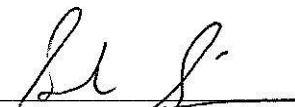
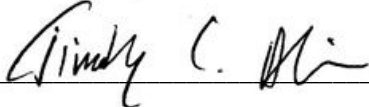


### Quarterly Research Performance Progress Report

Federal Agency to which the report is submitted	Office of Fossil Energy
FOA Name	Effective Methane Emissions Mitigation from Midstream Equipment/Facilities
FOA Number	DE-FOA-0001538
Nature of the Report	Research Performance Progress Report (RPPR)
Award Number	DE-FE0029021
Award Type	Cooperative Agreement
Name, Title, Email Address, and Phone Number for the Prime Recipient	<p><b>Technical Contact (Principal Investigator):</b> Sarah Simons, Research Scientist, <a href="mailto:sarah.simons@swri.org">sarah.simons@swri.org</a>, 210-522-2418</p> <p><b>Business Contact:</b> Robin Rutledge, Associate Specialist, <a href="mailto:robin.rutledge@swri.org">robin.rutledge@swri.org</a>, 210-522-3179</p>
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	<b><u>NOVEL SEAL DESIGN FOR EFFECTIVE MITIGATION OF METHANE EMISSIONS FROM RECIPROCATING COMPRESSORS</u></b>
Principal Investigator(s)	<p><b>Prime:</b> Sarah Simons, Ryan Cater, and Timothy Allison, Ph.D. – <i>SwRI</i></p> <p><b>Subcontractor and Co-Funding Partner:</b> Andreas Söderberg – <i>NextSeal AB</i></p> <p><b>Industry Partner:</b> Scott Schubring – <i>Williams Gas Pipeline</i></p>
Prime Recipient's DUNS number	00-793-6842
Date of the Report	October 30, 2018
Period Covered by the Report	Q8: July 1, 2018 - September 30, 2018
Reporting Frequency	Quarterly
Signature of Co-Investigator:	 <hr/> Sarah Simons
Signature of Principal Investigator:	 <hr/> Timothy Allison

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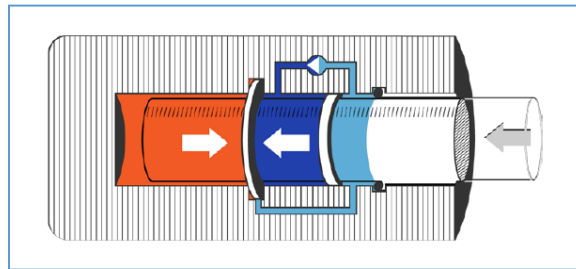
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## 1. INTRODUCTION

Methane emissions from reciprocating compressors in the U.S. natural gas industry account for over 72.4 Bcf per year according to a 2006 statement by the United States Environmental Protection Agency [1]. Methane has a global warming potential 50 times stronger than carbon dioxide, and reciprocating compressors are the machinery type with the highest contribution to methane emissions at natural gas transmission stations [1]. The largest contributing factor is leakage from the sealing components in the packing systems around the piston rods. Therefore, the team led by Southwest Research Institute® (SwRI®), NextSeal, and Williams have proposed the detailed design, fabrication, and full-scale testing of a novel seal design capable of reducing methane and natural gas leakage across the seals to virtually zero.

Current technology uses a series of specifically-cut, dry-ring seals held in place with springs and cups. However, designing seals based on today's technology inevitably leads to a trade-off between leakage reduction with minimal gaps between the seals and the rod versus allowing sufficient gaps, such that the friction between the parts is sufficiently reduced to allow movement. Once the piston moves, the pressure differential across the packing seals creates a twisting effect on the seal, allowing substantial amounts of natural gas to leak into the casing. Ring twisting also causes increased friction and wear to the sealing rings and compressor rod. This gas is typically vented into the atmosphere, normally producing leakage rates exceeding 11.5 standard cubic feet per hour for new, correctly-installed packing systems on well-aligned shafts [2].

This project takes the concept of liquid sealing and combines it with a novel, patented arrangement for pressure balancing across a seal arrangement (Patent No: U.S. 7,757,599 B2 [3]), as shown in Figure 1-1, to allow for successful implementation in a dynamic environment with moving parts. The proposed seal design has been successfully implemented and tested at the bench-scale level. The seal will be designed, modeled, and fabricated for full-scale operation and will be tested in a reciprocating compressor system at typical operating pressures for various scenarios in a stepwise, iterative method.



**Figure 1-1. Conceptual Drawing of Proposed Seal**

This project will be considered successful if the emission levels are reduced by a minimum of 95% compared to the leakage rates of industry standard rod packing seals operating in new condition with minimal wear. Emissions levels are measured for each test to ensure the project goals are being met. The team is collaborating with Williams to design the seal such that it can meet a reasonable target commercial system cost to minimize business risk.

The project is being performed in two sequential phases. The first phase consists of a thorough design review, analysis, and modeling of the liquid seal concept, as shown in Figure 1-1, and a hydraulic support system. The seal and support systems are customized to fit the compressor rod used for the dynamic testing. The first phase also includes assembly and commissioning of the test loop and static testing of the seal. The second phase consists of testing the liquid seal with the reciprocating compressor running (dynamic setting). Emissions are monitored and recorded for each test to evaluate the success of the design in achieving the state emissions reduction. This allows the real-world benefits of the technology to be demonstrated and quantified.

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

## **2. ACCOMPLISHMENTS**

### **2.1 Project Goals**

This project will plan, design, build, assemble, and operate a liquid seal in a full-scale environment. The project scope includes the conceptual design, modeling, and detail design of the liquid seal and subsystems; manufacture and testing of the seal; and specification of the success criteria for the proposed technology. This includes the design, development, and fabrication of all components of and related to the seal (i.e., control system and hydraulic support system). The liquid seal, control system, and hydraulic support system are being manufactured, fabricated, and installed along with the required instrumentation. Component-level commissioning is performed in a staged order. Static testing of the system is also being carried out during this first phase to provide valuable information for the go/no-go decision point prior to the initiation of the second phase. The overall goal for the project is to demonstrate the potential for methane emissions reduction of at least 95% of 1% of the total compressor mass flow when operating with a liquid seal compared to state-of-the-art dry seal packing systems.

The testing is to demonstrate operability of a liquid seal in static and dynamic environments. The demonstrated seal performance must achieve an overall methane emission reduction of 95% or greater of 1% of the total compressor mass flow. The performance of the primary test concept and associated subsystems (i.e., control system and hydraulic auxiliary system) is being monitored and characterized. Testing includes steady-state, dynamic, and limited endurance/wear operation. The data are analyzed in a staged order during all testing operations. Conclusions are being drawn regarding the readiness of the liquid seal for commercial application and emissions reduction, and a test report will be provided. The amount of emission reduction is being quantified.

The project work is split into two budget periods. Each budget period consists of 18 months. The milestones for each budget period are outlined in Table 2-1. This table includes an update on the status of the milestones in relation to the initial project plan. Explanations for deviations from the initial project plan are included.

### **2.2 Accomplishments**

The project is currently in Phase II. To date, SwRI and NextSeal have had an initial kickoff meeting at SwRI, one meeting on-site at SwRI in the 6th quarter, one meeting on-site in the 8<sup>th</sup> quarter, and ongoing bi-weekly project telecons to collaborate on the seal design and testing. Williams personnel also visited SwRI facilities to review the work to date and provided feedback. The following is a summary of the tasks completed to date:

- Performed baseline testing for both static and dynamic compressor operation to measure leakage rates with a new standard packing for comparison with the new seal design.
- Created a solid model of the existing packing cups and ring seals as a baseline for modifications to incorporate the new seal design.
- Developed a one-dimensional (1-D) computational fluid dynamics (CFD) flow model of the liquid seal pressure balancing concept - this evaluates pseudo-steady-state and dynamic conditions of the seal-piston-rod systems taking into account the dynamics of the piston system and fluid losses through the passages and manifold.
  - Performed dynamic simulations of normal and off-design events using pressure versus time data from the reciprocating cylinder.

- Calculated boundary parameters for the dimensions of the chambers containing the liquid and the active valve passageway.
- Completed fabrication of the new liquid packing seal design.
  - Completed static pre-test of the seal up to 100 psi.
- Completed support system design.
  - Created a P&ID of the support system.
  - Procured/fabricated all elements of the support system.
  - Received the hydraulic system and performed initial testing to verify operating range.
- Developed a monitoring software system to measure pressures, temperatures, flow rates, displacement of the active valve, and emissions.
- Fabricated a bench-scale-type test rig to verify fabrication and design parameters.
  - Initial static pressure test and limited tests of seal displacement vs. pressure were performed.
  - Multiple iterations of testing were performed with several modifications to the seal design until successful pressure balancing was achieved, resulting in zero observable leakage.
  - Dynamic testing with gas from the test compressor cylinder was successfully performed with zero observable gas leakage in the oil lines and only typical oil leakage into the gas chamber from normal lubrication during operation.
  - Oil flow rate was measured and an ideal range was found for successful operation of the seal.
- Installation and commissioning.
  - The packing seal was installed in the test compressor cylinder.
    - The packing seal casing was modified to accommodate the high-pressure oil inlet and low-pressure oil outlet lines.
  - Installed and connected the relevant instrumentation to the data acquisition system with the monitoring system developed for this testing.
  - Connected the hydraulic system to the new packing.
  - Commissioned the compressor cylinder and successfully verified oil flow to and from the new packing.
  - Connected the Coriolis meter to the oil drain line for emissions measurement of entrained gas leakage into the oil.
- Static testing.
  - Completed static hold testing of the packing seal in the test compressor with zero observable leakage over a range of pressures up to approximately 200 psia.
  - Quantified the oil flow rate required for successful sealing in static hold: 0.01 - 0.05 gpm.
  - No observable amount of leakage of gas into the oil or oil into the cylinder was found with the Coriolis meter or the rotameter. Clear tubing was used as an additional way to monitor leakage through observing whether gas bubbles were entrained in the oil. No bubbles were noted in the oil flow throughout the testing.

- Extended life testing was performed over two weeks in a pressurized hold condition. Minimal wear was found when each part was examined and measured with a micrometer and compared to the initial measurements. All of the seal parts with the exception of one was within the original manufacturing tolerances. The gas contact seal outer diameter had recorded wear of 0.001 inch.
- Closeout Activities/Preparation for Phase 2
  - Modify the hydraulic system based on initial bench-scale testing and static full-scale testing results.
    - Install a dampener (accumulator) and needle valve on the inlet oil line to damp the pump pulsations, ensuring the pump dynamics do not interfere or combine with the compressor dynamics.
    - Replace the inlet high-pressure oil plastic tubing with a stainless steel tube.
  - Continuation Application and Closeout Presentation for Phase 1 completed.
- Phase 2 Initiation Activities
  - Updated the original packing seal design to include the following:
    - Routed high-pressure oil inlet and low-pressure oil outlet flow passages through the flange packing cup to allow the packing seal to fit a wider range of cylinder designs.
    - Made additional minor modifications to improve the design after reviewing the previous test data. These modifications are described in detail in the quarterly confidential appendix.
    - Combined the low-pressure cup and high-pressure cup into a single part.
  - Manufactured the new design.
- Dynamic In-Cylinder Testing
  - Completed dynamic testing of the NextSeal packing seal in the test compressor cylinder operating over a range of speed from 300-1,300 rpm at pressures below 200 psi.
  - No observable amount of leakage of gas into the oil or oil into the cylinder was found with the Coriolis meter or the rotameter. Clear tubing was used as an additional way to monitor leakage through observing whether gas bubbles were entrained in the oil. No bubbles were noted in the oil flow throughout the testing.
  - No increase in wear to the seal was found when compared to the previous measurement taken after the static hold testing.

### ***2.3 Opportunities for Training and Professional Development***

There were no opportunities for training or professional development during this quarter.

### ***2.4 Dissemination of Results to Communities of Interest***

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

### ***2.5 Plan for Next Quarter***

During the next quarter, Phase 2 of the technical work on the project will continue. This work will include:

- In-cylinder dynamic testing at increased line pressures.

**2.6 Summary of Tasks for Next Quarter**

- In-Cylinder Dynamic Testing Pressurized Conditions
  - Dynamic Testing will be performed for Increased Line Pressures.
- Measuring Emissions for each Test Condition

**Table 2-1. Summary of Milestone Status**

Budget Period	Milestone Letter	Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments (Progress towards achieving milestone, explanation of deviations from plan, etc.)
BP1	A	Project Management Plan	10/30/2016	10/30/2016	Deliver a project management plan for review and approval by the DOE project officer.	none
	B	Detail Drawings of Seal Design, Modeling Results and Benchmark Testing	4/28/2017	3/31/2017	The compressor and test loop will be modified for this test. Benchmark testing of leakage with typical packing over a range of conditions will be performed. Modeling results of the seal will be reported and detail drawings of the seal specific to the compressor used for testing will be delivered.	none
	C	Detail Design of Support Systems	4/28/2017	4/28/2017	Piping and Instrumentation Diagrams (P&ID) of subsystems will be developed as well as a plan for integration with the seal.	none
	D	Procurement, Fabrication and Installation	7/31/2017	9/1/2017	Materials list will be developed and quotes from vendors will be obtained. The parts required for fabrication will be purchased and installed, and the set-up commissioned for testing.	none
	E	Test Plan	9/29/2017	9/29/2017	A test plan will be developed for the project based on the initial benchmark testing to include metrics for evaluating the performance of the seal.	none
	F	Critical Path Milestone FY1 – Static Testing with Emissions Measurement	9/29/2017	12/31/2017	Report on completion of static testing to include wear, leakage, emission levels.	none
BP2	G	Critical Path Milestone FY2 –Dynamic Test	12/31/2018	50%	Report on the completion of the dynamic testing and its associated metrics of success.	none
	H	Emissions Measurement	12/31/2018	50%	Report on the measured emissions level as compared current industry standard levels to evaluate the success in meeting the 95% reduction in emissions.	none
	I	Lifetime Testing	3/31/2019	25%	Report on the results of the lifetime testing as well as draw conclusions about possible failure modes.	none
	J	Final Report	4/30/2019	Not Started	Deliver the final report documenting the seal performance, wear, emissions, suitability for commercial application, and all relevant measurements	none
		On schedule				
		Behind schedule				

### 3. PRODUCTS

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

#### 3.1 Publications

One written work was published during the last quarter at the Gas Machinery Conference in Pittsburgh, Pennsylvania, in October 2018. The paper documented the methane emissions measurements that were recorded for the baseline emissions testing and the correlation that was found between the emissions leakage rate and the mean in-cylinder pressure (i.e., the pressure of the cylinder in relation to atmospheric pressure). No proprietary information regarding the novel seal concept was included.

#### 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.

#### 3.5 Participants & Other Collaborating Organizations

The work required to develop the novel seal design for methane emissions reduction in reciprocating compressors requires the technical knowledge and effort of many individuals. Three companies, SwRI, NextSeal, and Williams Gas Pipeline, are partnering to complete the work. This section provides a summary of the specific individuals and organizations who contributed in the 8th quarter.

#### 3.6 Southwest Research Institute (SwRI) – Prime Contractor

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

- Sarah Simons
  - Project role: Principal Co-Investigator
  - Nearest person month worked: 1
  - Contribution to project: Project management, design, and testing
  - Funding support: DOE
  - Collaborated with individual(s) in foreign country(ies): Yes
  - Country(ies) of foreign collaborator(s): Sweden
- Ryan Cater
  - Project role: Co-Investigator
  - Nearest person month worked: 2
  - Contribution to project: Testing, design work
  - Funding support: DOE



- Collaborated with individual(s) in foreign country(ies): Yes
- Country(ies) of foreign collaborator(s): Sweden

### **3.7 Other Organizations**

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

- NextSeal AB
  - Location of organization: Sweden
  - Partner's contribution to the project: Testing and design support
  - Financial support: Cash contribution
  - In-kind support: Labor hours
  - Facilities: N/A
  - Collaborative research: NextSeal supports the testing and design tasks
  - Personnel exchanges: N/A
- Williams Gas Pipeline
  - Location of organization: Houston, Texas
  - Partner's contribution to the project: Design and implementation support
  - Financial support: N/A
  - In-kind support: Labor hours
  - Facilities: N/A
  - Collaborative research: Williams supports the implementation and design of the seal
  - Personnel exchanges: N/A

## **4. IMPACT**

Preliminary baseline data analysis from testing indicated that the amount of leakage flow through typical reciprocating compressor packing is not dependent on the mass flow (or speed) of the compressor, but rather the mean in-cylinder pressure. The packing is acting as an orifice and the leakage rate through the packing is primarily related to the ratio of the in-cylinder pressure to the atmospheric pressure in the distance piece.

## **5. CHANGES/PROBLEMS**

There are no changes or problems to report. The project was funded over a three-year period in two budget periods of 18 months each. DOE personnel stated that SwRI can request to shorten the budget periods if the tasks for each budget period are successfully completed ahead of schedule. SwRI completed the primary tasks for Phase 1 by the end of February. The Phase 1 closeout presentation was given, and Phase 2 funding was awarded at the end of March. The initial scope of work for Phase 2 will be completed by March 2019. An additional task was funded for Phase 2 that will extend the timeline for completion until the originally planned end of Phase 2, September 2019.

**6. BUDGETARY INFORMATION**

A summary of the budgetary data for Phase 2 of the project is provided in Table 6-1. This table shows the initial planned cost, the actual incurred costs, and the variance. The costs are split between the federal and non-federal share. All tasks for Phase 1 have been completed.

**Table 6-1. Budgetary Information for Period 2**

Baseline Reporting Quarter	Budget Period 2
	7/1/2018-9/30/2018
	Cumulative Total
Baseline Cost Plan	
Federal Share	\$190,000
Non-Federal Share	\$65,523
Total Planned	\$73,730
Actual Incurred Cost	
Federal Share	\$189,773
Non-Federal Share	\$65,523
Total Incurred Costs	\$255,296
Variance	
Federal Share	\$227
Non-Federal Share	\$0
Total Variance	\$227

**7. REFERENCES**

- [1] Machu, Gunther and Matt Jackson, “A New Packing Ring Design-Improved Sealing Efficiency and High Durability,” Sealing Technology, September 2011.
- [2] R. Subramanian, L. L. Williams, T. L. Vaughn, D. Zimmerle, J. R. Roscioli, S. C. Herndon, et al. “Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol,” Environmental Science & Technology, Vol. 49, pp. 3,252-3,261, 2015.
- [3] Adolfsson, Bengt, “Sealing Arrangement for Relatively Movable Parts and Device Including Such a Sealing Arrangement,” U.S. Patent 7,757,599 B2, July 20, 2010.