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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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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. 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: (i) increasing the supply pressure of NG 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 (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 fifth and final 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 tandem 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 needed for injection.

The project work is split into three budget periods. Each budget period consists of one year. 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 fifth quarter of budget period 2, the project team completed the laboratory-scale investigations to determine the performance of NG foam. Data generated from these investigations were analyzed (milestone E in Table 7-2) and qualitative conclusions about the fluid properties of NG foam have been made.

During the tests, several operational issues were encountered. One of the issues was the failure of the water pump, which required the installation of a replacement pump. Other issues were related to the NG foam fluid in the closed system. Subsequent analysis of these issues yielded valuable “lessons learned” that should be applied to future yard-scale tests and field-scale demonstrations of the NG foam technology.

Also in the fifth quarter, the project team finalized plans for the budget period 3 (BP3) work and submitted the project continuation application. The BP3 plans required significant changes to the statement of project objectives (SOPO). Two meetings were held with DOE personnel to discuss the desired changes and also to provide a project continuation presentation.

The work completed in the fifth quarter of BP2 is discussed in greater detail in the following sections.

2.2.1 NG Foam Tests

In the first budget period, a literature review was conducted to identify known information pertaining to NG foam fluid properties. At the time of that review, NG foam data was not found. The BP2 laboratory tests were designed to address this knowledge gap and to explore NG foam properties that are pertinent to a hydraulic fracturing treatment. The three foam properties explored during the BP2 tests were:

1. NG foam mixing and foam stability
2. NG foam rheology
3. Compressibility effects of the NG foam during pressure transients

In the following sections, the BP2 tests are discussed in detail and the results of those evaluations are summarized.

2.2.1.1 NG Foam Mixing and Stability Investigations

The viscosity of a fracturing fluid is a key factor in determining how successful a fracturing treatment is. For example, the ability of the fluid to transport proppant to the fracture is related to the fluid's viscosity. Furthermore, the width of the fractures is also a function of the fluid viscosity.

For foam fracturing fluids, the viscosity of the foam depends on several factors. One of the factors that impacts the viscosity is how well the gaseous phase (the discrete phase) is mixed within the liquid or aqueous phase (the continuous phase). For a well-mixed foam, the discrete phase is uniformly dispersed within the continuous phase and the viscosity of the mixture tends to be significantly greater than the viscosity of the base liquid (i.e., the continuous phase). For foam that is not mixed well, the resulting mixture will more closely resemble a segregated multiphase flow, such as a stratified or bubbly flow. In this case, the viscosity of the mixture may not be uniform and, in general, will be much less than the well-mixed foam.

One of the objectives of the BP2 tests was to investigate how well the NG foam could be mixed in process conditions representative of an actual field application. To make this determination, two mixing methods were investigated using the pilot-scale test facility. In the first method, the methane stream and the base fluid stream (i.e., the mixture of water, guar, and a commercially available surfactant) were combined together at a tee. Then the gas and aqueous components were further mixed at a 100 μm sintered metal filter element immediately downstream of the tee (Figure 2-1). For the second method, the filter element was removed and the only mixing of the streams occurred at the tee.

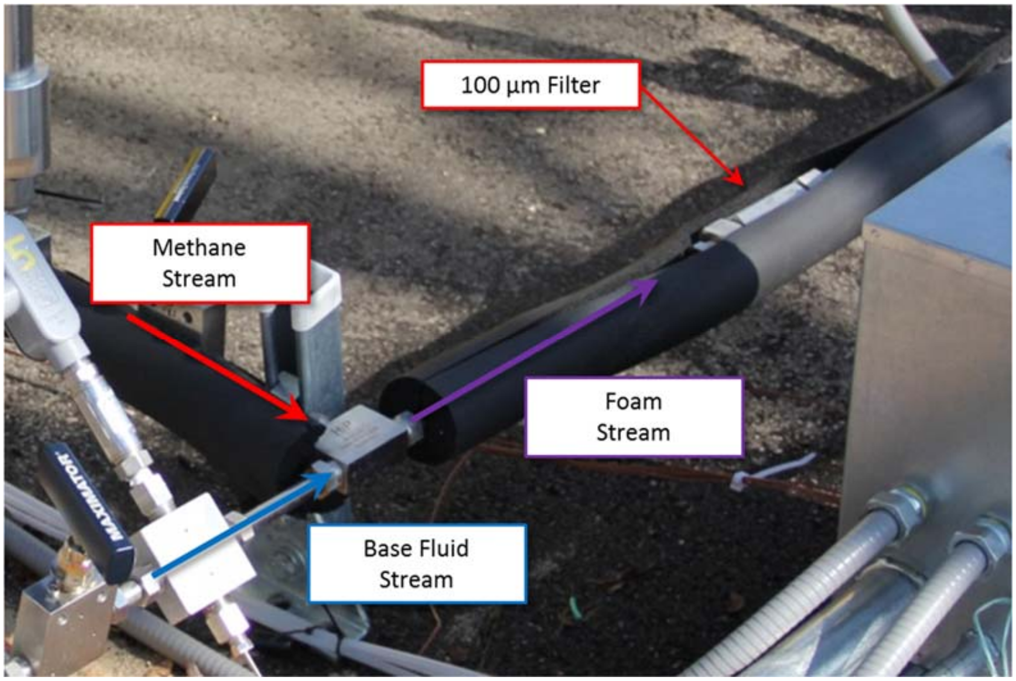

Figure 2-1. Two High Pressure Streams are Combined to Generate NG Foam

The NG foam mixture was observed using a high-pressure sight glass downstream of the mixing section. In qualitative terms, the foam was considered to be well mixed when the sight glass window was completely filled with foam having a uniform, milky white appearance. In these cases, the individual phases (the gaseous and aqueous phases) could not be discerned. Conversely, if separate phases were observed, the foam was considered to be not well mixed.

Three images of the view cell taken during the BP2 tests are shown in Figure 2-2. The image on the left depicts a mixture of methane and tap water (i.e., without guar and the surfactant). It is clear that the two phases have not generated foam but rather, a bubbly and stratified flow with the denser aqueous phase segregated to the bottom of the view cell. In this case, because the water did not contain a surfactant, a foam was not anticipated. The image in the middle depicts well mixed foam where the foam fills the entire view cell. These results were achieved using the 100 μm filter. The image on the right depicts foam generated once the filter element was removed. In this case, milky white foam is observed in most of the view cell; however, the presence of a segregated aqueous phase is also observed near the bottom of the viewport.

Figure 2-2. View Cell at Three Mixing Conditions

These results indicate that the turbulent mixing induced by the 100 μm filter yielded a well-mixed foam that was stable (i.e., the foam did not separate into its component phase) under flowing conditions. In the case where the filter element was removed, the foam appeared to be less stable.

The following conclusions were made based on these initial results:

1. Stable NG foam can be generated using the commercially available surfactant and viscosifier selected for the BP2 tests
2. The use of the 100 μm filter appears to have resulted in a more stable foam
3. Additional investigations are needed to identify an appropriate foam mixing method to deploy on a field-scale system

2.2.1.2 NG Foam Rheology Investigations

The BP2 tests also investigated other factors that impact the foam viscosity, including the foam *quality*, the shear rate, and the flow regime. The results of those investigations are discussed in the following paragraphs.

Foam *quality* is the ratio of the gaseous volume to the total mixture volume. For foams commonly employed in hydraulic fracture applications (e.g., nitrogen (N_2) and carbon-dioxide (CO_2) foams), the apparent viscosity of the foam increases as the quality increases. Figure 2-3 plots the relationship between the foam quality and apparent viscosity for a specific N_2 foam investigated by Reidenbach et al. [2]. In the figure, it can be seen that as the quality increases, the apparent viscosity of the foam increases as well.

Figure 2-3 also depicts the relationship between the shear rate of the flowing foam and the apparent viscosity. Foams commonly employed in hydraulic fracturing exhibit non-Newtonian, *shear thinning* behavior wherein the apparent viscosity decreases as the shear rate increases. As an example, in Figure 2-3, it can be observed that the apparent viscosity of 60% quality N_2 foam at a shear rate of 1000 sec^{-1} is approximately 50 cP. The apparent viscosity of the same 60% quality foam at 100 sec^{-1} is about 190 cP.

In this specific example, the increased shear rate results in a nearly fourfold reduction in apparent viscosity of the foam.

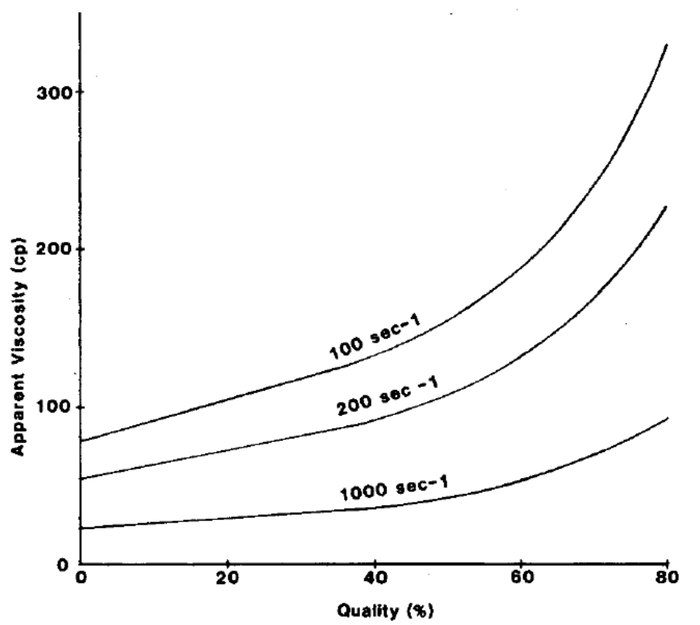

Figure 2-3. Apparent Viscosity, Quality, and Shear Rate for a N_2 Foam [2]

Data collected during the BP2 tests indicated that the NG foam was qualitatively similar to other foams in regard to the two relationships just described. Figure 2-4 plots data points for NG foam at 3,500 psi, 90°F to 95°F, at shear rates of 650 sec^{-1} and 1,000 sec^{-1}, and at qualities ranging from approximately 58.5% to 71%. These data indicate that the NG foam was *shear thinning* and that the apparent viscosity increased as the quality increased.

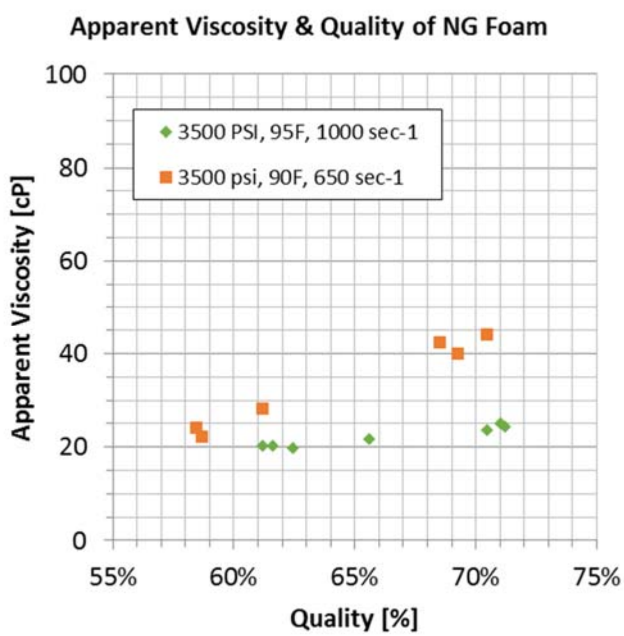

Figure 2-4. Apparent Viscosity, Quality, and Shear Rate for NG Foam

Data found in the open literature indicate that N_2 and CO_2 foams are often described as either *power-law* or *Herschel-Bulkley* (HB) fluids, where the fluid rheological properties of wall shear stress (τ) and apparent viscosity (μ) are power functions of the shear rate ($\dot{\gamma}$). The power-law and HB descriptions of wall shear are given below. The primary difference between the two relationships is that the HB description includes a *yield-stress* term (τ_0) describing the shear stress that must be overcome in order for the foam to begin to flow. For non-Newtonian, shear thinning fluids, the exponent (n) in the given relationships is a value less than 1.

$$\text{Power Law Fluid: } \tau = K\dot{\gamma}^n$$

$$\text{Herschel-Bulkley Fluid: } \tau = \tau_0 + K\dot{\gamma}^n$$

Though the data collected during the BP2 evaluations was limited, it seemed reasonable to *qualitatively* describe the NG foam as a power-law fluid. Measured shear stress and shear rate data for the NG foam at three operating conditions are plotted in Figure 2-5. In all three cases, a power fit of the data yields power law descriptions with exponents less than 1. It must be reiterated that the power law description of the NG foam is suggested in qualitative terms. To develop a definitive model, a significantly larger data set is required.

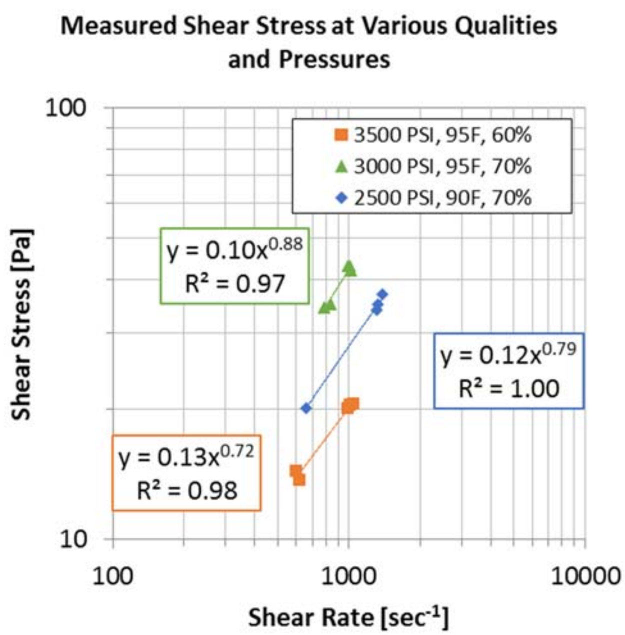

Figure 2-5. Measured Shear Stress and Shear Rate for NG Foam at Three Operating Conditions

NG foam rheology data generated at higher shear rates appeared to be in the turbulent flow regime and shared similarities to other foam data found in the available literature. Data given by Reidenbach et al. [2] demonstrates that in the turbulent regime, measured values of foam shear stress tend to collapse to a single curve that is a function the tube diameter and is NOT a function of foam quality. For example, the plots given in Figure 2-6 show the measured shear stress values for 60% and 70% quality N_2 foams, at a wide range of shear rates, and for four different tube diameters. In these plots, foam shear stress values in the laminar flow regime ($\dot{\gamma} < 2{,}000$) all collapse to a single curve, regardless of the tube ID. By comparing the two plots, it can be observed that the laminar curve *is* a function of the foam quality where the higher foam quality (70%) yields larger values of shear stress. In Figure 2-6, the transition from the laminar regime to the turbulent regime is manifest by the split into four unique curves that are related to the tube IDs.

In Figure 2-7, the 60% quality plot is superimposed on to the 70% quality plot to show that in the turbulent regime, the shear stress data all collapse to unique curves that are functions of the tube IDs rather than functions of foam quality.

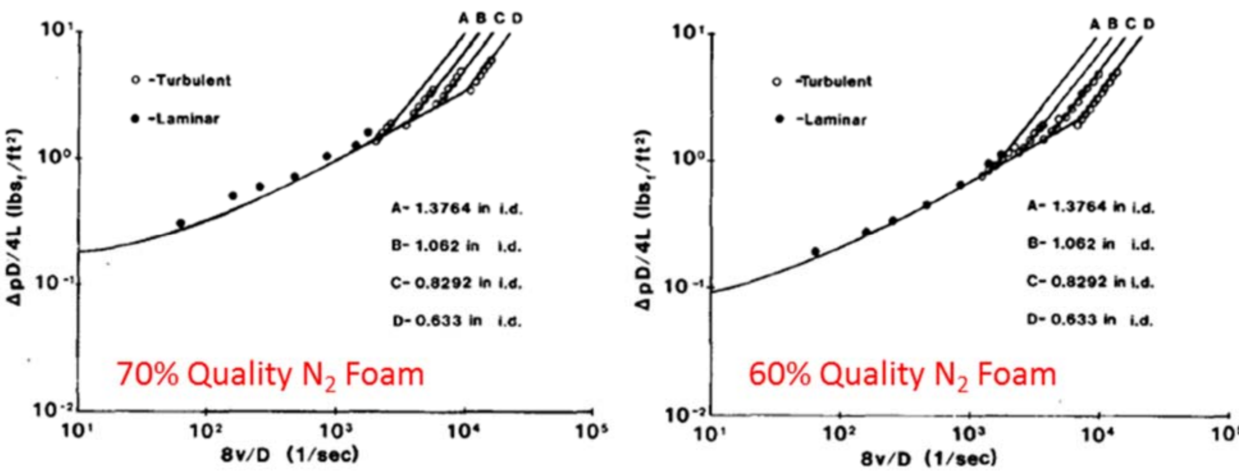

Figure 2-6. Shear Stress and Shear Rate for N_2 Foam, Two Qualities, and Four Tube IDs [2]

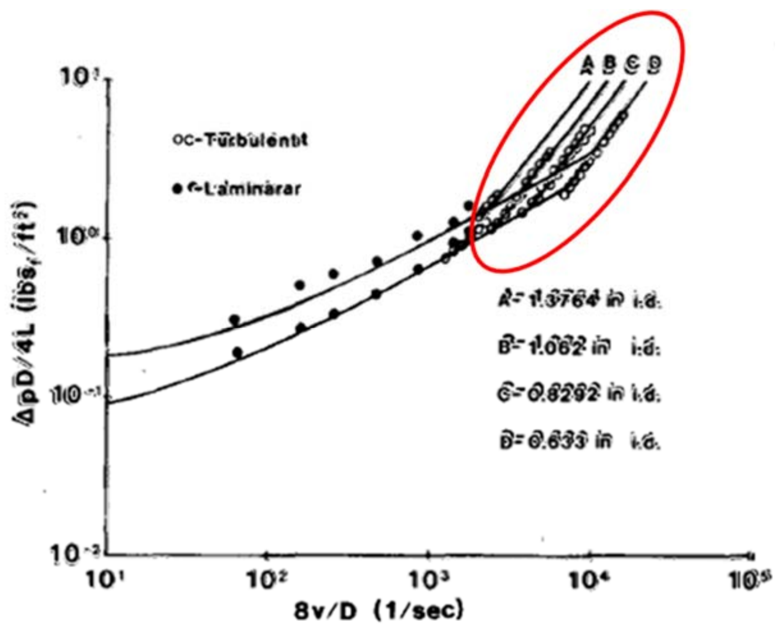

Figure 2-7. Overlaid Plots of 60% and 70% N_2 Foam

The data collected for the NG foam during the BP2 tests indicated that the NG foam exhibited a similar behavior. Figure 2-8 plots the measured shear stress values for the NG foam at foam qualities of 60%, 70%, and 80%. In this case, though there was some scatter in the data, the data points all collapsed to a single curve reasonably well.

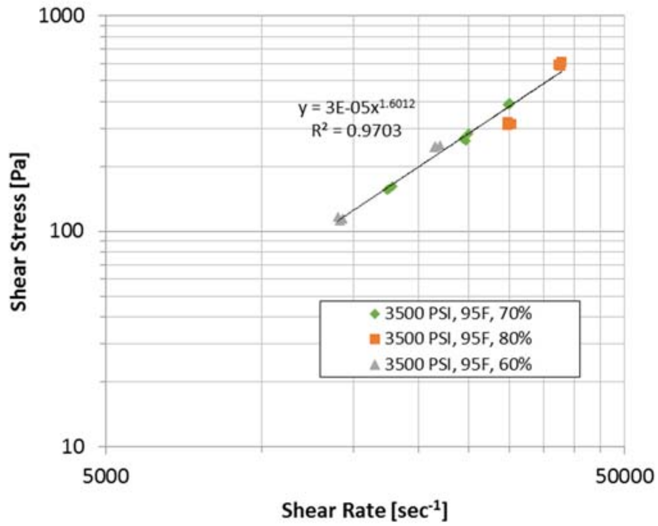

Figure 2-8. Measured Shear Stress Values for NG Foam at Three Different Qualities

As a result of these initial analyses, the following conclusions pertaining to the NG foam rheology were made:

1. NG foam is qualitatively similar to other foams
2. NG foam appears to be a shear thinning, power-law fluid
3. NG foam viscosity increases with foam quality
4. NG foam data was generated for both the laminar and turbulent flow regimes
5. To develop a definitive model of NG foam rheology, a significantly larger data set is required

2.2.1.3 Transient Flow Investigations

The final objective of the BP2 tests was to generate transient flow data so that the two-phase compressibility of the NG foam could be estimated for future process simulations. The dynamic simulation was achieved by closing a fast-acting solenoid valve, allowing pressure to build within the system, and then opening the valve again to reestablish flow through the test loop.

The measured pressure and valve position results from one dynamic test are shown in Figure 2-9. At the start of the test (time = 0 sec), the solenoid valve was open and 70% quality NG foam was flowing through the test loop at a rate of approximately 0.75 gpm. Note that due to an accumulation of guar residue on the 100 µm filter element, there was a substantial pressure loss (~900 psi) through the filter. When the valve was actuated, it was able to fully close in approximately 0.5 second. After the closure of the valve, flow into the test loop downstream of the fast-acting valve was completely stopped and the pressure downstream of the valve (the blue curve in Figure 2-9) decayed. The pressures upstream of the valve (the red and purple curves) both increased because the water and methane pumps continued to operate and pump fluid into the system at the 0.75 gpm rate. Because the foam was composed of 70% compressible gas, it was anticipated that the system would be quite compliant and that the rate of pressure increase upstream of the valve would be gradual.

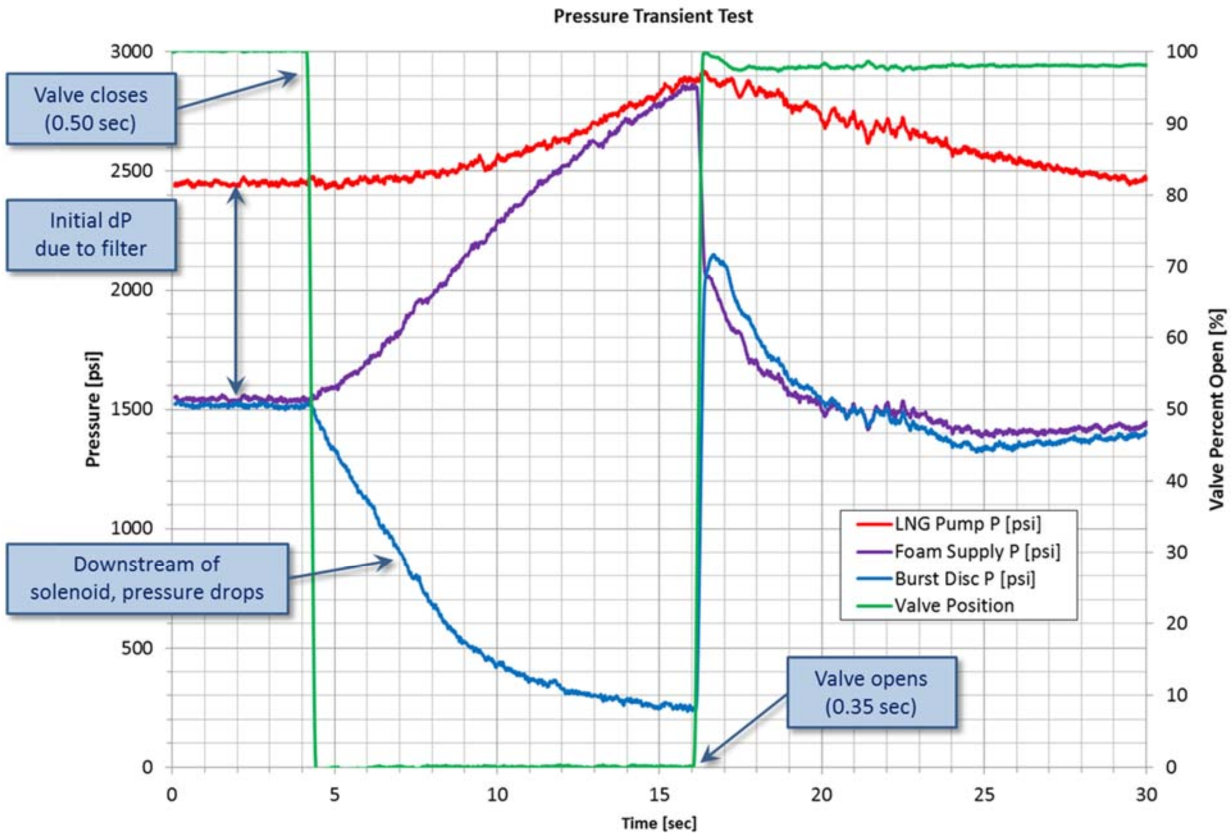

Figure 2-9. Measured Pressure and Valve Position Values During Transient Operation

In work yet to be completed, the transient results will be compared to simulations of the BP2 test stand modeled with 1-D fluid modeling software.

2.2.2 Operational "Lessons Learned"

As with any experimental test campaign, the project team encountered some unexpected operational issues during the execution of the BP2 tests. One of these issues was the failure of the main water pump. Other issues were related to operating with a mixture of NG and water in a closed system. In all cases, the team developed useful lessons learned that are discussed in detail in the following sections.

2.2.2.1 Water Pump Failure

A triplex water pump, an Aqua-Dyne EK20ES model, available at SwRI was used to pressurize the base fluid mixture for the BP2 tests. As described in the previous report, numerous issues with the pump were identified and addressed during commissioning. However, some of the issues recurred during the testing phase and, ultimately, the pump was replaced with an alternative unit.

Immediately following some tests where the base fluid was warmed to 120°F, the pump experienced a failure in which flow could not be maintained. The failure occurred when the fluid temperature was decreased from 120°F to the nominal operating condition of 90°F. The project team suspect that the change in temperature allowed for the polymer packings to become unseated and leakage paths to open. Once the packings *loosened* and became unseated, flow from the pump became intermittent and uncontrollable. The project team was not, however, able to prove conclusively that this was the cause of the problem.

To address the issue, a single-cylinder Haskel air-drive pump replaced the triplex pump. The volumetric flow rate range of the Haskel pump was considerably less than the Aqua-Dyne pump and required that some of the higher flow targets be eliminated. Still, this Haskel pump operated reliably and allowed the project team to explore a large number of the test points originally identified on the test matrix in the range of 1 gpm.

2.2.2.2 Hydrate Formation

Mixtures of water and hydrocarbons (e.g., methane) can result in *hydrate* formation at certain pressures and temperatures. Hydrates are ice-like structures that can cause blockages in process equipment. During the design of the BP2 tests, the methane-water hydrate formation curve was explored (

Figure 2-10) and it was determined that the target operating conditions (see the green dashed line in the figure) were well outside of the hydrate formation region.

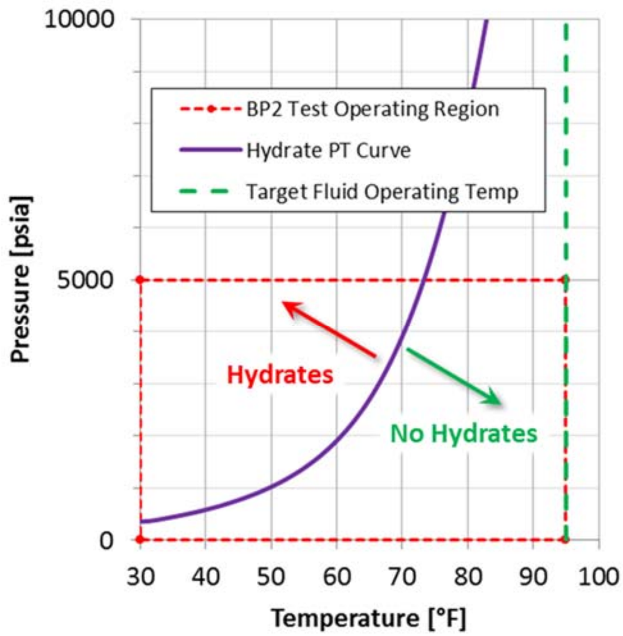

Figure 2-10. Methane-Water Hydrate Formation Curve

What was not considered at the time was that some of the small diameter (0.25 in.) sensing lines would be exposed to a cold operating environment (represented by the dashed red lines in

Figure 2-10). In a few instances, hydrates are suspected to have clogged sensing lines. In these cases, the operating pressure was approximately 3,500 psi and ambient temperatures were approximately 50°F. When the clogging occurred, an erroneous reading of -12 psid was observed for the differential pressure sensor indicating that the upstream sensing line (the high-pressure side) was clogged. On these occasions, the issue was corrected by simply waiting for the ambient temperature to increase.

These observations will be helpful when designing the final system. Precautions will be taken to ensure that all static lines remain insulated from the potentially cold ambient conditions.

2.2.2.3 Ice Formation

Significant cooling can occur when methane gas expands across a valve from high-pressure to low-pressure (Joule-Thomson effect). This effect is illustrated in the methane pressure-enthalpy diagram shown in Figure 2-11. In the diagram, the nominal operating point is 4,000 psia and 90°F. If the gas expands to nearly atmospheric pressure, the final temperature is on the order of -100°F. This presents a potentially hazardous scenario if water is present because ice can form in process piping, resulting in clogs.

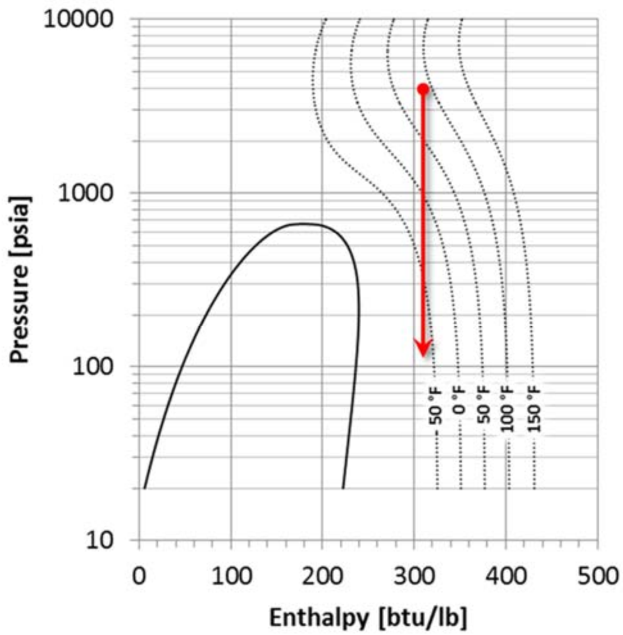

Figure 2-11. Pressure-Enthalpy for Methane

On a few occasions during initial commissioning with the LNG pumps, expansions occurred through valves in the system. In these instances, ice formation was suspected in the main flow lines.

In designing future tests and field-scale processes, careful attention will be given to the process piping design to ensure that the necessary pressure relieving devices are in place. Furthermore, venting protocols will be developed to address events where expansion of the gas generates ice within the process.

2.2.3 Modification of SOPO and BP3 Continuation Application/Meeting

In the original SOPO for BP3, it was anticipated that existing laboratory-scale equipment would be installed at a field site with the intent of performing a hydraulic fracturing treatment using NG foam as the fracturing fluid. The transformation of natural gas to the temperature and pressure required for fracturing would be accomplished using the thermodynamic process identified in BP1. It was anticipated that the field demonstration would also provide some preliminary data on downhole performance of NG foam.

During the course of the BP2 work, the project team identified some constraints that would limit the success of such a field demonstration and communicated those constraints to the DOE project team during a meeting that occurred on February 9, 2017. At the conclusion of that meeting, it was agreed by all parties that the BP3 SOPO would be modified. The modified BP3 SOPO, the BP3 continuation application, and a revised Budget Justification form were delivered to DOE on February 27, 2017.

The project team also gave a project continuation presentation to personnel at DOE NETL and DOE Fossil Fuels on March 22, 2017 to describe the findings from the BP2 work and to discuss the BP3 work.

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 of the BP2 test results was given at the 2017 American Institute of Chemical Engineers (AIChE) Spring Meeting on March 26, 2017 in San Antonio, TX.

2.5 *Plan for Next Quarter*

In the next quarter, it is anticipated that the BP3 work will begin pending authorization from DOE. During the next quarter, design modifications of the test stand will take place and a test matrix will be generated.

Summary of tasks for next quarter

- Design modifications for the pilot-scale facility
- Develop a BP3 test matrix
- Identify needed equipment and purchase

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*

In March 2016, a presentation was given at the 2017 AIChE Spring Meeting held in San Antonio, TX (https://aiche.confex.com/aiche/s17/meetingapp.cgi/Paper/482168).

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: post processing of data
    - 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: None

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 supports 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

In the past quarter, changes to the BP3 SOPO were presented and agreed on by the project team and the DOE project team. Those changes along with the two previous no-cost time extensions have resulted in significant modifications to the project milestones and the completion dates. The updated dates and milestones are documented below and in

Table 7-2.

- Milestone D – Test Facility Modifications Complete
  - Original Milestone D Completion Date: April 17, 2017
  - New Milestone D Completion Date: October 31, 2017
- Milestone E – Test Data Acquired and Analyzed
  - Original Completion Date: September 29, 2017
  - New Completion Date: March 31, 2018

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 final quarter of BP2, $85,374 was spent. These costs primarily included charges for the subcontract and the cost-share for SLB. Overall, at the end of BP2, the project has remained on budget.

Table 7-1. Budgetary Information for Period 5

Baseline Reporting Quarter	Budget Period 2					
	Q1	Q2	Q3	Q4	Q5	Cumulative Total
	1/1/2016 - 4/01/2016	4/2/2016 - 7/08/2016	7/08/2016 - 9/30/2016	10/1/2016 - 12/31/2016	1/1/2017 - 3/31/2017	
Baseline Cost Plan	$141,000	$157,000	$138,000	$125,445	$47,495	$608,940
Federal Share	$112,800	$125,600	$110,400	$100,356	$46,102	$495,258
Non-Federal Share	$28,200	$31,400	$27,600	$25,089	$1,393	$113,682
Total Planned	$141,000	$157,000	$138,000	$125,445	$47,495	$608,940
Actual Incurred Cost	$10,200	$109,980	$201,003	$201,966	$85,374	$608,522
Federal Share	$10,200	$90,272	$170,030	$167,920	$56,099	$494,521
Non-Federal Share	$0	$19,708	$30,974	$34,046	$29,275	$114,002
Total Incurred Costs	$10,200	$109,980	$201,003	$201,966	$85,374	$608,522
Variance	$130,800	$47,020	($63,003)	($76,521)	($37,879)	$418
Federal Share	$102,600	$35,328	($59,630)	($67,564)	($9,997)	$737
Non-Federal Share	$28,200	$11,692	($3,374)	($8,957)	($27,882)	($320)
Total Variance	$130,800	$47,020	($63,003)	($76,521)	($37,879)	$418

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 is 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 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. Actual completion date is 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. (see Milestones NOTE below). 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 (see Milestones NOTE below). This is considered a critical path milestone.	With the delayed completion of the test stand, testing and data analysis is now scheuled for completion by March 31, 2017
3	F	Test Facility Modifications Complete	April 17, 2017 **New: October 31, 2017**	Not Started	Modifications to the BP2 test stand are complete and the test matrix has been generated.	none
	G	Test Data Acquired and Analyzed	September 29, 2017 **New: 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 Resour. Res., **51**(7), pp. 5839–5845.

[2] Reidenbach, V. G., Harris, P. C., Lee, Y. N., Lord, D. L., and others, 1986, "Rheological Study of Foam Fracturing Fluids Using Nitrogen and Carbon Dioxide," SPE Prod. Eng., **1**(01), pp. 31–41.