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 Group Leader-R&D, griffin.beck@swri.org 210-522-2509 SwRI Project No. 20758 **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 – *SwRI* SwRI Project No. 20758 **Subcontractors/Co-Funding Partners**: Sandeep Verma, Ph.D. – *Schlumberger* Leo Chaves – *Chevron*
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Signature of Principal Investigator:	 Griffin Beck

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1. INTRODUCTION

Southwest Research Institute® (SwRI®), Schlumberger Technology Corporation (SLB), and Chevron Corporation® (Chevron) 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 11 million gallons of water per well. 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 a majority of the water is being developed as a cost-effective and environmentally clean fracturing fluid. Using NG will result in significantly less consumption 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 process will minimize 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 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. Due to the inherent compressibility of NG, more energy is required to compress the gas than what is required to pump 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 five 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, the Pilot-Scale Foam Test Facility (PFTF) was constructed at the SwRI facilities in San Antonio, Texas. The PFTF 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 foam; such data are not available in the literature. In the third phase, the PFTF was used to further explore the feasibility of this novel technology and provided a more substantial data set that can be used to implement the technology in the field. In the fourth phase (the current phase), laboratory tests, process models, and pilot-scale tests were expanded to investigate the effects of realistic fluids and operating conditions. Specifically, the effects of multi-constituent NG mixtures, water impurities, and elevated operating temperatures on foam stability are being investigated. Furthermore, the impact of NG mixtures on the compression process efficiency and equipment footprint was identified. In the fifth phase, the potential for NG foam to enhance oil and gas recovery will be investigated in a series of laboratory fracture network tests.

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, and included pilot-scale investigations that demonstrated that stable NG foam can be generated at elevated pressure. The third budget period (BP3) was completed December 31, 2018, and included expanded pilot-scale tests to further investigate the fluid properties of NG foam using a range of base fluid mixtures. The fourth budget period (BP4), began January 1, 2019. This report covers work completed during the fourth and final quarter of BP4. 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 five budget periods. The milestones for each budget period are outlined in Table 6-1. 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, NG-based foam stability and rheology test data collected at SwRI's *pilot-scale foam test facility* (PFTF) were analyzed. The rheology data indicate that NG foam is a suitable medium for hydraulic fracturing and exhibits behavior typical of other foamed fluids when quality and temperature are varied. Also in the fourth quarter, a model for a Duvernay shale reservoir was developed. The model was used to compare fracture growth and reservoir production when stimulated with NG foam and other common fluids. Initial results of this study are discussed in this report. These and other accomplishments are discussed in the confidential appendix to this report.

2.3 Opportunities for Training and Professional Development

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

2.4 Dissemination of Results to Communities of Interest

In the fourth quarter, a close-out presentation was given to DOE personnel discussing the findings and progress in BP4.

2.5 Plan for Next Quarter

In the first quarter of BP5, work will focus on creating a design for a small-scale foam generator to be used in the planned fracture network tests. Also, a portion of the foam rheology work planned for BP4 was not completed. This work will continue in Q1 of BP5.

2.6 Summary of Tasks for Next Quarter

The following tasks are expected in the next quarter:

- Perform closed-loop rheometer tests at SLB facilities
- Complete the preliminary design of the small, portable foam generator
- Identify long-lead components for the small, portable foam generator

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

No new publications were generated during the last quarter.

3.2 Technologies or Techniques

No new techniques or technologies have been developed during 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. SwRI, SLB, and Chevron 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 approximately one person-month per year during the last quarter.

- Griffin Beck
  - Project role: PI
  - Nearest person-month worked: 0.5
  - Contribution to project: BP4 test design, operation, and project management
  - Funding support: DOE
  - Collaborated with individual(s) in foreign country(ies): No
  - Country(ies) of foreign collaborator(s): None
  - Traveled to a foreign country(ies): No
  - If traveled to a foreign country(ies), duration of stay: N/A

4.2 Other Organizations

For this project, SwRI is collaborating with SLB and Chevron. SLB is a subcontractor and cost-share supporter for this project. Chevron is a cost-share supporter for this project. More information about their participation is listed below.

- SLB
  - Location of organization: United States
  - Partner's contribution to the project: Analysis and design support, laboratory testing, reservoir modeling
  - Financial support: N/A
  - In-kind support: Labor hours in the first budget period
  - Facilities: N/A
  - Collaborative research: SLB staff supported reservoir modeling tasks during the first quarter
  - Personnel exchanges: N/A
- Chevron
  - 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 the first budget period
  - Facilities: N/A
  - Collaborative research: Chevron staff provided technical expertise for the project
  - 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. This project has provided much-needed information to the 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 nonflammable gases, namely nitrogen and carbon dioxide. However, published literature is not available for the rheological properties of NG foam. The data generated by this project will be critical in future design work, particularly in understanding the impact of the gas compression machinery.

6. CHANGES/PROBLEMS

During the past quarter, it became clear that a portion of the foam stability and rheology work would not be completed due to some personnel availability issues. To address this issue, the project team has requested to DOE that unused BP4 funds (i.e., those funds dedicated the rheology work) be released and the work be allowed to continue concurrently with the planned BP5 activities. The disposition of this request is unknown at the time of this reporting. A new completion date of June 30, 2020, is proposed for this work. This change is reflected in the updated milestones and delivery dates shown in Table 6-1, Milestone I.

Table 6-1: 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 commissioning, 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: March 31, 2018**	Complete March 30, 2018	Modifications to the BP2 test stand are complete and the test matrix has been generated.	The test stand modifications were completed on March 30, 2018.
	G	Test Data Acquired and Analyzed	3/31/2018 **New: December 31, 2018**	Complete December 31, 2018	Measured data will provide detailed information about the rheology properties of NG foam.	Initial data processing is complete. Further processing will occur as needed.
4	H	Test Facility Modifications Complete	August 13, 2019	Complete October 8, 2019	Modifications to support high-temperature stability tests are complete	Facility upgrades were completed and tests were executed.
	I	Test Data Acquired and Analyzed	12/31/2019 **New: June 30, 2020**	In Progress	Data collected on the pilot-scale foam test facility and the closed-loop rheometer will be used to determine the effect of water quality, gas composition, and operating temperature on the stability of natural gas-based foam	
	J	Compression Cycle Models Updated	September 30, 2019	Complete December 31, 2019	Cycles have been modeled with realistic natural gas compositions	Model updates are in progress
	K	Initial Reservoir Model Complete	September 30, 2019	Complete December 31, 2019	Initial reservoir models will be used to explore potential production benefits related to natural gas-based foam	Reservoir model parameters are currently being explored/defined
5	L	Portable Foam System Complete	June 30, 2020	In Progress	The portable foam system has been designed, built, and commissioned	Design work for the foam system is underway.
	M	Test Data Acquired and Analyzed	December 31, 2020		Fracture network data has been generated and analyzed	
	N	Final Reservoir Model Complete	September 30, 2019		The reservoir model has been updated with additional information generated by the fracture network tests	

7. BUDGETARY INFORMATION

A summary of the budgetary data for the BP4 portion of the project is provided in Table 7-1. This table shows the planned costs over the four quarters, the actual incurred costs to date, and the variance for the current budget period. The costs are split between the Federal and Non-Federal share.

During the fourth quarter of BP4, a total of $204,971 was used in support of the project efforts described previously. The variance between the planned costs and the actual costs are due to delays in invoicing and the reporting of cost share contributions by the project subrecipient and cost share contributors. Some of SLB's work (SLB is the project subrecipient and a cost share contributor) has been delayed and will occur concurrently in BP5. It is fully anticipated that the federal and cost-share funds dedicated to these activities will be fully utilized. In the case of Chevron, a project cost-share contributor, there have been some delays in finalizing the subcontract documentation. These delays have prevented Chevron from reporting cost-share contributions to date. Nevertheless, Chevron continues to fully participate in the project activities and it is expected that the cost share obligation will be fully satisfied once the subcontract is in place and contributions can be reported.

Table 7-1: Budgetary Information for Budget Period 4

Budget Period 4				
Reporting Quarter	**Q1**	**Q2**	**Q3**	**Q4**
Start	**1/5/2019**	**3/30/2019**	**7/6/2019**	**9/28/2019**
End	**3/29/2019**	**7/5/2019**	**9/27/2019**	**1/3/2020**
Baseline Cost Plan	$148,932	$406,734	$658,888	$804,755
Federal Share	$106,721	$322,311	$532,253	$635,909
Non-Federal Share	$42,211	$84,423	$126,634	$168,846
Total Planned	***$148,932***	***$406,734***	***$658,888***	***$804,755***
Actual Incurred Cost	$25,305	$94,200	$334,066	$539,037
Federal Share	$25,305	$94,200	$334,066	$539,037
Non-Federal Share	$0	$0	$0	$0
Total Incurred Costs	***$25,305***	***$94,200***	***$334,066***	***$539,037***
Variance	$123,628	$312,533	$324,821	$265,718
Federal Share	$81,416	$228,110	$198,187	$96,872
Non-Federal Share	$42,211	$84,423	$126,634	$168,846
Total Variance	***$123,628***	***$312,533***	***$324,821***	***$265,718***