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Name, Title, Email Address, and Phone Number for the Prime Recipient	**Technical Contact (Principal Investigator):** Tim Allison, Ph.D., Research Scientist, tim.allison@swri.org, 210-522-3561 **Business Contact:** Robin Rutledge, Associate Specialist, robin.rutledge@swri.org, 210-522-3179
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	**NOVEL SEAL DESIGN FOR EFFECTIVE MITIGATION OF METHANE EMISSIONS FROM RECIPROCATING COMPRESSORS**
Principal Investigator(s)	**Prime:** Timothy Allison, Ph.D. – *SwRI* **Subcontractor and Co-Funding Partner**: Andreas Söderberg – *NextSeal AB* **Industry Partner:** Scott Schubring – *Williams Gas Pipeline*
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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 [2]. 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 [2]. 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 [1].

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.

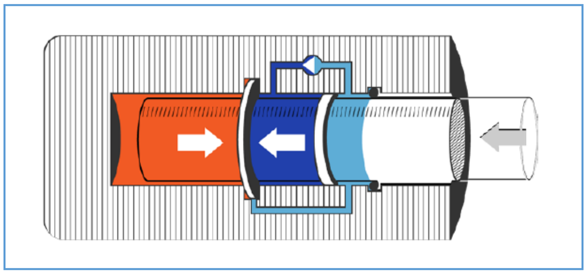

Figure 1-1. Conceptual Drawing of Proposed Seal

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 stated emissions reduction. This allows the real-world benefits of the technology to be demonstrated and quantified. A final task (Task 7) was added to the SOPO and Phase II scope in July 2018 for leakage measurements from standard packing from two reciprocating compressors, evaluation of leakage rates from worn packing, and development of a leakage model that incorporates compressor geometry, operating conditions, and packing wear.

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 goal of Task 7 is to have a validated analytical model for packing leakage predictions that incorporates compressor operating conditions and packing wear and matches the test data within 20%.

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 is 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, with primary focus on Task 7 (standard packing leakage measurement) since Tasks 1-6 were completed in the 9th quarter. 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 in the 8th quarter, and ongoing bi-weekly project telecoms 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
  - Successfully completed dynamic testing of the NextSeal packing seal in the low pressure test compressor cylinder operating over a range of speed from 300-1,300 rpm at pressures up to 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.
  - Successfully completed dynamic testing of the NextSeal packing seal in the high pressure test compressor cylinder operating over a range of speed from 300-1,300 rpm at pressures up to 1,200 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.

- Task 7 Baseline Packing Leakage Testing and Modeling
  - Performed baseline leakage testing for conventional packing rings on JGA/2 compressor with high- and low-pressure cylinders under both static and dynamic conditions.
  - Determined limiting test conditions achievable within existing motor, JGT/4 compressor, and cooler hardware.
    - Hosted visits from Ariel Engineering and Field Service support to discuss loop design, measurement plan, and test conditions.
  - Completed closed-loop piping design for JGT/4 compressor, including:
    - CAD modeling of test loop
    - Pulsation, thermal, modal, and harmonic forced response analyses of piping
    - Bottle and piping design drawings
  - JGT/4 Test setup and preparation:
    - Issued purchase orders for piping and bottles
    - Planned foundation modifications for piping and precooler supports
    - Installation and leveling of compressor skid
    - Coupling hub installation on motor and compressor
    - Dry cooler installation
    - Specified and ordered components for ancillary systems (lubrication oil, fill/vent, instrumentation)
  - Packing leakage model development:
    - Compiled literature and industry feedback on existing packing leakage models and expected leakage rates for compressor packing and elastomeric reciprocating seals.
    - Performed initial comparisons of leakage predictions and guidelines with JGT/2 leakage data

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*

The original scope of work for this project has successfully been completed as described by Tasks 1-6 in the SOPO. During the next quarter, work on the additional task added to the scope of the technical work, Task 7, will continue. This work will include final assembly of the JGT/4 compressor system, operation and leakage measurements with new and worn packing, and final leakage model development based on comparison with the data.

2.6 *Summary of Tasks for Next Quarter*

- Final assembly of JGT/4
  - Final motor and cylinder alignment, bottle installation, piping installation and field welds
  - Instrumentation and lube oil systems
  - Electrical connections
- Operation of JGT/4 to obtain packing leaking leakage data
  - Commissioning, break-in of new packing
  - Baseline measurements of normal packing leak rates
  - Modification of packing to worn state and reinstallation into cylinder
  - Measurements of worn packing leak rates
- Packing leakage model development
  - Compare JGT/4 leakage data to model predictions
  - As needed, evaluate and incorporate model improvements potentially including cylinder geometry, non-average operating conditions, and wear amount

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	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	12/31/2018	Report on the completion of the dynamic testing and its associated metrics of success.	none
	H	Emissions Measurement	12/31/2018	12/31/2018	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	Wear Evaluation	3/31/2019	12/31/2018	Report on the results of the wear evaluation as well as draw conclusions about possible failure modes.	none
	J	Baseline Testing of Commercially Available Seals	8/30/2019	52%	Report on gas leakage measurements of commercially available packing seals over a range of operating conditions.	Test delays due to long component lead times for bottles, piping.
	K	Wear Evaluation	9/15/2019	10%	Correlation between leakage rate and amount of material lost.	
	L	Leakage Prediction Model	9/30/2019	25%	Analytical model used to predict seal leakage based on wear and operating conditions.	none
	M	Final Report	12/29/2019	Not Started	Deliver the final report documenting the NextSeal performance, wear, and emissions as well as baseline emissions modeling for commercially available packing seals.	none

(green)	On schedule
(red)	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, Baseline Emissions Measurements from Reciprocating Compressor Packing, was published during the 9th quarter at the Gas Machinery Conference in Pittsburgh, Pennsylvania, in October

2017. 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 have contributed in the 9th quarter.

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

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

- Tim Allison
    - 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): No
- Ryan Cater
    - Project role: Co-Investigator
    - Nearest person month worked: 1
    - Contribution to project: Design, Modeling and Testing
    - Funding support: DOE
    - Collaborated with individual(s) in foreign country(ies): No
- Jacob Rodriguez
    - Project role: Technician support
    - Nearest person month worked: 1
    - Contribution to project: JGT/4 system assembly
    - Funding support: DOE
    - Collaborated with individual(s) in foreign country(ies): No

- Ray Farias
  - Project role: Technician support
  - Nearest person month worked: 1
  - Contribution to project: JGT/4 system assembly
  - Funding support: DOE
  - Collaborated with individual(s) in foreign country(ies): No
- Rick Skinner
  - Project role: Technician support
  - Nearest person month worked: 1
  - Contribution to project: JGT/4 system assembly
  - Funding support: DOE
  - Collaborated with individual(s) in foreign country(ies): No

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
- Ariel Corporation
  - Location of organization: Mt. Vernon, Ohio
  - Partner's contribution to the project: Design and implementation support
  - Financial support: N/A
  - In-kind support: Labor hours
  - Facilities: N/A
  - Collaborative research: Ariel supports the JGT/4 Compressor for leakage testing
  - 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

The project was funded over a three-year period in two budget periods of 18 months each. 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 was completed ahead of schedule by January 2019. An additional task (Task 7) was funded for Phase 2 that was anticipated to extend the timeline for completion until the originally planned end of Phase 2, September 2019.

A no-cost extension was requested on 7/26/2019 to extend the project end date from 9/30/2019 to 3/31/2020. The extension is needed to complete the additional Task 7 scope, which includes the operation of a 700-hp Ariel JGT system. The lead time for pulsation bottles and piping that are required for compressor operation was longer than anticipated due to high demand from suppliers. As a result of delivery delays, an extension is needed to allow sufficient time for testing, data postprocessing, and finalization of a leakage model based on the data. There are no other changes or problems to report.

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 project tasks for Phase 1 and Phase 2 (excluding the new additional Task 7) have been completed.

Table 6-1. Budgetary Information for Period 2

Baseline Reporting Quarter	Budget Period 2	
	4/1/2019 – 6/30/2019	Cumulative Total
Baseline Cost Plan		
Federal Share	$99,452	$476,693
Non-Federal Share	$0	$157,111
Total Planned	$99,452	$476,693
Actual Incurred Cost		
Federal Share	$83,665	$457,723
Non-Federal Share	$0	$157,111
Total Incurred Costs	$83,665	$457,723

Baseline Reporting Quarter	Budget Period 2	
	4/1/2019 – 6/30/2019	Cumulative Total
Variance		
Federal Share	$15,787	$18,970
Non-Federal Share	$0	$0
Total Variance	$15,787	$18,970

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.