Quarterly Research Performance Progress Report

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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*
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Signature of Principal Investigator:	Griffin Beck

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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 field 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 identifying and designing modifications to the pilot-scale test facility that will support the objectives of the tests in BP3. This work included further development of the BP3 test matrix, identifying and selecting an appropriate water pump, and identifying available equipment for the modified rheometer section. These updates are discussed in detail below.

2.2.1 BP3 NG Foam Test Objectives

As discussed in the previous quarterly report, the BP3 tests will advance the NG foam fracturing by meeting the following objectives:

- Additional base fluid compositions regularly used in the industry will be tested to determine compatibility with NG foams.
- An extensive set of NG foam rheology data will be collected that can be used to simulate, design, and implement NG fracture treatments on a larger, industrial scale. These tests will explore a wider range of flow rates pertinent to both well bore conditions and formation conditions.
- Additional techniques to generate and maintain stable foam at field conditions will be explored.

A majority of the work in the previous quarter focused on designing test modifications that will allow the test objectives to be achieved.

2.2.2 BP3 Test Matrix Update and Fluid Quantity Estimates

The test matrix developed for the BP3 tests was discussed, in detail, in the previous quarterly report. Work in the past quarter identified the targeted operating ranges for the various test parameters.

Table 2-1 displays test parameters of interest and the range of values that will be explored for each parameter. In the past quarter, the nominal foam flow rate was updated to 0.66 gpm based on the minimum flow rate available from the selected water pump. The table shows five foam flow rate levels that can likely be achieved using the modified flow control mechanism in the tube rheometer section.

Table 2-1. Test Matrix Parameters

Foam Flow Rate (gpm)	Quality (%)	Pressure (psi)	Temperature (°F)	Base Fluid Composition	Rheometer Diameter (in)
0.07	60	2,500	90	30 ppt Guar	0.109
0.20	70	5,000	125	70 ppt Guar	0.312
0.33	80	6,500	160	Viscoelastic surfactant fluid	
0.46				Slickwater fluid	
0.66					

The test matrix was used to generate a preliminary estimate of the various fluid and additive quantities required for the BP3 tests. The preliminary estimates for the quantities are listed in Table 2-2. Note that the listed quantities do not yet provide for all of the commissioning and daily start-up activities. That work is ongoing at the time of this reporting.

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

Material	Quantity
Waste Water (water requiring disposal services)	1,574 gal.
LNG	1,572 gal.
Friction Reducer	1 gal.
Viscoelastic Surfactant	13 gal.
Foaming Agent	6 gal.
Water Gelling Agent	41 lb.
Clay Stabilizer	54 lb.

2.2.3 Rheometer Section Modifications

In the past quarter, additional efforts focused on designing improvements to the rheometer flow control mechanism and identifying commercially available equipment for the improvements. The improvements to the rheometer flow control, which have been discussed in previous quarterly reports, will permit a nearly continuous sweep of flow rates through the rheometer section and will provide a broader range of rheology data.

An updated schematic of the rheometer section is shown in Figure 2-1. The total flow rate and density of the foam entering the rheometer section will be measured using a high-pressure Coriolis mass flow meter (FE 003). As the foam enters the rheometer section, the foam can either be made to flow through the tube rheometer section (i.e., the tube with differential pressure taps on either end) or through the bypass section that contains the second flow meter (FE 004) and the control valve (CV 002). When the control valve is fully open, the foam will bypass the rheometer section and flow through the second flow meter (FE 004) and through CV 002. Note that a manually operated needle valve (VLV XXX) will be located at the outlet of the rheometer section to serve as an adjustable restriction. As CV 002 is closed, the foam will begin to flow through the rheometer section at a low flow rate, which will permit testing at lower shear rates than those achieved in the BP2 tests. As the control valve is closed further, the flow through the rheometer will increase until the entire foam flow is directed through the rheometer section.

For the BP3 tests, additional controls have been added to the differential pressure sensor (DP 001) lines. These controls will allow the sensing lines to be filled with N_2 gas to a specified pressure. Then, once the test stand has achieved a steady-state operating condition at a pressure slightly above the N_2 pressure, the sensing lines will be opened to the process fluid by actuating solenoid valves (SOL 004 and 005). These controls were implemented to shield the differential pressure sensor from some of the potentially damaging pressure transients experienced in the BP2 tests.

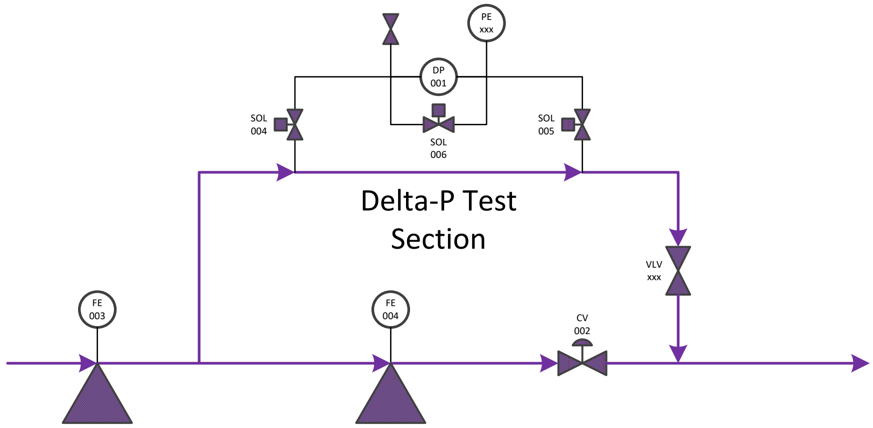

Figure 2-1. An Alternative Flow Control Method for the Tube Rheometer Section

The necessary hardware and instrumentation for the modifications have been identified. Two Rheonik RHM04L Coriolis mass flow meters have been selected to provide foam flow and density measurements. These units can provide 0.5% mass flow measurement uncertainty in the range of 0.4 to 22 lbm/min (the vast majority of the BP3 tests will range between 0.4 and 4.0 lbm/min). Control valves from two manufacturers, Low Flow and Badger Meter, have been sized and quotes are pending. Finally, appropriate solenoid and manual valves have been identified from High Pressure Equipment company.

2.2.4 Water Pump

In the past quarter, a number of water pumps were considered for the BP3 tests. In general, for pumps that could achieve the full range of targeted pressures and flow rates, the pump cost was in excess of $70,000 and exceeded the current budget. Pumps that were within the budget were not capable of achieving the entire range of operating conditions. The targeted operating conditions of the water pump are provided in Table 2-3.

Table 2-3. Targeted Operating Conditions for BP3 Water Pump

Parameter	Minimum Value	Maximum Value
Flow Rate [gpm]	0.1	1.0
Temperature [°F]	50	160
Pressure [psig]	100	7,500

Initial pump selections comprised triplex piston pumps. Simplex and duplex piston pumps were also considered for selection, but they were ultimately eliminated from the selection process because these pumps induce more pulsations into the working fluid than a triplex pump. Specifically, the pulse magnitude above mean flow for a simplex pump is roughly 60%. For duplex pumps and triplex pumps, the pulses above mean flow are approximately 25% and 13%, respectively. The triplex pumps considered for purchase were a Cat 1810 pump and a Tritan 3085 SX pump. The main limitation with these pumps is that they could not produce the targeted minimum flow of 0.1 gpm. In both cases, a minimum flow rate of 0.2 gpm must be maintained in order to adequately lubricate the pump during operation. Financially, the Tritan 3085 SX pump and Cat 1810 pump are desirable, priced at roughly $33,000 and $24,000, respectively.

Chemical injection and metering pumps were also considered due to their ability to provide low flow rates. However, it was discovered that a majority of chemical injection pumps were not able to provide the full range of operating conditions. Manufacturers such as Graco and Morrill were considered, but ultimately they were unable to provide an adequate water pump. Other metering pump options included a Tritan P-15 chemical injection pump and a Milton Roy pump. A rough order of magnitude of $100,000 was provided for the Milton Roy pump, so that option was not pursued further. At roughly $37,000, the Tritan P-15 pump was considered a viable option.

ProMinent and Lewa offered custom-built diaphragm pumps. A custom-built diaphragm pump is an attractive option because it can be designed specifically to achieve the desired operating conditions. However, the cost for a custom-built diaphragm pump from either ProMinent or Lewa was approximately $70,000 and, consequently, not within the budget.

Considering the pump options described above, the final selection was narrowed down to three pumps: (1) Cat 1810 triplex pump, (2) Tritan 3085 triplex pump, and (3) Tritan P-15 chemical injection pump. The final selection was based on the relative fluid pulsation amplitude of each pump. The pulsation amplitude that each pump would induce on the working fluid was calculated, assuming an identically sized pulsation dampener was attached to the discharge of each pump. The result of this study found that the normalized pulsation amplitude of the Cat 1810 pump was 0.93 and the normalized pulsation amplitude of the Tritan 3085 pump was 1.47. The pulsation of the Tritan P-15 pump ranged between 3.02 for the lowest flow rate, which would utilize a single piston, and 0.36 for the highest flow rate, which would utilize the entire range of pistons.

Based on the pulsation results, it seemed that the Cat 1810 triplex pump was the most desirable option. It induces pulsations of smaller amplitude than the Tritan pumps and it is the least expensive option. The cost of this pump is $23,900. Quotes were also acquired for pulsation dampeners adequately sized for the Cat 1810 pump. A summary of the pump capabilities is provided in Table 2-4.

Table 2-4. Water Pumps Considered for BP3 Tests

Pump Name	Pump Style	Max Pressure [psig]	Minimum Flow Rate [gpm]	Maximum Flow Fate [gpm]	Maximum Liquid Temperature [°F]	Normalized Pulsation Amplitude [psig/psig]	Cost
Cat 1810	Triplex	10,000	0.2	1.0	160	0.93	$23,900
Tritan 3085 SX	Triplex	40,000	0.2	1.0	N/A	1.47	$32,644
Tritan P-15	Chemical injection	7,500	0.1	1.0	140	0.36 – 3.02	$37,131
ProMinent	Custom diaphragm	7,500	0.1	1.0	160	Not considered	$68,164
Lewa	Custom diaphragm	7,500	0.1	1.0	160	Not considered	$69,680
Milton Roy	Metering	Not considered. Cost exceeds budget.					$100,000
Morrill Industries	Chemical injection	Not considered. No applicable product available.					
Graco	Chemical injection	Not considered. No applicable product available.					

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 presentation [2] providing an overview of the BP1 and BP2 work was given at the 2017 Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting on August 2, 2017 in Pittsburgh, PA.

2.5 *Plan for Next Quarter*

In the next quarter, the BP3 work will continue to focus on design modifications of the test stand and finalizing the test matrix.

Summary of tasks for next quarter

- Design modifications for the pilot-scale facility
- Obtain quotes and begin procurement
- 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 presentation [2] providing an overview of the BP1 and BP2 work was given at the 2017 Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting on August 2, 2017 in Pittsburgh, PA.

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, 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 companies, 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 *Southwest Research Institute (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: 0
  - Contribution to project: BP3 test design
  - Funding support: DOE
  - Collaborated with individual in foreign country: No
  - Country(ies) of foreign collaborator: None
  - 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 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 also 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. Also, the BP2 tests will provide key details on the response of the foam fluid in a fracture-type event. 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, along with some on-going scheduling conflicts, will likely delay the test facility modifications until the end of the 2017 calendar year. However, at the time of this reporting, these delays are not anticipated to affect the overall project deadline of March 31, 2018. 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: December 31, 2017
- Milestone G – Test Data Acquired and Analyzed
  - Original Milestone G Completion Date: March 31, 2018 (Unchanged)

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, $21,953 was spent. This value is considerably less than the baseline cost plan for this quarter due to the delay in ordering equipment. It is expected that once equipment acquisition begins, the variances will decrease and the actual spending will be reconciled with the baseline plan. 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 2					
	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	$0	$0	$0	$27,639
Federal Share	$5,686	$21,953	$0	$0	$0	$27,639
Non-Federal Share	$0	$0	$0	$0	$0	$0
Total Incurred Costs	$5,686	$21,953	$0	$0	$0	$27,639
Variance	$7,378	$232,272	$163,039	$86,168	$72,053	$560,909
Federal Share	$7,378	$201,667	$132,434	$55,563	$41,448	$438,490
Non-Federal Share	$0	$30,605	$30,605	$30,605	$30,605	$122,419
Total Variance	$7,378	$232,272	$163,039	$86,168	$72,053	$560,909

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 thwas 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 thwas 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: December 31, 2017**	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.
	G	Test Data Acquired and Analyzed	March 31, 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 Resources Research, **51**(7), pp. 5839-5845.

[2] Beck, G., 2017, “Development and Field Testing Novel Natural Gas Surface Process Equipment for Replacement of Water as Primary Hydraulic Fracturing Fluid,” 2017 Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting, Pittsburgh, PA.