Quarterly Research Performance Progress Report

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Name, Title, Email Address, and Phone Number for the Prime Recipient	**Technical Contact (Principal Investigator):** Griffin Beck Research Engineer, griffin.beck@swri.org 210-522-2509 **Business Contact:** Robin Rutledge, Senior Specialist, robin.rutledge@swri.org, 210-522-3559
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	**Development and Field Testing Novel Natural Gas Surface Process Equipment for Replacement of Water as Primary Hydraulic Fracturing Fluid**
Principal Investigator(s)	Griffin Beck, 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	January 30, 2018
Period Covered by the Report	October 1, 2017 – December 31, 2017
Reporting Frequency	Quarterly
Signature of Principal Investigator:	Griffin Beck

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 (NG) to replace water as a low-cost fracturing medium with a low environmental impact. Hydraulic fracturing is used to increase oil and NG production by injecting high-pressure fluid, primarily water, into a rock formation, which fractures the rock and releases trapped oil and NG. This method was developed to increase yield and make feasible production areas that would not otherwise be viable for large-scale oil and NG 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. According to recent data, fracturing applications in North America can consume as much as 9.7 million gallons of water per well [1]. 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 NG to replace water will be developed as a cost-effective and environmentally clean fracturing fluid. Using NG 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 NG as the primary fracturing medium: (1) increasing the supply pressure of NG to wellhead pressures suitable for fracturing and (2) mixing the required chemicals and proppant that are needed for the fracturing process at these elevated pressures. The second step (NG-proppant mixing at elevated pressures) still requires technology advancements but has previously been demonstrated in the field with other gases such as nitrogen (N_2) and carbon dioxide (CO_2). However, the first step (a compact, on-site unit for generating high-pressure NG at costs feasible for fracturing) has not been developed and is currently not commercially available. The inherent compressibility of NG 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.

The project work is being performed in three sequential phases. The first phase included a thorough thermodynamic, economic, and environmental analysis of potential process concepts, as well as detailed design of three, top-performing processes. The work completed in the first phase allowed the selected thermodynamic pathway of direct compression to be optimized for the intended application. In the second phase, a pilot-scale facility was constructed at the SwRI facilities in San Antonio, TX. The pilot-scale facility was used to generate NG foam at elevated pressures similar to those found in a field application. The facility was used to investigate various properties of NG; such data are not available in the literature. In the third and final phase, the pilot-scale facility will be used to further explore the feasibility of this novel technology and will provide a more substantial data set that can be used to implement the technology in the field.

The first budget period (BP1) for this project was completed in December 2015. Work from this first effort demonstrated that the use of a direct-compression system for fracturing is commercially viable and has economic potential. Work for the second budget period (BP2) was completed on March 31, 2017. The investigations pursued during this budget period have shown that stable NG foam can be generated at elevated pressures.

This report covers the work completed in the second quarter of the current budget period. 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 test a novel approach to use readily available wellhead (produced) NG 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 conjunction with, water-based hydraulic fracturing fluids to reduce water usage and the volume of flow-back fluids. The process will use NG at wellhead supply conditions and produce a fluid at conditions suitable for injection.

The project work is split into three budget periods. The milestones for each budget period are outlined in Table 7-2. This table includes an update on the status of each 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 focused on purchasing the components required to modify the pilot-scale test facility and on incorporating those modifications into the test stand. This work included calibration of existing pressure instruments, testing of the two LNG pumps, and the repair of two, key loop components: the differential pressure sensor used in the foam rheology measurements and the back pressure regulator. The repairs required for these two components have delayed the project schedule. Updated target completion times are identified in section 6.

Additional work during the past quarter focused on identifying the compression equipment necessary to implement a field demonstration of the NG foam fracturing technology. Updated findings are discussed in section 2.2.2.

Also during the past quarter, key members of the project team presented a paper at a major industry conference held in San Antonio, TX and participated in a DOE NETL Oil & Gas Program Peer Review held at the NETL offices in South Park Township, PA. These accomplishments are discussed in more detail in the following sections.

2.2.1 Major Component Acquisitions

As described in previous reports, a significant amount of work during BP3 has focused on designing improvements to the pilot-scale test facility to enhance the control capabilities and to allow for a broader range of flow rates to be explored. The majority of the components necessary to implement the modifications were purchased and received during the past quarter. The major components are described in the following paragraphs.

2.2.1.1 *Water Pump (PMP 003)*

As described in the previous quarterly report, a CAT Pump, Model 1810 was selected to replace the water pump used during a portion of the BP2 work. This CAT pump was received and has been installed in the test loop. Nominal operating conditions for the pump are summarized in Table 2-1 and an image of the pump, along with the pulsation dampener, installed in the loop is shown in Figure 2-1.

Figure 2-1 CAT Model 1810 High-Pressure Water Pump and Pulsation Dampener

Table 2-1 Cat Model 1810 High-Pressure Water Pump

Pump Style	Maximum Pressure [psig]	Minimum Flow Rate [gpm]	Maximum Flow Rate [gpm]	Maximum Liquid Temperature [°F]
Triplex	10,000	0.2	1.0	160

The minimum pump flow rate, 0.2 gpm, is slightly greater than the targeted minimum flow rate of 0.15 gpm identified in previous reports. As such, the nominal foam flow rate for the BP3 tests has been increased to 0.66 gpm from the 0.51 gpm targeted during BP2 tests. Further, the estimated material quantities required for the BP3 tests have been updated in Table 2-2.

Table 2-2. Estimated Material Quantities Required for BP3 Tests

Material	Quantity
Waste Water (water requiring disposal services)	1,980 gallons
LNG	2,110 gallons
LN_2	365 gallons
Friction Reducer	1 gallon
Viscoelastic Surfactant	17 gallons
Foaming Agent	7.5 gallons
Water Gelling Agent	51 pounds
Clay Stabilizer	70 pounds

2.2.1.2 Rheometer Section

Past reports have described in detail the planned improvements to the rheometer flow control that will permit a nearly continuous sweep of flow rates through the rheometer section and will provide a broader range of rheology data (see diagram in Figure 2-2). The major components required to implement these improvements were received during the past quarter and, at the time of this reporting, are being installed.

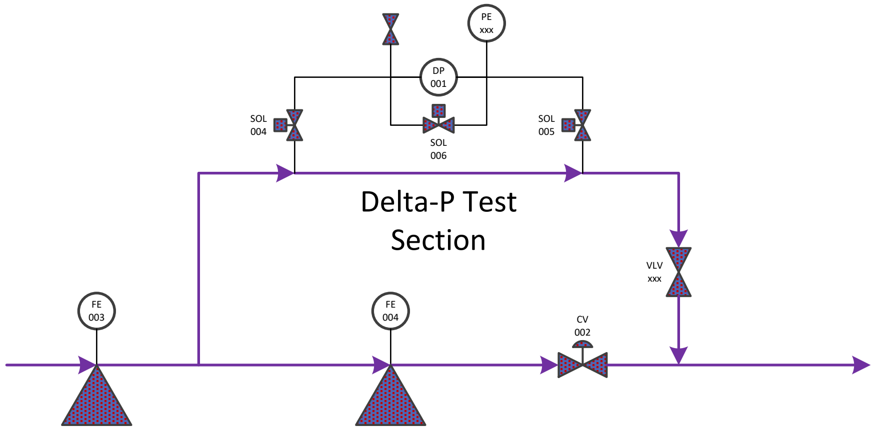


Figure 2-2. An Alternative Flow Control Method for the Tube Rheometer Section

Two Rheonik RHM04L Coriolis mass flow meters (FE 003 and FE 004) were purchased to provide foam flow and density measurements. A Research Control Valve Model HP-1711 (CV 002) was purchased to control the amount of flow that either enters or bypasses the rheometer section. Images of the RHM04L and the RCV HP-1711 installed in the system are shown in Figure 2-3 and Figure 2-4, respectively.

Figure 2-3 Rheonik RHM04L Coriolis Flow Meter Installed in Rheometer Section

Figure 2-4 Research Control Valve HP-1711 Control Valve Installed in Rheometer Section

2.2.1.3 Component Testing, Calibration, and Repairs

As the build efforts for the pilot-scale test stand have progressed, additional effort has focused on calibrating process instruments and functional tests of various components. The static and differential pressure sensors for the pilot-scale test facility were calibrated at the SwRI Calibration Laboratory (A2LA Certificate #3759.01). All of the static pressure sensors were found to be within acceptable calibration limits; however, the differential pressure sensor was found to be outside of the manufacturer-recommended limits. A shift in the sensors zero was observed. Rather than the expected 4 mA signal under no differential pressure, the sensor was producing an approximately 3 mA signal, indicating that some type of damage may have occurred during storage. This sensor was returned to the manufacturer for inspection and repair. At the time of this reporting, the sensor had not yet been returned to SwRI.

Two additional components were returned to the manufacturer recently for functional checks and repairs: the low-flow LNG pump (PMP 001) and the back pressure regulator (BPR 001). The soft goods on the LNG pump (e.g., the piston packing) were replaced and the manufacturer tested the unit using liquid nitrogen (LN_2). During these tests, it was observed that the pump could not operate at low flow rates and high pressures. For example, when trying to operate around 7,500 psi at the low flow rates of 0.072 gpm and 0.1 gpm, the pump could not maintain the pump prime and cavitation would begin. At an increased flow rate of 0.2 gpm, the pump was able to operate at 7,500 psi. These results show that the pump currently is not capable of operating over the full range specified by the manufacturer; however, the lower flow rates where it was difficult to maintain prime are not of interest in the BP3 test campaign.

The Tescom back pressure regulator was also returned to the manufacturer for inspection, replacement of wearable components, and factory testing. A status update on the valve had not been received at the time of this reporting.

2.2.2 Field-Scale Demonstration Equipment

During the conceptual design of the foam fracturing process (BP1), the project team had preliminary discussions with turbomachinery vendors to confirm the limits of commercially available hardware before proceeding with detailed design and thermodynamic cycle optimization. At the end of this phase, the envisioned machinery setup was a combination of centrifugal and reciprocating compression stages all operated while trailer mounted.

During the current budget period, after the foam fracturing process was fully specified and optimized, these discussions were resumed. Through updated discussions with a reciprocating compressor packager, it was learned that approximately seven reciprocating compressor packages would be needed to support the high flow rate identified in BP1 (50 bbl/min). In talking with SLB, this was unacceptable, so the focus shifted to a fully centrifugal machinery solution to reduce overall compressor footprint.

The project team reached out to centrifugal compressor vendors again to see if any could provide a completely centrifugal solution. Three vendors indicated that they would be able to provide centrifugal equipment in support of the complete foam fracturing cycle. These vendors were GE Oil and Gas, Elliot Turbo, and Dresser-Rand. Each vendor indicated that although they could provide a centrifugal compression system that could meet the desired flow rate and discharge pressure, doing so while trailer mounted was outside their experience base, as machines of this type typically require a permanent foundation. Discussions with these vendors are ongoing to resolve this issue and to obtain a complete budgetary estimate.

2.3 *Opportunities for Training and Professional Development*

No opportunities for training and professional development occurred during this last quarter.

2.4 *Dissemination of Results to Communities of Interest*

A paper presentation [2] providing an overview of the BP2 work was given at the 2017 Society of Petroleum Engineers Annual Technical Conference and Exhibition on October 10, 2017, in San Antonio, TX.

The project team participated in a DOE NETL Oil & Gas Program Peer Review on December 4, 2017, in South Park Township, PA.

2.5 *Plan for Next Quarter*

In the next quarter, the BP3 work will focus on completing the modifications to the pilot-scale test facility and on the initial commissioning activities.

Summary of tasks for next quarter

- Finalize pilot-scale facility equipment updates
- Begin modifications to the data acquisition system
- Continue to develop a cost estimate to deploy a field demonstration of the technology

3 PRODUCTS

With any technical work, results will be documented and reported to the appropriate entities. In addition, 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*

A paper presentation [2] providing an overview of the BP2 work was given at the 2017 Society of Petroleum Engineers Annual Technical Conference and Exhibition on October 10, 2017, in San Antonio, TX.

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

3.2 *Technologies or Techniques*

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

3.3 *Intellectual Property*

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

4 PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

The work required to develop the high-pressure NG processing system for fracturing requires the technical knowledge and effort of many individuals. In addition, two organizations, SwRI and SLB, are collaborating to complete the work. This section provides a summary of the specific individuals and organizations who have contributed in the last quarter.

4.1 *SwRI – Prime Contractor*

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

- Griffin Beck
  - Project role: Principal Investigator
  - Nearest person-month worked: 1
  - Contribution to project: BP3 test design, procurement, and project management
  - Funding support: DOE
  - Collaborated with individual(s) in foreign country(ies): No
  - Country(ies) of foreign collaborator(s): None
  - Traveled to foreign country(ies): Yes, Mexico
  - If traveled to foreign country(ies), duration of stay: 5 days

4.2 *Other Organizations*

In this project, SwRI is collaborating with 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 second budget period
  - Facilities: N/A
  - Collaborative research: SLB staff supported the design and testing tasks for the second budget period
  - Personnel exchanges: N/A

5 IMPACT

The use of NG foam is expected to have a smaller environmental footprint and may enhance gas and oil recovery compared to traditional, water-based fluids. Despite these potential benefits, fracturing with NG foams has not been widely adopted due in part to limited fluid property data. The BP2 tests have provided much-needed information to industry to advance fracturing with NG foams.

As noted in previous reports, past research efforts by others have investigated the rheological properties of foams generated with inert gases, namely nitrogen and carbon dioxide. However, published literature is not available for the rheological properties of NG foam. The data generated by the BP2 tests provide the first set of publically available NG foam rheology data. The scheduled BP3 tests will provide additional rheology data needed by the oil and gas industry. These data will be critical in future design work, particularly in understanding the impact on the gas compression machinery.

6 CHANGES/PROBLEMS

The contract modification was not received until the end of May 2017, delaying the project start by nearly two months. The delayed start, some on-going scheduling conflicts, and the lead-times on component acquisitions and repairs will delay the completion of test facility modifications until late February 2018 and testing until March 2018 or later. As such, a *no-cost time extension* (NCTE) will be requested to delay the project deadline by at least three months. The updated dates and milestones are documented below and in Table 7-2.

- Milestone F – Test Facility Modifications Complete
  - Original Milestone F Completion Date: September 29, 2017
  - New Milestone F Completion Date: February 28, 2017
- Milestone G – Test Data Acquired and Analyzed
  - Original Milestone G Completion Date: March 31, 2018
  - New Milestone G Completion Date: June 30, 2018

In addition to the delays currently identified, the project team has been in communication with DOE in efforts to discuss additional funding for future work. Much of the future work of interest to the project team would address some of the project *weaknesses* identified by the peer review. Note that the project *weaknesses* identified in the peer review are additional areas of research rather than shortcomings of the work accomplished thus far under the project. These areas of additional research, many of which have been discussed internally by the project team, require additional funding not available under the current project. If such work were funded, it is likely that current testing efforts would be delayed in an effort to incorporate some of the additional work, which would be more cost-effective than pursuing multiple test mobilizations.

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 for the current budget period. The costs are split between the Federal and Non-Federal share.

In the second quarter of BP3, $206,202 was spent. This value reflects the increased equipment procurement activities this past quarter as well as the receipt of two sub-recipient invoices. A baseline cost plan for the entirety of BP3 is included in the table to reflect the planned activities.

Table 7-1. Budgetary Information for Period 2

Baseline Reporting Quarter	Budget Period 3					
	Q1	Q2	Q3	Q4	Q5	Cumulative Total
	4/1/2017 - 7/07/2017	7/8/2016 - 9/29/2017	9/30/2017 - 1/5/2018	1/6/2018 - 3/30/2018	3/31/2018 - 7/6/2018	
Baseline Cost Plan	$13,064	$254,225	$163,039	$86,168	$72,053	$588,548
Federal Share	$13,064	$223,620	$132,434	$55,563	$41,448	$466,129
Non-Federal Share	$0	$30,605	$30,605	$30,605	$30,605	$122,419
Total Planned	$13,064	$254,225	$163,039	$86,168	$72,053	$588,548
Actual Incurred Cost	$5,686	$21,953	$206,202	$0	$0	$233,841
Federal Share	$5,686	$21,953	$158,920	$0	$0	$186,559
Non-Federal Share	$0	$0	$47,282	$0	$0	$47,282
Total Incurred Costs	$5,686	$21,953	$206,202	$0	$0	$233,841
Variance	$7,378	$232,272	($43,163)	$86,168	$72,053	$354,707
Federal Share	$7,378	$201,667	($26,486)	$55,563	$41,448	$279,570
Non-Federal Share	$0	$30,605	($16,677)	$30,605	$30,605	$75,137
Total Variance	$7,378	$232,272	($43,163)	$86,168	$72,053	$354,707

Table 7-2. Summary of Milestone Completion Status

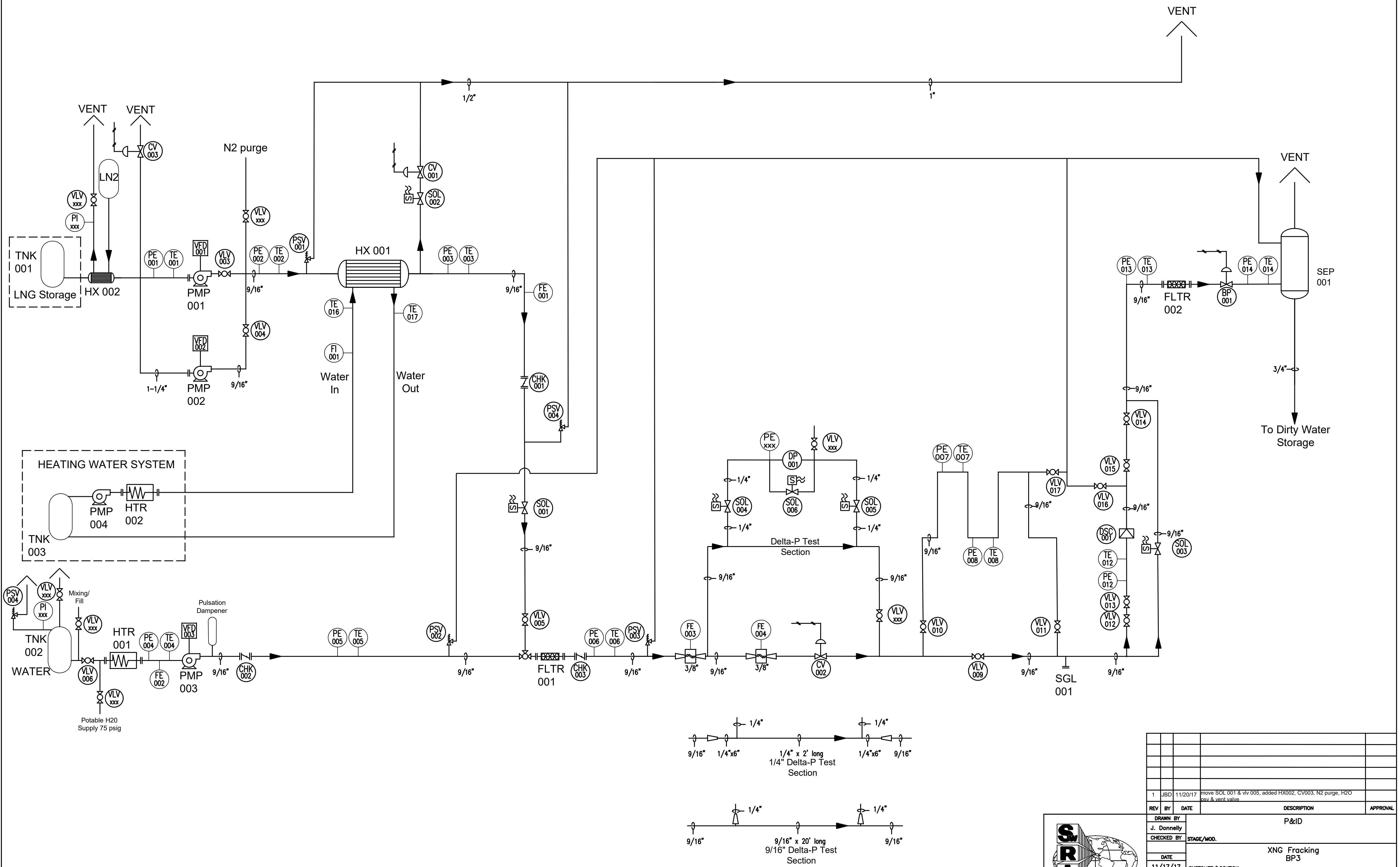
Budget Period	Milestone Letter	Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments (Progress towards achieving milestone, explanation of deviations from plan, etc.)
1	A	Top 2 to 3 Thermodynamic Cycles Identified	January 2, 2015 **New: June 9, 2015**	Complete June 9, 2015	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. Actual completion date was June 9, 2015.
	B	Top Thermodynamic Cycle Identified	May 1, 2015 **New: September 30, 2015**	Complete September 30, 2015	At least one combination of thermodynamic paths and sets of equipment has 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. This is considered a critical path milestone.	Start of this work was delayed due to delay in execution of full contract. Actual completion date was September 30, 2015.
	C	Finalized Detailed Design	September 30, 2015 **New: December 31, 2015**	Complete, December 31, 2015	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. This is considered a critical path milestone.	With the delay in execution of the full contract, this milestone was completed on December 31, 2015.
2	D	Compressor/Pump Train Set-up Complete	March 17, 2016 **New: December 30, 2016**	Complete, December 30, 2016	The laboratory-scale compression/pump test train will be assembled/constructed. This is considered a critical path milestone.	Due to a delay in contract execution, delays with component deliveries, and delays related to comissioning, the construction was completed Dec. 30, 2016.
	E	Test Data Acquired and Analyzed	September 30, 2016 **New: March 31, 2017**	Complete, March 31, 2017	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. This is considered a critical path milestone.	With the delayed completion of the test stand, testing and data analysis was completed March 31, 2017.
3	F	Test Facility Modifications Complete	October 31, 2017 **New: February 28, 2018**	In Progress	Modifications to the BP2 test stand are complete and the test matrix has been generated.	A preliminary test matrix has been generated. Design of the various test loop modifications is ongoing. A majority of components have been received and test stand construction is ongoing.
	G	Test Data Acquired and Analyzed	3/31/2018 **New: June 30, 2018**	Not Started	Measured data will provide detailed information about the rheology properties of NG foam.	None

8 REFERENCES

[1] Gallegos, T. J., Varela, B. A., Haines, S. S., and Engle, M. A., 2015, "Hydraulic Fracturing Water Use Variability in the United States and Potential Environmental Implications: HYDRAULIC FRACTURING WATER USE VARIABILITY IN THE U.S.," Water Resour. Res., **51**(7), pp. 5839–5845.

[2] Beck, G., Nolen, C., Hoopes, K., Poerner, M., Phatak, A., and Verma, S., 2017, "Laboratory Evaluation of a Natural Gas–Based Foamed Fracturing Fluid," *SPE Annual Technical Conference and Exhibition*, Society of Petroleum Engineers, San Antonio, TX USA.

9 APPENDIX



REV	BY	DATE	DESCRIPTION	APPROVAL
1	JBD	11/20/17	move SOL 001 & vlv 005, added HX002, CV003, N2 purge, H2O psv & vent valve	

DRAWN BY	P&ID
J. Donnelly	
CHECKED BY	STAGE/MOD.
	XNG Fracking BP3
DATE	
11/17/17	CUSTOMER/LOCATION

SCALE	SWRI JOB No.	FIGURE NUMBER	SHT.	REV.
NTS	18–2075805		1 OF 1	1

ASHT.DWG