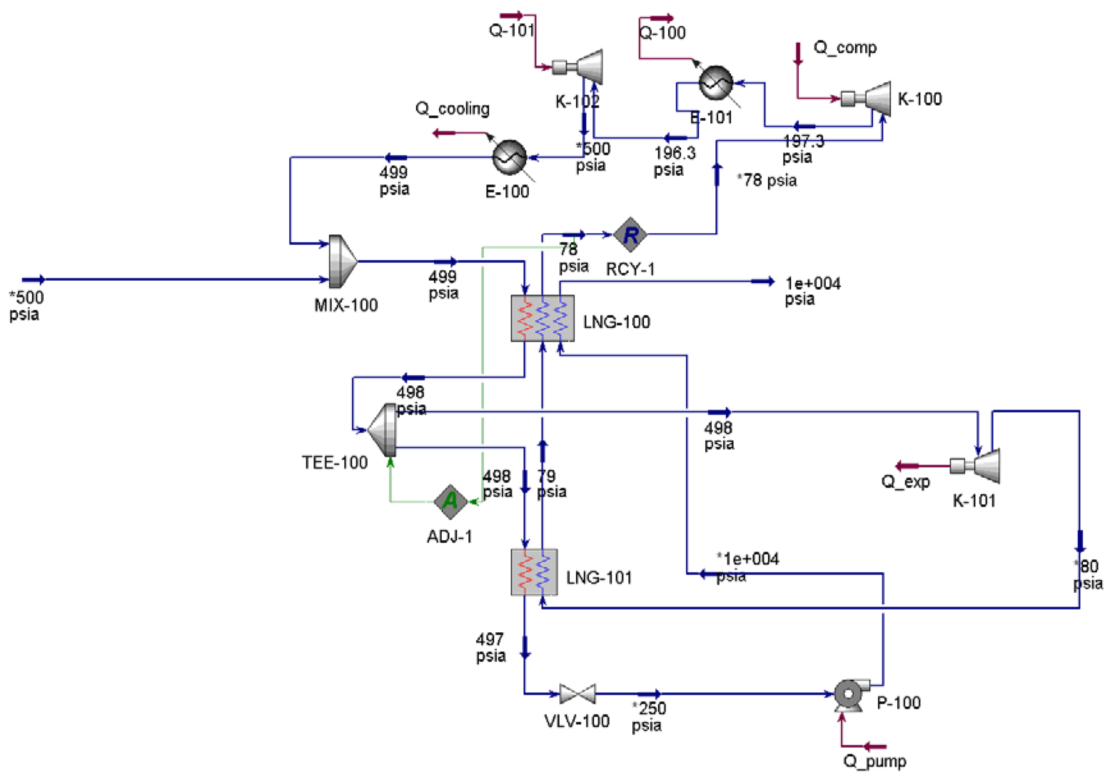


Figure 2-8. Pre-cooled Cycle Diagram with Annotated Pressures

Figure 2-9 shows this cycle in a P-h diagram. In this diagram, the combined stream is shown in green, the process stream in red, and the recycle loop in blue. The magenta arrows represent the heat exchange taking place in the three-passage heat exchanger while the black arrow represents the two-passage heat exchanger.

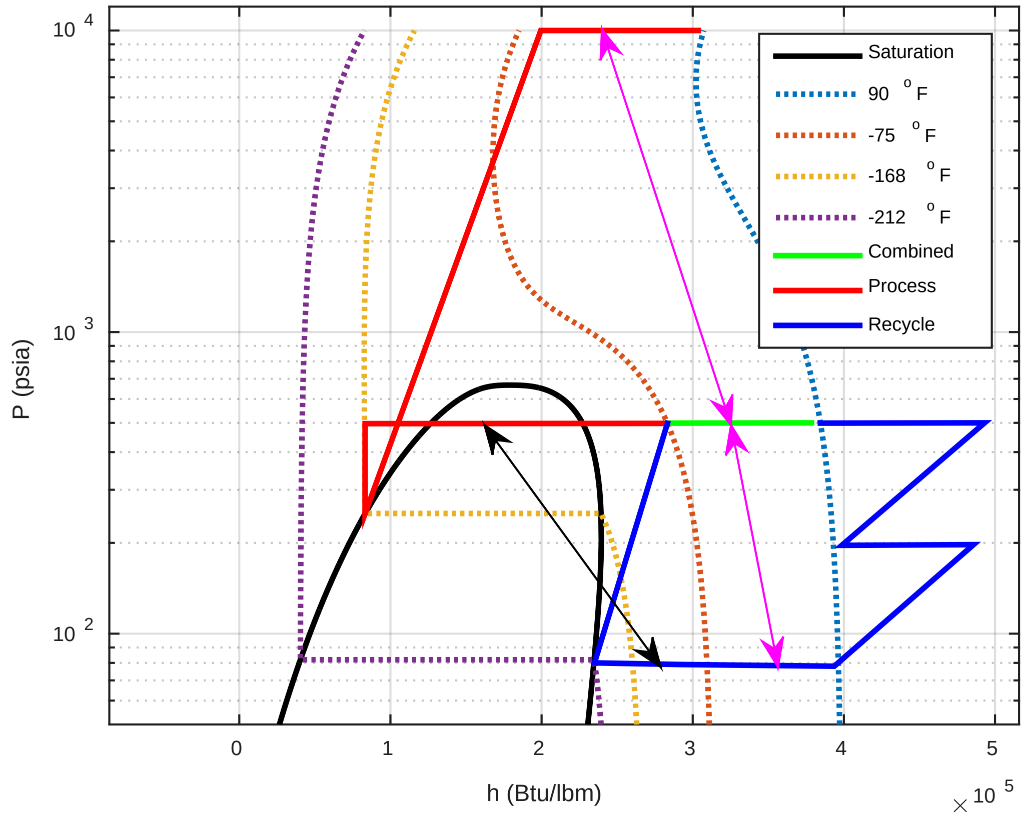


Figure 2-9. Pre-cooled Cycle P-h Diagram

(In this diagram, the three-passage heat exchanger is represented with the magenta arrows while the two-passage heat exchanger is represented with the black arrow.)

The total power required for this cycle is 38 MW. This includes the power for the recycle compressors and pump. It also assumes that all of the power produced by the expander can be used to offset some of the power required for compression or pumping.

This cycle will also require 44 MW of heat to be rejected in the intercooler and aftercooler associated with the recycle compressor. As in the direct compression method, this heat rejection will make use of either dry air cooling or an evaporative cooling scheme. Work is ongoing to quantify further the performance, capital cost, operating power, as well as footprint of these cooling mechanisms, as all of the considered processes will make use of ambient temperature cooling.

Comparison metrics

Table 2-4 lists the comparison metrics for the pre-cooled cycle.

Table 2-4. Design Metrics for Pre-cooled Cycle

Parameter	Value
Total Power Required	38 MW
Compressor Power	40 MW
Pump Power	8.4 MW
Expander Power	11 MW
Specific Power	585 Btu/lbm
Heat Rejected	44 MW
Number of Compressors	1
Number of Expanders	1
Number of Pumps	1
Number of Heat Exchangers	2
Number of Coolers	2
Total Equipment Count	7

2.2.2.3 <u>Nitrogen Direct Refrigeration Cycle</u>

In the nitrogen direct refrigeration cycle, a methane stream is cooled by a separate nitrogen loop through a series of heat exchangers prior to pumping. This process is shown schematically in Figure 2-10 with temperatures and pressures annotated in Figure 2-11 and Figure 2-12, respectively. The nitrogen loop consists of an intercooled compressor and an expander to reduce the temperature of the nitrogen. It also utilizes the remaining refrigeration in the high-pressure methane (sCH_4) stream to precool the process stream as well as the nitrogen cycle prior to expansion.

The process stream of the nitrogen refrigeration cycle is very similar to the process stream in the methane refrigeration cycles. Both streams are cooled to a subcooled state with little pressure drop and then passed through a throttling valve to reduce the pressure to a suction pressure that commercially available cryogenic pumps can tolerate.

Using this cycle and the boundary conditions outlined in Table 2-1, the total power required was calculated to be 53 MW. The heat rejected to cool the compressed inter-stage streams in the nitrogen compressor is 57 MW.

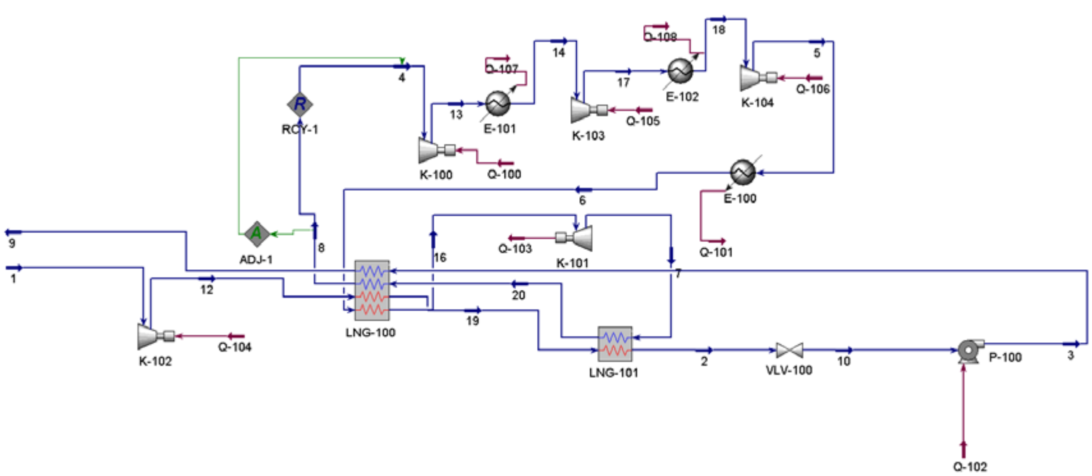


Figure 2-10. Schematic of Nitrogen Direct Refrigeration Cycle

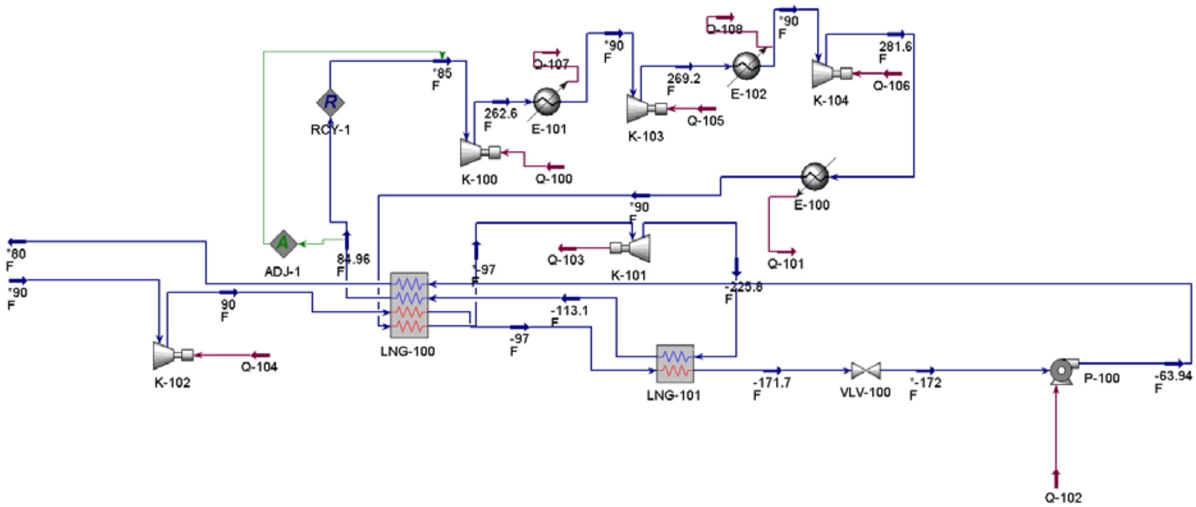


Figure 2-11. Schematic of Nitrogen Direct Refrigeration Cycle with Annotated Temperatures

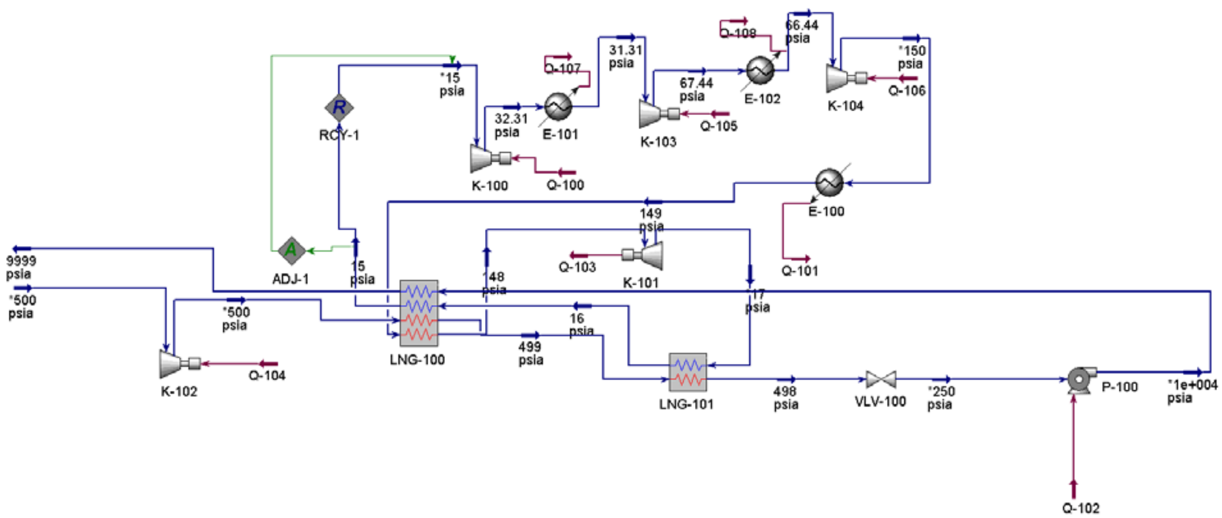


Figure 2-12. Schematic of Nitrogen Direct Refrigeration Cycle with Annotated Pressures

Figure 2-13 shows a P-h diagram for methane showing the process stream. In this diagram, the black arrow represents the two-passage heat exchanger and its heat transfer to the separate nitrogen loop, while the magenta arrows represents the four-passage heat exchanger and its heat transfer to the nitrogen loop.

Comparison metrics

Table 2-5 lists the comparison metrics for the nitrogen refrigeration cycle.

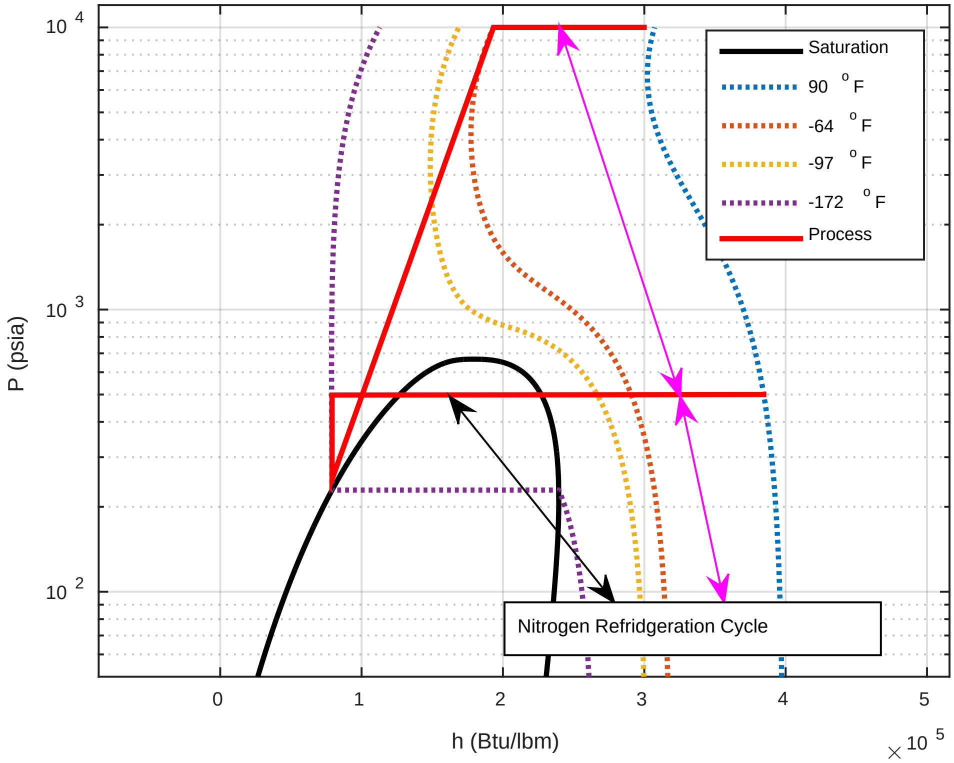


Figure 2-13. P-h Diagram for Methane Showing Process Stream of the Nitrogen Direct Refrigeration Cycle

(The black arrow represents the two-passage heat exchanger and its heat transfer to the separate nitrogen loop while the magenta arrow represents the four-passage heat exchange and its heat transfer to the nitrogen loop.)

Table 2-5. Design Metrics for Nitrogen Direct Refrigeration Cycle

Parameter	Value
Total Power Required	53 MW
Compressor Power	58 MW
Pump Power	7.4 MW
Expander Power	15 MW
Specific Power	812 Btu/lbm
Heat Rejected	57 MW
Number of Compressors	1
Number of Expanders	1
Number of Pumps	1
Number of Heat Exchangers	2
Number of Coolers	3
Total Equipment Count	8

2.2.3 Metrics for Cycle Comparison

Once the initial thermodynamic cycle analyses are complete, the results must be compared to each other in order to select the top three cycles. A set of metrics has been developed in order to identify the optimal cycles for further analysis. These metrics include various aspects of the system design, including the thermodynamic parameters, initial and recurring costs, system complexity and operational difficultly, safety, and mobility.

Table 2-3 shows the thermodynamic cycle parameters that will be considered for the cycle comparison. These parameters are reported for each of the cycles described in this report. The first parameter is the total power required. This is the net positive power that must be supplied to each cycle for steady-state operation. In addition, the electric power consumed or produced by individual components such as compressors, pumps, and expanders are also listed for each cycle. A key parameter listed is the specific power. This is the net power used by the cycle divided by the injection mass flow. This can be used to directly compare the various cycles and compare the new cycles to commercially available small LNG production systems. As discussed above, cooling is required by all the cycles. The heat rejected parameter provides the total amount of cooling needed for that cycle. The last sets of values are the numbers of various types of equipment. This gives insight into the complexity of each of the cycles and the amount of equipment needed.

Table 2-6 shows the other metrics that will be considered in the cycle selection in addition to the thermodynamic parameters. In this table, the metric is described on the left-hand side and a weight factor is assigned to each metric on the right. The weight factor indicates the importance of the metric. For example, the size and weight are considered more important than the operational difficulty. The last metric shown, maturity, does not have a weight factor. Instead, this will be used as a multiplier. For example, the direct compression concept is more mature than the other cycles; therefore, it will have a higher maturity multiplier. The metrics shown in Table 2-6 include: initial equipment cost per kg (as capital expenditure, or CAPX), specific energy (which is likely to be a large contributor to operational costs, or OPEX), operational difficulty/automation in relation to labor costs (also OPEX), and maintenance costs (also OPEX). The other metrics included are size and weight (important for transportation), safety, and mobility. Size, weight, and mobility are highly important because the system will be moved from site to site for use. In the future work, the method used to assign values to each cycle will be determined. For example, scores will be assigned to ranges of size and weight. Then, this ranking system will be applied to the cycles for selection of the top three cycles.

Table 2-6. Metrics for Top Cycle Selection

Description	Weight Factor
Cost/kg (CAPX)	10
Specific Energy (OPEX)	10
Size and Weight (footprint)	10
Operational difficulty/Automation (OPEX)	5
Maintenance Required (OPEX)	5
Safety	5
Mobility	10
Maturity	Multiplier

2.2.4 Commercially Available Equipment

In the past quarter, an effort began in parallel to the cycle analyses that aimed to identify commercial vendors for some of the major pieces of equipment being modeled in the thermodynamic cycles. The primary goals of this effort were to, first, determine whether the equipment modeled in the analysis was commercially available and, second, to identify the operational limitations of the available equipment.

The project team recognized early on that any analyses conducted must be constrained by available equipment limitations, such as maximum allowable working pressures and temperatures, and flow rates. Ideally, the processes designed should make use of commercial off-the-shelf (COTS) equipment and require little to no specialized equipment. The following sections briefly summarize the findings to date. Additional inquiries will be made as the cycle analyses reach maturity and the equipment requirements can be further specified and discussed with equipment manufacturers.

2.2.4.1 Compression Equipment

All three of the processes described in Section 2.2.2 require a multistage compression process; however, the direct compression method places the most rigorous pressure demands on the compressor. That process calls for a three-stage compression process to boost methane (CH_4) from an inlet condition at 500 psia and 80°F to 10,000 psia and 100°F at three equal pressure ratios. The maximum flow rate required at the inlet conditions is approximately 2,500 acfm. Figure 2-14 below displays the typical operating ranges for a wide variety of gas compressors and the anticipated operating point of the direct compression process (indicated by the red star). It can be observed that the designed operating point is slightly outside of the typical operating conditions of the compressors represented by the given data. It can also be observed that either a multistage reciprocating (Recip.) compressor or a multistage centrifugal compressor could be likely candidate machines if current machinery technologies extend the represented operational ranges.

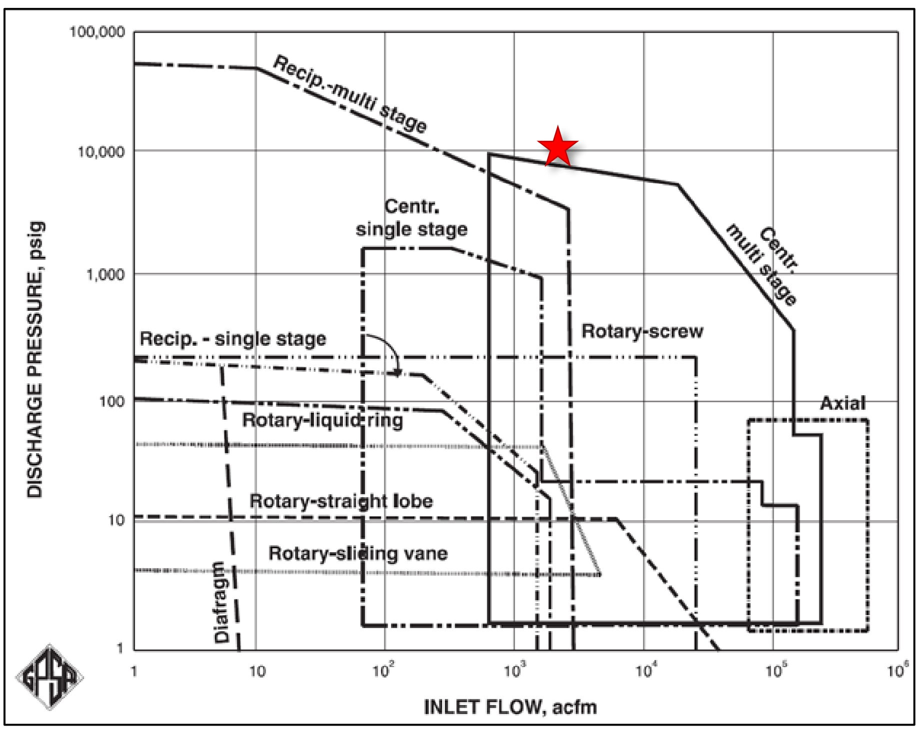


Figure 2-14. Typical Compressor Volumetric Flow and Discharge Pressures

Centrifugal compressor data sheets obtained from two centrifugal compressor vendors revealed that high pressure machines are currently manufactured that may be able to support the process flow rates. The Vertical Split HP centrifugal machines manufactured by GE Oil & Gas can be designed to handle inlet flows of 8,000 acfm and discharge pressures up to 10,000 psig. Similarly, the Datum compressor line manufactured by Dresser-Rand has units that handle inlet flows up to 8,000 acfm at 10,000 psig discharge pressure as well as developmental units that support inlet flows up to 5,400 acfm with discharge pressures at 15,000 psig. Additional inquiries will be made to confirm that the two compressors discussed above could operate at the lower anticipated flow rate of 2,500 acfm. Reciprocating compressors are also being considered and detailed information about these compressors will be acquired in future work.

2.2.4.2 Cooling Equipment

For all cycles analyzed thus far, some cooling equipment will be required for compressor inter-stage cooling, whether as part of the process stream, as is the case for the direct compression process, or as an element in the separate refrigeration system, as is the case with the other cycles discussed previously. The two cooling mechanisms that have been considered are dry air cooling and evaporative cooling.

Dry Air Cooling

For the dry air cooling, the process fluid flows through a fin-fan type of heat exchanger. The process fluid is methane for the direct compression and pre-cooled processes and nitrogen for the nitrogen direct refrigeration process.

The primary benefit to using dry air cooling methods would be that water or some other cooling fluid is not required. The primary disadvantage to this approach is the large footprint and initial cost of the equipment. An initial sizing estimate provided by Harsco Industrial Air-X-Changers revealed the following:

- Direct Compression Cycle: Info not supplied by the time of reporting
- Pre-Cooled Cycle: 26 trailer mounted heat exchangers to reject 44 MW of heat
- Nitrogen Refrigeration Cycle: 69 trailer mounted heat exchangers to reject 57 MW of heat

For the direct compression cycle, the maximum allowable tube pressure in units manufactured by Harsco is 9,700 psig. Additional vendors have been identified but information has not been obtained at the time of this reporting. Preliminary discussions with the contacted vendors suggested that pressures up to 10,000 psig would likely be possible.

Evaporative Cooling

For the evaporative cooling process, the process fluid would flow through some type of heat exchanger (i.e., shell-and-tube or printed-circuit heat exchanger) and heat would be transferred to water on the other side of the exchanger. The water would then flow to an evaporative cooler where heat would be rejected to the atmosphere.

The primary advantage to this approach is that the evaporative cooling method likely requires a significantly smaller footprint to achieve the same amount of cooling. An initial sizing estimate was obtained from the evaporative cooler manufacturer, Evapco. An Evapco AT 8-548BS unit was recommended that could provide 1,000 tons of cooling (approximately 3.5 MW) for water entering the evaporative cooler at 95°F and exiting at 85°F for ambient conditions in which the wet-bulb temperature is 78°F. The recommended unit is 48 feet long and has been mounted to an 18-wheeler trailer in previous applications. With this piece of equipment, seven trailers would be required for the direct compression process.

Potential disadvantages to this approach include the usage of water for the cooling water loop and the additional equipment required to operate the water loop. For the evaporative cooler method, water must be circulated through the heat exchanger and into the evaporative cooler. Each evaporative cooler would need to circulate approximately 3,000 gallons of water per minute (gpm) to achieve the 1,000 tons of cooling (based on the manufacturer's published recommendation of 3 gpm/ton at the 95/85/78°F temperatures mentioned previously). It is important to note that the 3,000 gpm would be a circulatory flow rate and not the rate at which water would be consumed. The actual water consumption would be limited to the evaporation rate.

The recommended evaporative coolers have a reservoir of water that supply the cooling water loop and collect the water as it sprays over the cooling media. These reservoirs would need to be filled at each fracturing location (transporting the evaporative coolers with water in the reservoir would not be possible). Initial calculations suggest that each of the AT8-548BS coolers would require a minimum of 1,750 gallons of water in addition to the water required for the loop piping, heat exchangers, and other equipment. This water would likely need to be transported to the fracturing site (supply of clean water at the site may not be feasible) and would need to obtain a specified level of purity (i.e., particle content, mineral content, and others). For the direct compression process that would utilize seven evaporative coolers, it is estimated that two tanker trucks (assuming each can transport 9,500 gallons) would be sufficient for the initial filling process. As the analyses mature, calculations that are more detailed will be made to obtain a better estimate of the actual water consumption for the designed process. It should also be noted that any water not consumed during the fracturing process could then be transported away from the site and recycled for another fracturing application, as it will have had no direct contact with any fracturing media or other chemicals.

With regard to the auxiliary equipment, water pumps would be required to circulate the water through the cooling loop. Inquiries made to water pump manufacturers indicated that the power required for the 3,000 gpm flow rate would likely be in the range of 75 to 125 HP (0.06 to 0.09 MW) for each evaporative cooler. The power required to operate the water loop is small compared to the overall process power requirement but the equipment footprint, particularly for the intended mobile application, must be considered carefully.

Additionally, the evaporative cooling methods would require some form of heat exchanger between the process fluid and the water. Shell-and-tube heat exchangers are commonly used. An information request was submitted to one shell-and-tube heat exchanger manufacturer capable of designing to the elevated pressures. Sizing and budgetary estimates had not been received at the time of this reporting.

2.2.4.3 Cryogenic Pumps

For the two refrigeration processes described in Section 2.2.2, the methane is liquefied first and then pumped to the final pressure of 10,000 psia. These processes require the use of a cryogenic pump. Two manufacturers have been identified that make reciprocating pumps with outlet pressure capabilities in the required range, though the flow capabilities are nearly an order of magnitude less than the total flow rate required. One of the manufacturers, Cryostar, produces a pump with five pistons (a quintuplex pump) that has a flow capability of 291 gpm at 10,000 psia. The maximum required flow rate currently considered in the process analysis is nearly 1,500 gpm and would require about five of the Cyrostar pumps. The Cryostar reciprocating pumps currently have an inlet pressure limitation of 250 psig, which would necessitate a pressure drop from the designed inlet pressure of 500 psia at some point during the refrigeration process. This required pressure drop has been included in the process analysis discussed previously.

Another manufacturer, ACD, also produces a quintuplex piston pump capable of the required outlet pressures. The 5-SLS pump has a flow capacity of 237 gpm at 10,000 psia. To achieve the maximum flow rate, seven of the ACD pumps would be required. At this pressure and flow rate, the pump power is 1,500 HP (1.1 MW). The ACD pump has a slightly higher inlet pressure limitation of 400 psig.

2.2.4.4 Other Equipment

The refrigeration processes considered so far rely on two other major pieces of equipment that have yet to be investigated: multi-stream heat exchangers and the compressor/expanders. These two items are believed to be highly process specific and a decision was made to delay inquiries into these items until the process analyses achieved a greater level of maturity. Once flow rates, pressures, and temperatures are better defined, inquiries can be made to determine the availability of these items.

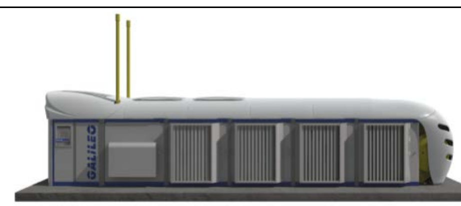
2.2.4.5 Commercially Available LNG Production Processes

A survey was conducted to identify commercially available LNG production processes. This was done with two purposes: 1) to identify any cycle designs that could be useful for this work and 2) to have a baseline of the power required for production of LNG. The subject work is focused on production of high-pressure natural gas (sCH_4), but the majority of the cycles use LNG production and pumping to reach this end goal. Therefore, it is useful to compare the proposed cycles to commercially available LNG production systems.

Small Scale LNG Production

Table 2-7 outlines the various small-scale LNG production systems available. The specific energy for each of these systems was calculated based on the information available in each manufacturer's datasheet. Note that the specific energies listed in Table 2-7 for the commercial systems are all higher than the specific energies calculated for the three thermodynamic cycles listed above. The direct compression system is an order of magnitude lower in specific energy and the other two cycles are within the same order of magnitude. The LNG flow rates for the three small-scale systems are much lower than that required for a fracturing system. A fracturing system requires an LNG flow rate of approximately 1,300,000 gal/day. This is 26 times higher than the maximum flow rate show in Table 2-7.

Table 2-7. Summary of Commercially Available Small-scale LNG Production Systems [1-3]

Manufacturer	Specific Energy, Btu/lbm (with pumping to 10,000 psia included)	Max Production Rate, gal/day	Image
GE	1,302	50,000	
Galileo	1,250	9,000	
Dresser-Rand	n/a	6,000	
Fracturing Process	305 to 812	1,300,000	n/a

Large Scale LNG Production

There are several commercial large-scale LNG production processes. The most common is the Air Products and Chemical, Inc. (APCI or C3MR) process, which is shown in Figure 2-15. This process uses a three-stage cooling process for production of LNG. In the first stage, a propane refrigeration system is used to pre-cool the natural gas, and in the second and third stages, a mixed refrigerant is used for cooling. As indicated above in the discussion of the thermodynamic cycles, the mixed refrigerant cycle is being considered for the subject work.

Large-scale LNG systems report their performance based on the LNG produced. The units of MTPA (million metric ton per annum) are reported for the process. This is used to compare the various LNG processes. The APCI process produces in the range of 4 to 5 MTPA. This equates to 280 to 350 lbm/s of production. The fracturing system will need to be capable of producing up to 61.7 lbm/s. This is approximately 20% of the production rate of an APCI LNG production plant.

The other LNG large-scale production process that was considered for the subject work is the nitrogen refrigeration cycle. The nitrogen cycle can be configured for single-stage or dual-stage refrigeration. This cycle produces from 0.7 to 1.0 MTPA of LNG. The mass flow for this process is 49 to 70 lbm/s. This is within the range of the 61.7 lbm/s required for the fracturing process.

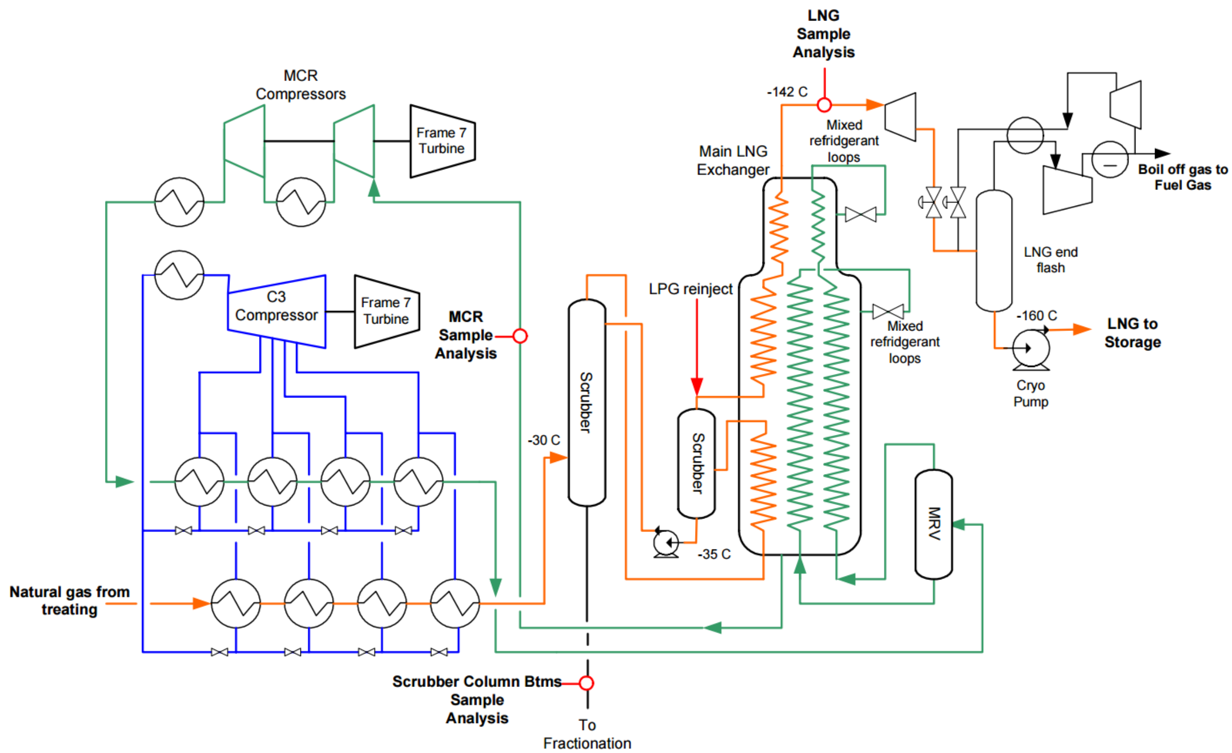


Figure 2-15. Schematic of APCI Large-scale LNG Production Process [4]

The LNG production rates and specific energy for the APCI and nitrogen refrigeration cycles are compared to the fracturing process in Table 2-8. As discussed above, the mass flow range for the fracturing process is within the range of the commercial nitrogen refrigeration process. A comparison of the specific energies shows that the specific energies of the fracturing process are the same order of magnitude as the commercial processes. It is interesting to note that the large-scale LNG production specific energy is half of the small-scale LNG production systems.

Table 2-8. Summary of Commercially Available Large-scale LNG Production Processes [5-7]

Process	Production Rate (lbm/s)	Specific Energy (Btu/lbm)
APCI (Mixed refrigerant)	280 to 350	453
Commercial nitrogen refrigeration	49 to 70	580
Fracturing process	61.7	305 to 812

2.3 *Opportunities for Training and Professional Development*

During this last quarter, the initial thermodynamic analyses of each of the cycles were completed. In this task, some members of the project team had the opportunity to learn how to use the software APSEN HYSYS. The PI from SLB, Sandeep Verma, is fluent in HYSYS and provided the other teams members with advice on how to construct and tune thermodynamic cycle models in HYSYS.

2.4 *Dissemination of Results to Communities of Interest*

No results have been disseminated to communities of interest during this quarter.

2.5 *Plan for Next Quarter*

During the next quarter, several tasks will be completed. The list below outlines the planned work. First, the thermodynamic cycle analyses will be completed. This includes finishing the analysis on the pre-compression, direct refrigeration with mixed refrigerant, and pre-cooled cycle with two-stage refrigeration. After these analyses are complete, the top three concepts will be selected with the metrics defined during this quarter. Then the detailed analysis of the top three cycles will begin. In addition, the review of the commercially available equipment will continue during the next quarter.

Summary of tasks for next quarter

- Thermodynamic analyses
  - Pre-compression cycle
  - Direct refrigeration with mixed refrigerant
  - Pre-cooled cycle with two stage refrigeration
- Selection of top concepts
- Begin detail analyses
- COTS review

Table 2-9. Summary of Milestone Status

Budget Period	Milestone Letter	Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments (Progress towards achieving milestone, explanation of deviations from plan, etc.)
1	A	Top 2 to 3 Thermodynamic Cycles Identified	January 2, 2015 **New: May 12, 2015**	In Progress 70% Complete	At least two combinations of thermodynamic paths and sets of equipment have been identified as being capable of accomplishing natural gas compression from approximately 200-1,000 psi inlet to 10,000 psi outlet	Completion of this milestone has been delayed by execution of full contract. Planned completion date is extended to May 12, 2015.
1	B	Top Thermodynamic Cycle Identified	May 1, 2015 **New: August 31, 2015**	In Progress 5% Complete	At least one combination of thermodynamic paths and sets of equipment have been identified as being capable of accomplishing natural gas compression from approximately 200-1,000 psi inlet to 10,000 psi outlet in an economically feasible fashion. (see Milestones NOTE below). This is considered a critical path milestone.	Start of this work was delayed due to delay in execution of full contract. Planned completion date is extended to August 31, 2015.
1	C	Finalized Detailed Design	September 30, 2015 **New: November 30, 2015**	Not Started	A laboratory-scale compression/pump test train will be designed to accomplish natural gas compression from approximately 200-1000 psi inlet to 10,000 psi outlet in an economically feasible fashion. (see Milestones NOTE below). This is considered a critical path milestone.	With the delay in execution of the full contract, it is anticipated that this milestone will be completed on November 30, 2015.
2	D	Compressor/Pump Train Set-up Complete	March 17, 2016	Not Started	The laboratory-scale compression/pump test train will be assembled/constructed. This is considered a critical path milestone.	none
2	E	Test Data Acquired and Analyzed	September 30, 2016	Not Started	Measured data will confirm that the laboratory-scale compression/pump test train is able to accomplish natural gas compression from approximately 200-1000 psi inlet to 10,000 psi outlet in an economically feasible, compact, and portable fashion (see Milestones NOTE below). This is considered a critical path milestone.	none
3	F	Field Test Set-up Complete	April 17, 2017	Not Started	The equipment for the field testing has been set-up and commissioned at the test site. The test set-up is ready for the start of operation.	none
3	G	Field Test Data Acquired and Analyzed	September 29, 2017	Not Started	Measured data will show that the field-tested, laboratory-scale compression/pump train is able to accomplish natural gas compression from approximately 200-1000 psi inlet to 10,000 psi outlet in an economically feasible, compact, and portable fashion (see Milestones NOTE below). This is considered a critical path milestone.	none

3 PRODUCTS

With any technical work, results will be documented and reported to the appropriate entities. Also, the work may produce new technology or intellectual property. This section provides a summary of how the technical results of this project have been disseminated and lists any new technology or intellectual property that has been produced.

3.1 *Publications*

No written works have been published during this last quarter. Also, no abstracts for future papers or conferences have been submitted for this project.

3.2 *Websites or Other Internet Sites*

The results of this project have not been published on any websites or other internet sites during the last quarter.

3.3 *Technologies or Techniques*

No new techniques or technologies have been developed in the last quarter.

3.4 *Intellectual Property*

No intellectual property, such as patents or inventions, have been submitted or developed in the last quarter.

4 PARTCIPANTS & OTHER COLLABORATING ORGANIZATIONS

The work required to develop the high-pressure natural gas (sCH_4) processing system for fracturing requires the technical knowledge and effort of many individuals. Also, two companies, SwRI and SLB, are partnering to complete the work. This section provides a summary of the specific individuals and organizations who have contributed in the last quarter.

4.1 *Southwest Research Institute (SwRI) – Prime Contractor*

The following list provides the PI and each person who has worked at least one person-month per year (160 hrs of effort) in the last quarter.

- Melissa Poerner, P.E.
    - Project Role: Principal Investigator
    - Nearest person month worked: 1
    - Contribution to Project: Project management, thermodynamic cycle review, identification of commercially available equipment
    - Funding Support: DOE
    - Collaborated with individual in foreign country: No
    - Country(ies) of foreign collaborator: n/a
    - Traveled to foreign country: No
    - If traveled to foreign country(ies), duration of stay: n/a

4.2 *Other Organizations*

In this project, SwRI is collaborating with Schlumberger (SLB). SLB is a subcontractor and cost share supporter for this project. More information about their participation is listed below.

- Schlumberger
    - Location of Organization: United States
    - Partner's Contribution to the Project: Analysis and design support
    - Financial Support: n/a
    - In-kind Support: Labor hours in first budget period

- Facilities: n/a
- Collaborative Research: SLB staff supports the analysis and design tasks for the first budget period
- Personnel Exchanges: n/a

5 IMPACT

During this quarter, a large effort was made to identify and develop thermodynamic cycles where high-pressure natural gas (sCH_4) could be produced for fracturing of gas fields. During this work, it was found that there did not exist an appreciable number of commercially available systems for the flow rate and pressure range desired. Therefore, the existing technology that was designed for smaller-scale and larger-scale LNG production systems was modified and applied to a new size range. The further development of this new system can provide a new capability to the oil and gas industry that can be applied to intermediate high-pressure natural gas (sCH_4) production operations.

6 CHANGES/PROBLEMS

During the first quarter, the full contract was not completed. Therefore, this delayed the start of the technical work. During the second quarter, the technical work was started and attempts were made to accelerate the work pace. Based on the work completed during the second quarter and the workload anticipated for the rest of the first budget period, the schedule for the project was adjusted. The completion date for the milestones in the first budget period were shifted as outlined below and in Table 2-9. It is anticipated that the project work for the first budget period will be completed on November 30, 2015, which is two months after the original due date (September 30, 2015).

- Milestone A – Top 2 to 3 thermodynamic cycles identified
  - Original Completion Date: January 2, 2015
  - New Completion Date: May 15, 2015
- Milestone B – Top thermodynamic cycle identified
  - Original Completion Date: May 1, 2015
  - New Completion Date: August 31, 3015
- Milestone C – Finalized Detailed Design
  - Original Completion Date: September 30, 2015
  - New Completion Date: November 30, 2015

7 BUDGETARY INFORMATION

A summary of the budgetary data for the project is provided in Table 7-1. This table shows the initial planned cost, the actual incurred costs, and the variance. The costs are split between the Federal and Non-Federal share.

For the second quarter in budget period 1, $49,772 was spent. All of this cost was for labor charges. The technical work on this project started during the middle of February 2015, which is the middle of the second quarter of this project. This is because the full contract between SwRI and DOE and subcontract between SwRI and SLB was not put in place until that time. The planned costs for the first quarter should reflect the work that was planned during this last quarter. The costs for this last quarter are slightly below half of what was planned. Since technical work was performed during half of the second quarter, only half of the planned budget should be used; therefore, the actual costs are representative of the planned budget.

Table 7-1. Budgetary Information for Period 1

Baseline Reporting Quarter	Budget Period 1		
	Q1	Q2	Cumulative Total
	10/1/2014 - 12/31/2014	1/1/2015 - 3/31/2015	
Baseline Cost Plan	$112,000	$103,000	$215,000
Federal Share	$89,600	$82,400	$172,000
Non-Federal Share	$22,400	$20,600	$43,000
Total Planned	$112,000	$103,000	$215,000
Actual Incurred Cost	$15,754	$49,772	$65,525
Federal Share	$15,754	$37,203	$52,957
Non-Federal Share	$0	$12,569	$12,569
Total Incurred Costs	$15,754	$49,772	$65,525
Variance	$96,246	$53,228	$149,475
Federal Share	$96,246	$53,228	$149,475
Non-Federal Share	$73,846	$32,628	$106,475
Total Variance	$96,246	$53,228	$149,475

8 REFERENCES

1. "LNG/CNG Solutions," GE Oil & Gas, http://biogassydostraskane.se/wp-content/uploads/2013/07/CNG-solutions-short.pdf, 2011.

2. "CryoBox – Nano LNG-Station," Galileo, http://www.galileoar.com/en/lng, 2014."Distributed Small Scale LNG," Dresser-Rand, http://lng.dresser-rand.com/docs/2336_LNGo_01312014.pdf, 2013.

4. Nezhad, S., et al., "Thermodynamic Analysis of Liquefied Natural Gas (LNG) Production Cycle in APCI Process," *Journal of Thermal Science*, vol. 21, no. 6, pp. 564 to 571, 2012.

5. "Refrigeration Basics and LNG," University of Oklahoma, http://www.ou.edu/class/che-design/che5480-07/Refrigeration%20Basics%20and%20LNG.pdf, accessed January 2015.

6. "Air Products' full range of liquefaction process options" Air Products Brochure, http://www.airproducts.com/~/media/Files/PDF/industries/lng/lng-air-products-full-range-of-liquefaction-process-options.pdf, 2013.

7. Pak, J., "Nitrogen Expansion Cycle Enhances Flexibility of Small-Scale LNG," *Gas Processing*, July 2013.