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Project Title	**NOVEL SEAL DESIGN FOR EFFECTIVE MITIGATION OF METHANE EMISSIONS FROM RECIPROCATING COMPRESSORS**
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1. EXECUTIVE SUMMARY

The objective of this project was to reduce leakage of compressor rod packing because rod packing accounts for a significant portion of leakage of compressors. To meet the objectives, the project team designed, manufactured, and tested a liquid seal in a full-scale setting to demonstrate the operability of the seal, verify the performance of components, and demonstrate the potential for producing a seal that reduces methane emissions by a minimum of 95% of 1% of the total mass flow of the compressor with minimal wear to the seal.

After an engineering design effort, SwRI implemented and tested the design. The testing was performed on a JGA/2 compressor capable of 100 HP. The compressor was instrumented with a Coriolis flow meter to measure the leakage past the packing. Static and dynamic testing was performed with leakage measurements. Static pressure holds up to 200 psi showed zero observable leakage. The required oil flow rate for sealing was 0.01-0.05 gpm. Dynamic testing up to 200 psi also showed no observable amount of leakage of gas into the oil or oil into the cylinder. Prolonged testing was performed to identify wear of the novel packing. No increase in wear to the seal was found when compared to the previous measurement taken after the static hold testing. The validation data showed a successful reduction of leakage by a minimum 95% of 1% the total compressor mass flow as no significant leakage was measured and additional testing showed minimal wear.

Additionally, the project team measured the leakage rate of standard packing seals in dynamically operating reciprocating compressors over a range of horsepower and operating conditions. Baseline testing (with standard packings) was performed on both a JGA/2 compressor capable of 100 HP and a JGT/4 compressor capable of 700 HP. The baseline measurements were used to develop and improve a packing leakage model based on wear rate, mean cylinder pressure, and mean temperature (the model uses other fluid properties based on pressure and temperature). The model showed the largest error when compressor ratios were small.

Used packings (from a field unit after running 8,000 hours) were also tested in the JGT/4 compressor. The used packing showed an increase in leakage compared to the baseline packing. Both the used and baseline packing were measured with calipers and compared. The used packing did not show a significant difference from the baseline packing. The improved model developed with the test data showed a maximum of 25% error for all the testing conditions.

2. 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 has 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 took the concept of liquid sealing and combined 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, to allow for successful implementation in a dynamic environment with moving parts. The proposed seal design was successfully implemented and tested at the bench-scale level and in operation in a reciprocating compressor system at typical operating pressures for various scenarios in a stepwise, iterative method.

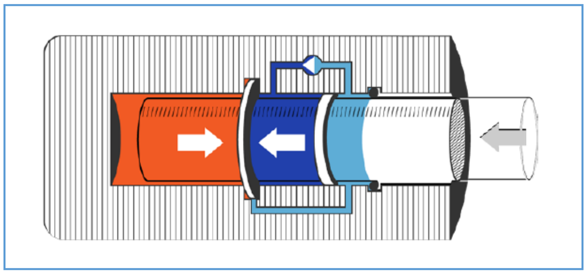


Figure 1. Conceptual Drawing of Proposed Seal

The project's primary success criterion was to reduce emission levels by a minimum of 95% compared to the leakage rates of industry standard rod packing seals operating in new condition with minimal wear. Emission levels are measured for each test to ensure the project goals are being met. The team collaborated with Williams to design the seal such that it could meet a reasonable target commercial system cost to minimize business risk.

The project was performed in two sequential phases. The first phase consisted of a thorough design review, analysis, and modeling of the liquid seal concept, as shown in Figure 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 included assembly and commissioning of the test loop and static testing of the seal. The second phase consisted of testing the liquid seal with the reciprocating compressor running (dynamic setting). Emissions were monitored and recorded for each test to evaluate the success of the design in achieving the stated emissions reduction. This allowed 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 incorporated compressor geometry, operating conditions, and packing wear.

This report comprehensively covers the work completed in both project budget periods. The project goals and accomplishments related to those goals are discussed. Details related to any products developed are outlined, although confidential detailed design information and test results are provided in a confidential appendix provided to DOE. Information on the project participants and collaborative organizations is listed and the impact of the work done is reviewed. The current budget is reviewed.

3. ACCOMPLISHMENTS

3.1 *Project Goals*

This project successfully planned, designed, built, assembled, and operated a liquid seal in a full-scale environment. The project scope included 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 were manufactured, fabricated, and installed along with the required instrumentation. Component-level commissioning was performed in a staged order. Static testing of the system was carried out during the 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 was 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 Task 7 effort successfully developed a validated analytical model for packing leakage predictions that incorporates compressor operating conditions and packing wear and matches the test data within 25%.

The testing in Tasks 1-6 was 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) was monitored and characterized. Testing included steady-state, dynamic, and limited endurance/wear operation. The data were analyzed in a staged order during all testing operations. Conclusions were drawn regarding the readiness of the liquid seal for commercial application and emissions reduction, and a test report is provided in a separate confidential appendix to this repor.

The project work was split into two budget periods. Each budget period originally consisted of 18 months, but the second period was extended to 24 months due to delays in test setup for Task 7. The milestones for each budget period are outlined in Table 1. This table includes the final milestone status in relation to the initial project plan. Explanations for deviations from the initial project plan are included.

3.2 *Accomplishments*

The following is a summary of the tasks completed during project execution:

- 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 torsional analysis for all operating conditions.
  - JGT/4 test setup and preparation:
    - Piping field welds
    - Hydro tested pipe spools
    - Added pipe supports
    - Painted pipes and bottles
    - Installed lube oil system
    - Installed drainage and leakage lines
    - Developed the software for the DAQ
    - Wired all ancillary systems
    - Wired VFD to Motor
    - Installed all instrumentation
    - Finalized loop setup
  - JGT/4 Testing
    - Baseline packing leakage testing perform
    - Used packing leakage testing performed
    - Used and Baseline Packing measured for wear
  - 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
    - Updated model with baseline and used packing results from the JGT/4 Compressor

Table 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	2/29/2020	3/30/2020	Report on gas leakage measurements of commercially available packing seals over a range of operating conditions.	none
	K	Wear Evaluation	3/15/2020	3/30/2020	Correlation between leakage rate and amount of material lost.	none
	L	Leakage Prediction Model	3/31/2020	3/30/2020	Analytical model used to predict seal leakage based on wear and operating conditions.	none
	M	Final Report	6/30/2020	6/30/2020	Deliver the final report documenting the NextSeal performance, wear, and emissions as well as baseline emissions modeling for commercially available packing seals.	none

4. PRODUCTS

With any technical work, results have been 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.

4.1 *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.

Two additional papers have been accepted for publications in the 2020 Gas Machinery Conference. The first is title "Testing Variable Orifices For Optimization of Reciprocating Compressor Pulsation Control and Performance." The second is titled "Testing Rod Seal Leakage of a 700 HP Reciprocating Compressor." Both will be published pending final submission and approval.

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.

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

- Tim Allison
    - Project role: Principal Co-Investigator
    - Contribution to project: Project management, design, and testing
    - Funding support: DOE
    - Collaborated with individual(s) in foreign country(ies): No

5.2 *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

6. IMPACT

6.1 *Task 7.0: Baseline Packing Leakage Testing and Modeling*

The goal of this task was to develop a leakage model that incorporates the wear on the packing rings. The task involved measuring the leakage of gas through packing seals on two Ariel compressors. The first, described above, is the JGA/2. The second was a JGT/4 compressor capable of 100-700 HP. The JGT/4 was set up on a new flow loop at SwRI. Figure 2 shows the JGT/4 compressor, which is configured with 4 throws. Each throw is also a different stage of compression to boost the pressure. The compressor was assembled and commissioned on site. The JGT/4 was installed with Ariel BTS packing rings, which are standard in all new Ariel compressors. Additionally, Phillips 66 Syncon R&O 150 oil was used for lubrication of the seals.

The commissioning process was set forth by the Start-up Check List as described in the Ariel Packager Standards Manual. For commissioning, the lube oil system was cleaned through a filter. When installing the JGT skid on location, out of the plane and soft foot measurements were performed to meet the standard. The piston end clearance and rod runout were measured intolerance. The compressor and motor shafts were verified for alignment. SwRI personnel also validated the safety shutdowns that were coded into the DAQ. Ariel personnel verified the commissioning process and aided in the initial startup. After the initial startup, the engine was run for 100 hours to break in the seals. The seals were determined to be broken in when they stopped reducing in leakage at a constant speed and pressure. After seal break-in, the leakage for the packing seals was measured.

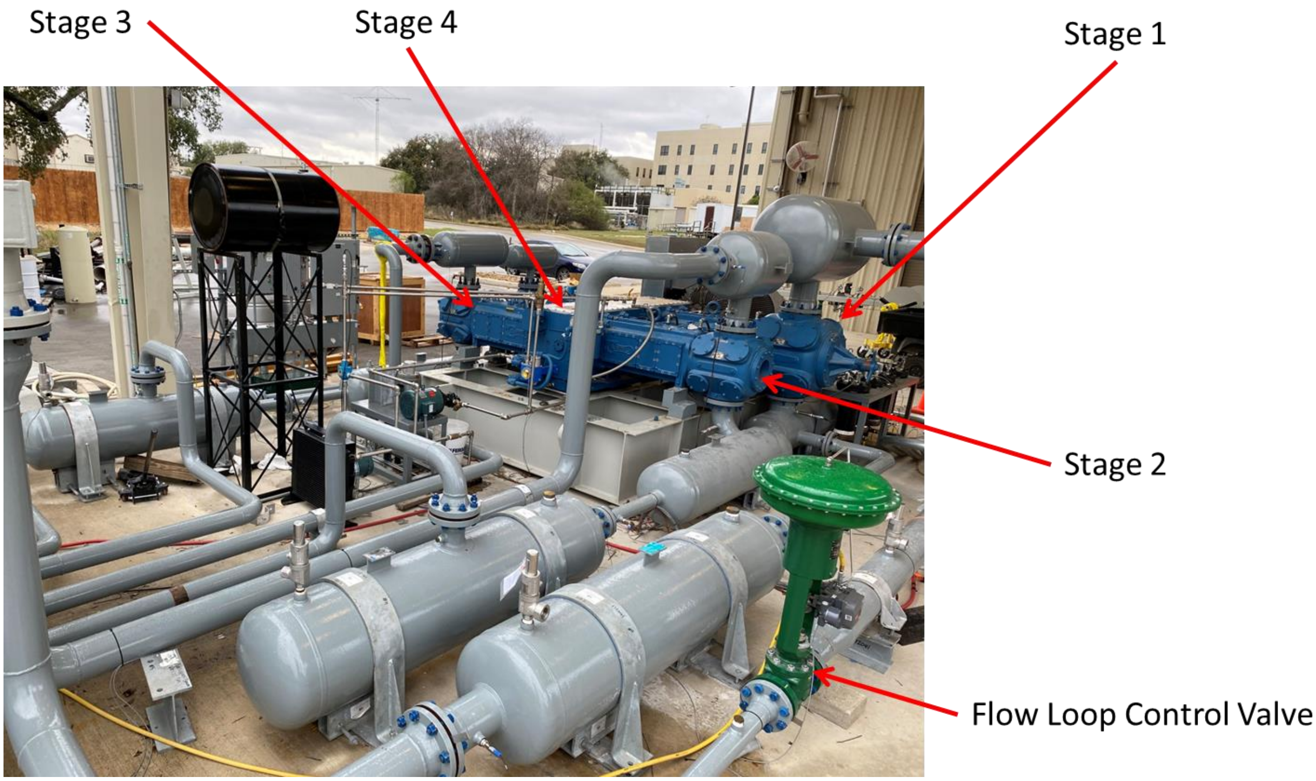


Figure 2. JGT/4 Compressor Installed at SwRI

Figure 3 shows the P&ID for the JGT/4 flow loop. The test setup is a closed loop that recirculates the flow. The loop was filled with pure nitrogen during testing. SwRI utilized a LabJack Data Acquisition (DAQ) and Python user interface to control the flow loop and collect data. The operator controlled the flow loop with a control valve between the stage 4 discharge and stage 1 suction by opening/closing a supply valve to add mass, and opening/closing a vent valve to remove mass. The instrumentation included a pressure transduces and thermocouple on the suction and discharge of each stage. These measurements allowed the operator to set each test point.

The leakage was measured with a mass flow meter (P/N FMA-A2117) with 1% accuracy and 5-point NIST certification calibration. The leakage flow measurement setup is shown in Figure 4. Each cylinder has ports for a hydraulic drain and leakage from the packing. Both the hydraulic drains/vents and packing leakage vent were connected in a collection pot. The collection method allows for all packing leakage to be collected (both radially and through the tangent face). The collection pot separates the hydraulic liquid (from the drains) from the gas via gravity. For the SwRI setup, the gas was vented to the atmosphere after passing through the mass flow meter.

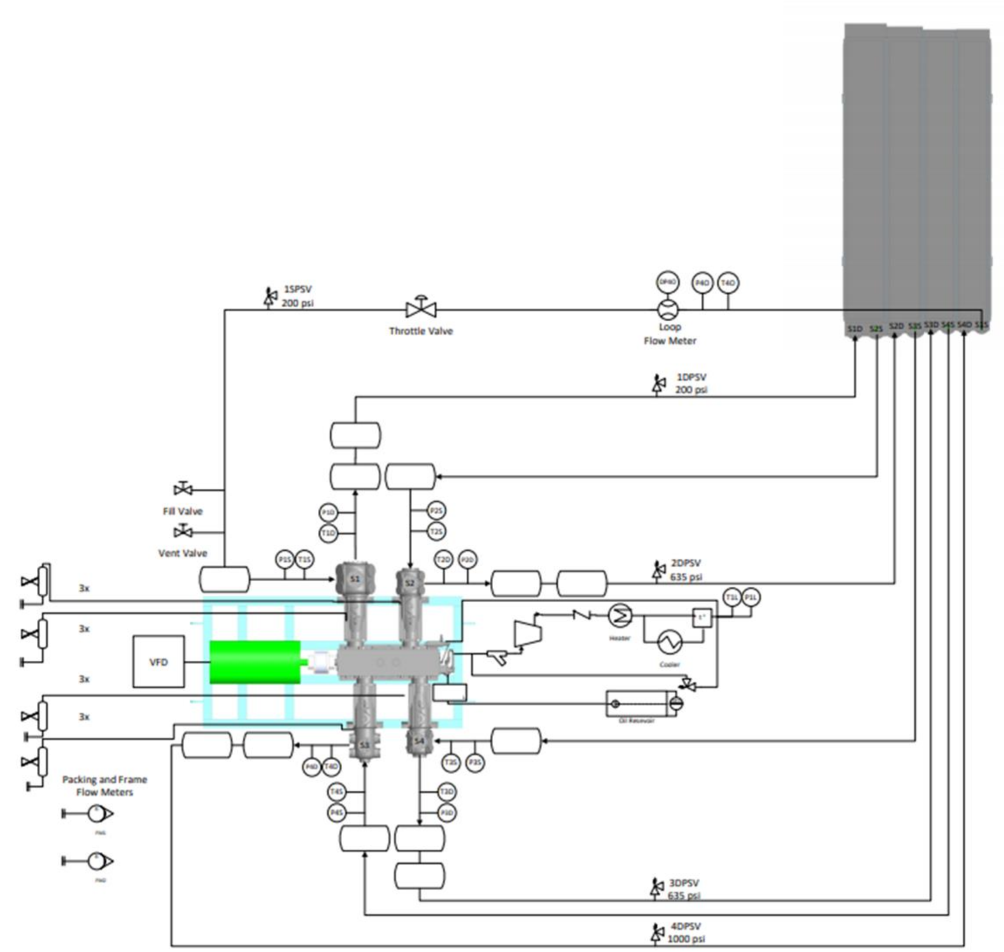
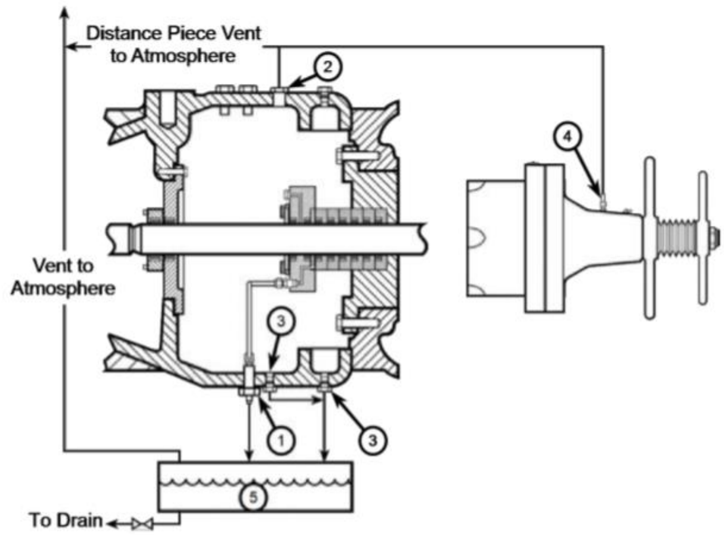
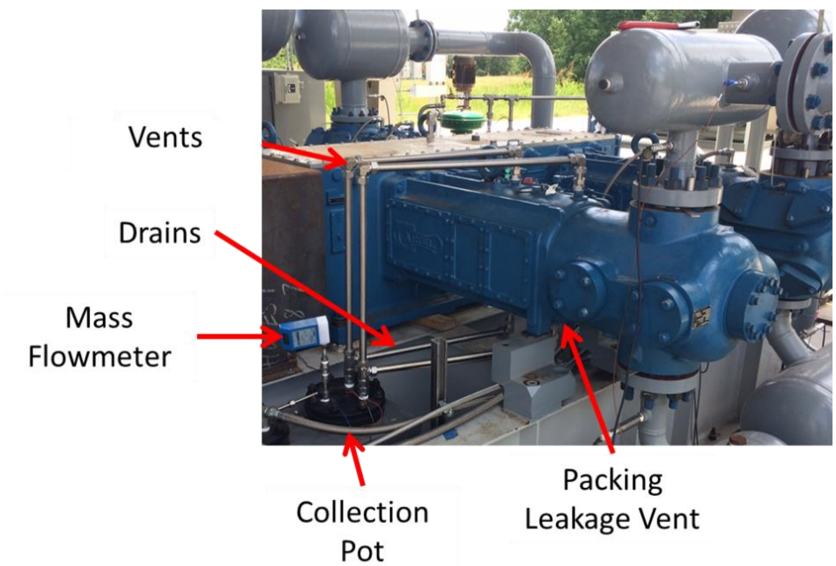


Figure 3. JGT/4 Flow Loop Process and Instrumentation Diagram



1. Packing Vent/Drain
2. Distance Piece Vent
3. Distance Piece Drain
4. VVCP Gas Vent
5. Oil Separation Pot

(a)



(b)

Figure 4. Leakage Measurement Setup (a) Schematic, (b) Actual Setup

Similarly, the JGA/2 compressor was instrumented to measure the collected leakage. The JGA/2 loop is fully described in Figure 5. The JGA/2 had installed BD packing rings during the leakage tests. Figure 5 shows the packing and JGA/2 testing setup. The testing was performed for multiple pressures and motor speeds.

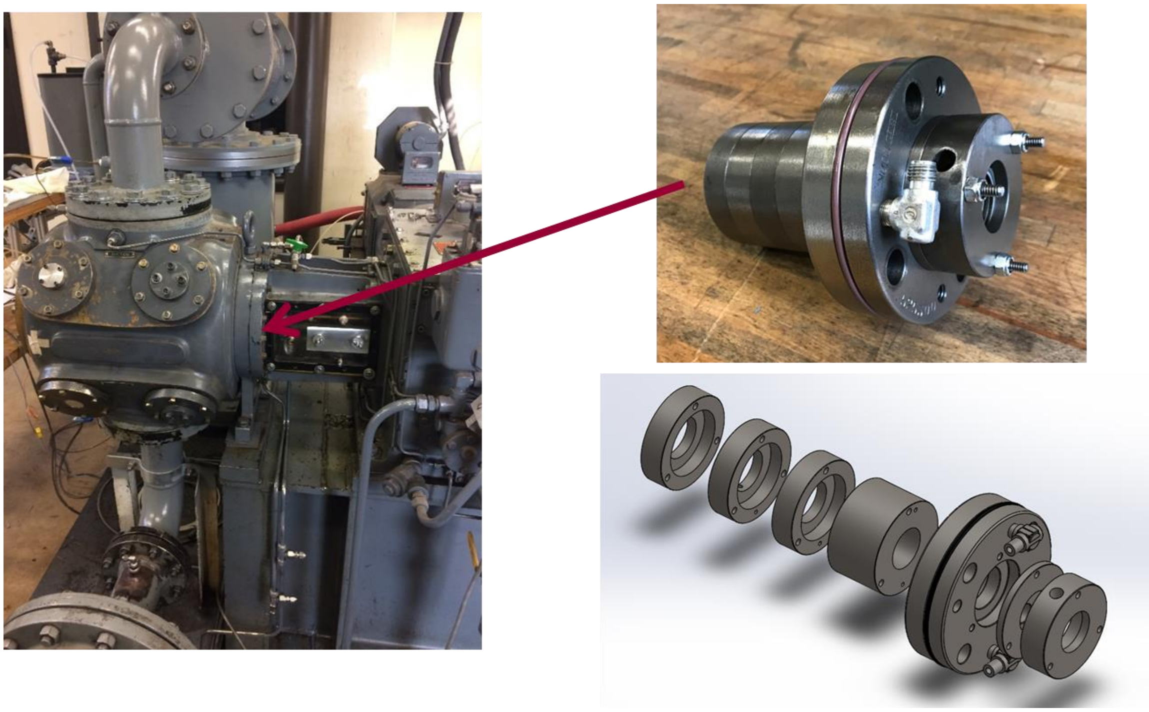


Figure 5. JGA/2 Emissions Setup

6.2 *Subtask 7.1 Baseline Testing*

SwRI collected leakage from stage 3 and stage 4 cylinders of the JGT/4 compressor for the baseline testing. The leakage was collected for a range of mean cylinder pressures between 100 and 600 psi corresponding to 1.3-2.8 pressure ratios. Figure 6 shows the data collected during this subtask. The leakage follows a linear trend that is dependent on the mean cylinder pressure. The leakage ranged from 0.028 to 0.11 SCFM.

Existing estimations for leakage are simplistic, such as 1% of production or a 0.2 SCFM flat rate. The industry generally accepts 0.1-0.2 SCFM to be considered “new” packing and 2-4 SCFM to be “worn” packing. Although these give a ballpark estimate (both would give higher results than for the baseline packing), they do not account for the operating conditions of the compressor, nor for the wear. Estimates will improve by incorporating a model that is dependent on the physics of the operating conditions.

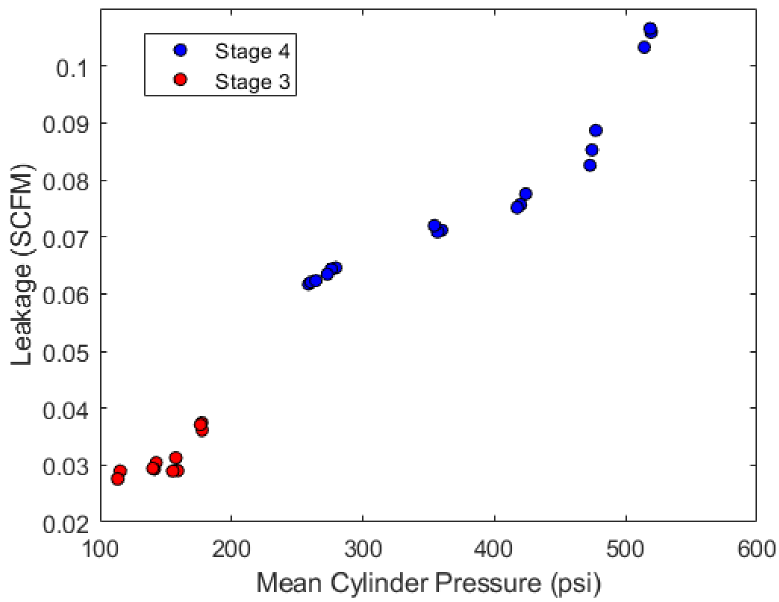


Figure 6. Baseline Leakage Data for the JGT/4 Compressor

The packing seal leakage can be estimated using the correlation in EQ.1.

$$\dot{V}_{leak} = W_r 0.98 \cdot d_{rod} \cdot P_{avg} \sqrt{\frac{n \cdot \left(2/_{n+1}\right)^{n+1/_{n-1}}}{28.96 \cdot Z_{avg} \cdot T_{avg} \cdot SG}} \qquad \text{EQ.1}$$

Where,

- $\dot{V}_{leak}$ is the volumetric leakage (SCFH)
- d_{rod} is the packing rod diameter (in)
- P_{avg} is the mean cylinder pressure (psi)
- n is the ratio of specific heats (-)
- Z_{avg} is the mean cylinder compressibility factor (-)
- T_{avg} is the mean cylinder temperature (Rankine)
- SG is the specific gravity (-)
- W_r is the wear rate.
    - W_r can range from 1 to 40 depending on the wear of the packings

The packing seal estimate was compared to the correlation as shown in Figure 7. The mean cylinder pressure is determined by using a reciprocating compressor model based on the measured suction/discharge pressures and temperatures. An example of the model, for stage 3, is shown in Figure 9. The model shows the compression stroke from 200-360°. The pressure begins to compress until it reaches the discharge pressure. Then the pressure remains constant as gas exits the cylinder. The mean cylinder pressure is the average pressure over this stoke. The actual data show some agreement with the model. The error ranges from 7-29% for the stage 4 data and by 14-35% for the stage 3 data. For both sets cylinders, the error was largest for smaller values of mean cylinder pressure. Figure 8 shows the model error compared to the compression ratio. Both cylinders show a similar trend of decreasing error based on an increased compression ratio. This is due to the methodology of determining the mean cylinder pressure. The model, shown in Figure 9, is based on an ideal gas. The larger the compression ratio, the more mass that are in the cylinder, and the gas is closer to an ideal gas. Additionally, the model does not perfectly collect the valve dynamics of the cylinder. It is expected, that the leakage model would further improve with direct measurement of the mean cylinder pressure compared to the current method of estimating the mean cylinder pressure.

Additionally, a Principle Component Analysis (PCA) was performed for the data measured in the study. The PCA is a technique for reducing the dimensionality of datasets by identifying the variables that account for the largest variation. In the data collected, the average pressure accounts for 95% of the variation in the leakage, followed by the compression ratio with 3.5%. All other variables account for less than 1% of the variation of the leakage.

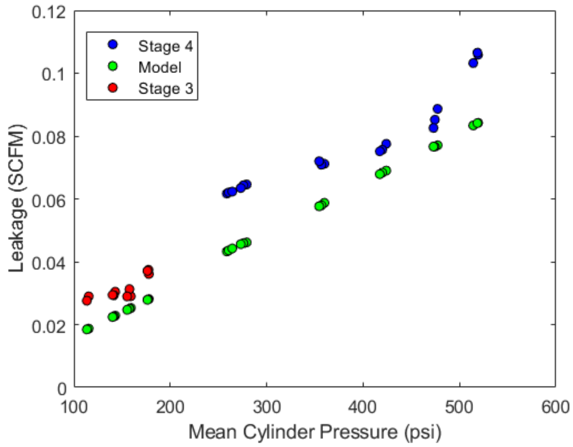


Figure 7. Baseline Testing Compared to Seal Leakage Correlation

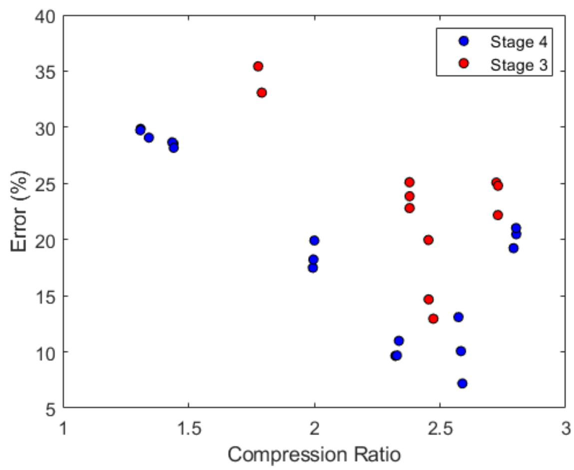


Figure 8. Model Error Compared to Compression Ratio

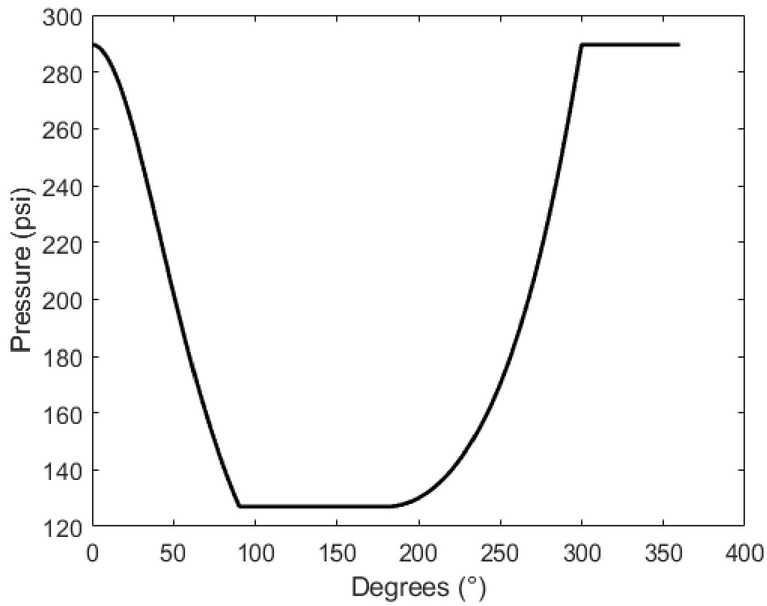


Figure 9. Estimated Pressure versus Rotational Angle for Stage 3

The packing seals also take some time to reach a steady-state seal leakage. Figure 10 shows the baseline packing leakage over time. During startup (8:00), the model predicts low leakage because there is no pressure in the cylinder. The compressor increased in loading from 8:00-10:30 before coming to a steady-state. The initial seal leakage is much higher than the model but then reduces to an expected value after heating up and receiving more lubrication. The test showed that there will be an initial leakage during startup that is much higher than the steady-state performance of the seal. Typical industry applications have an initial break-in and then remain at steady state for extended periods of time.

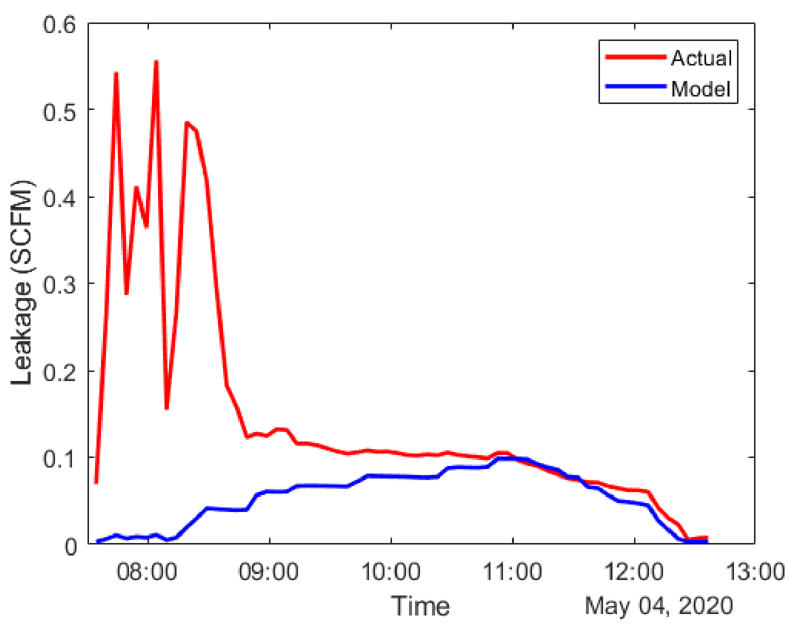


Figure 10. Packing Leakage Over Time

Additionally, SwRI tested the leakage for the packing of the in-house JGA/2 compressor. Figure 11 shows the leakage from the JGA/2 compressor. The rod diameter is 1.125'' compared to the 2'' rod diameter in the JGT/4 compressor. The measured data shows large errors for multiple points at low pressure. The large error is attributed to the physics shown in Figure 11. These test points were taken at different RPMs (starting from low to high) after the initial startup. Therefore, these points had not fully reached a steady-state temperature and pressure. The model shows that the JGA/2 packing showed good agreement with the model when the wear rate was 3. The JGA/2 and JGT/4 compressors had different types of packing installed for the baseline testing. The results show how the type of packing can affect the leakage, even if they are both new.

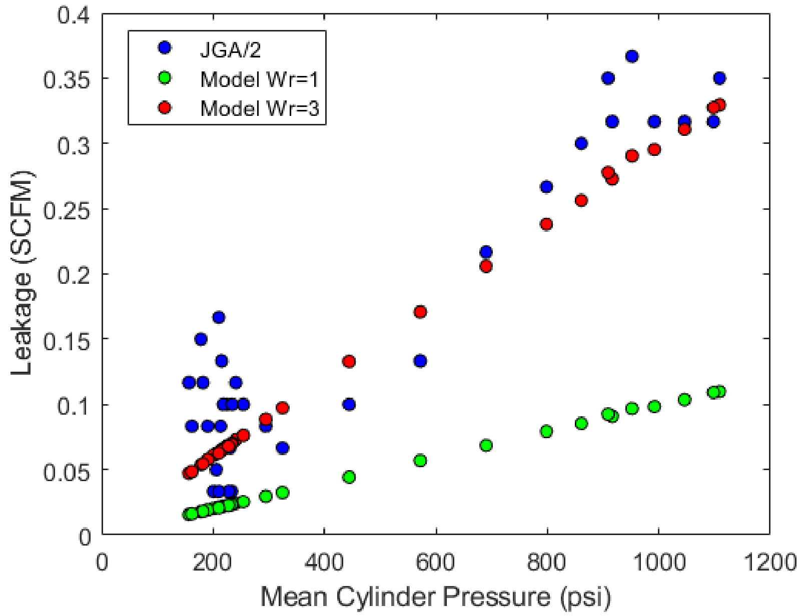


Figure 11. Baseline Packing Testing for the JGA/2 Compressor Subtask 7.2 Wear Evaluation

SwRI received two sets of packing that were removed from a field compressor after a yearly maintenance cycle (referred to as used packing). The packings had approximately 8,000 hours of runtime on a previous machine. The machine operated with suction pressure of 250 psi, a discharge pressure of 860 psi, and an interstage pressure of 450 psi. The packing stacks were installed on the SwRI JGT/4 compressor. A similar test was performed to evaluate the leakage of stage 3 and stage 4 compressor with the used packing installed. Figure 13 shows the leakage for the used stage 3 packing while Figure 14 shows the leakage for stage 4 packing. Stage 4 leakage was an order of magnitude larger than the baseline testing. The leakage agrees with the model when the wear rate is 10. The leakage rates reached 0.8 SCFM. Yet, the stage 3 packing did not show any significant increase in leakage compared to the baseline model with the wear rate of 1. Although both packings ran for the same number of hours (8,000), their conditions were such that the wear rate was different. Additionally, there might be some additional factors by transporting used packing to a different compressor. Specifically, the packings would have used to the shape of the original rod. Putting the packings on a new rod creates some uncertainty in the data shown, which is higher than the stage 3 packing that also had 8,000 hours. Still, the data shows an estimate for an leakage in a used packing.

Prior to testing, the used packing rings were measured with calipers to determine the amount of wear. The packing contains a set of seven ring sets. Figure 12 shows the packing rings after being torn down. Inside the torn packing, there was ring material (in the form of shavings/dust) found in each of the stacks. The removed material appeared to be from the ID of the rings and was found in both the baseline (after 100 hours of operation) and used packings. Each ring was measured in three locations and the averages are shown in Table 2. The measurements show locations where the used ring is both rings are both larger and smaller than the baseline packing. The wear is difficult to quantify using this method because a majority of rings are split rings made up of three pieces. The split allows them to expand to the shaft OD when installed face. Wear patterns were visually inspected using an optical microscope and analyzed for obvious heat or mechanical damage. No significant damage or deep wear patterns were observed. Therefore, actual wear cannot be determined.

Figure 12. Torn Down Packings with Baseline Left and Used Right

Table 2. Packing Ring Measurements

	Stage 3 Baselin	Stage 3 Used	Difference	Stage 4 Baseline	Stage 4 Used	Difference
Ring 1	1.8727	1.8623	0.0103	1.8627	1.8790	-0.0163
Ring 2	1.8750	1.8763	-0.0013	1.8840	1.8667	0.0173
Ring 3	1.8653	1.8867	-0.0213	1.8910	1.8733	0.0177
Ring 4	1.8737	1.8650	0.0087	1.8937	1.8710	0.0227
Ring 5	1.8640	1.9040	-0.0400	1.9067	1.9157	-0.0090
Ring 6	1.8967	1.8730	0.0237	1.8933	1.8723	0.0210
Ring 7	1.9463	1.9873	-0.0410	1.9873	1.9920	-0.0047

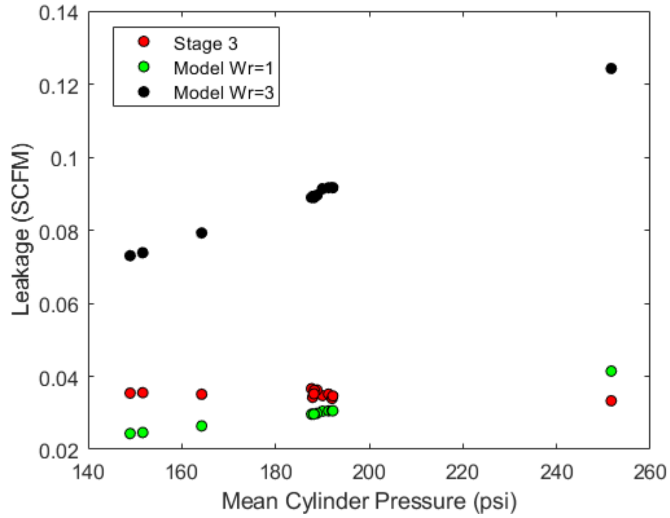


Figure 13. Stage 3 Used Packing Testing

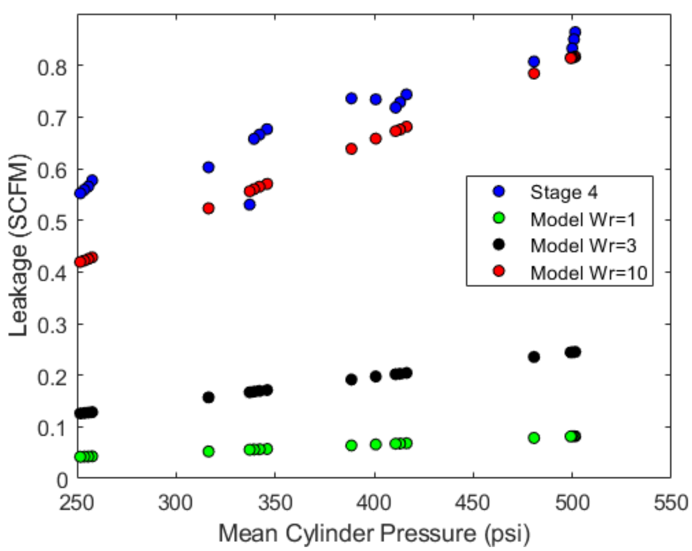


Figure 14. Stage 4 Used Packing Testing

6.3 *Subtask 7.2 Leakage Prediction Model*

The packing leakage model described in EQ.1 was updated to reflect the measured baseline testing from the testing campaign. The result was updating the constant shown in EQ.2

$$\dot{V}_{leak} = W_r 1.2 \cdot d_{rod} \cdot P_{avg}\sqrt{\frac{n\cdot\left(2/_{n+1}\right)^{n+1/_{n-1}}}{28.96\cdot Z_{avg}\cdot T_{avg}\cdot SG}} \qquad \text{EQ.2}$$

The updated results are shown in Figure 15. The trend model shows better agreement with EQ.2 The updated model reduces the error of stage 4 to a maximum of 13% and the error of stage 3 to a maximum of 21%. Figure 16 shows the error for all the data collected. The JGA data uses a W_r of 3 while the stage 4 used packing uses a W_r of 10. The JGA data shows the largest error. This is in part due to the lack of steady-state for some data as described in Subtask 7.1. The JGT/4 data fall within 25% of the predicted value. It should be noted that the model was built on the results of a single compressor. A model fit to the leakage rates of multiple compressors, or multiple compressors would further improve the results.

The data collected also shows a wide range of wear rates (W_r). The current model suggests discrete valves of the wear rate (1, 3, or 10) but in practice, this should be a continuous value determined by many specific factors. Additionally, worn packing could have much higher wear rates than those found for the current testing. The current dataset is not large enough to develop a method of determining the wear of a packing radius. Kaufmann et al. [4] used an experimental methodology to describe a packing wear rate shown in EQ.3. Their model determines the inner radius of the packing seal ($R^{(i)}$) based on, run time (t), wear constant (K), poisons ratio (v), density (ρ), shear modulus (G), rod diameter (G), and the high side pressure (p_1). Yet, wear models like these do not fully capture how the amount of wear corresponds to leakage. Additionally, packing rings can wear rapidly under adverse conditions, such as when the oil supply is removed or when they are overheated. There are also many other factures (such as the design of packing rings) that cannot currently be captured into the determination of the wear rate. These events are also difficult to capture in a wear rate for EQ.2.

$$\frac{dR^{(i)}}{dt} = \frac{\frac{Kv(\rho^2-1)}{1-2v+\rho^2}\left[G\left(\frac{D}{R^{(i)}}-2\right)+p_1\frac{2(1-v)}{1-(1/\rho)^2}\right]}{1+\frac{1}{2G}\left\{\frac{\left[G\left(\frac{D}{R^{(i)}}-2\right)+p_1\frac{2(1-v)}{1-(1/\rho)^2}(1-2v-\rho^2)\right]}{1-2v+\rho^2}+p_1\frac{2v}{1-(1/\rho)^2}\right\}} \qquad \text{EQ.3}$$

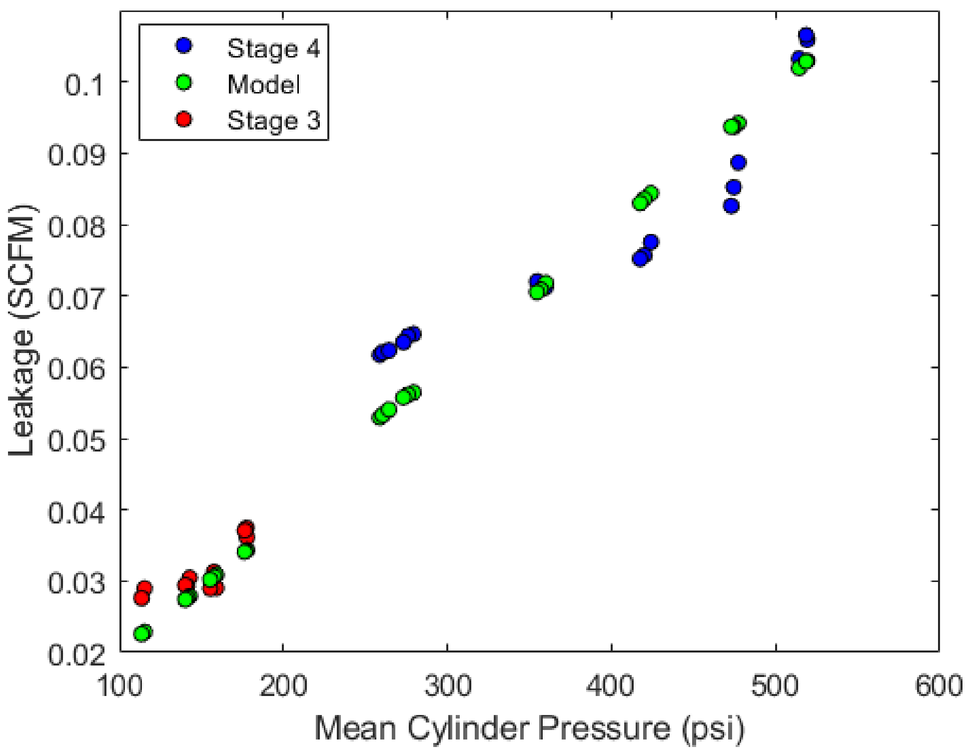


Figure 15. Baseline Data Compared to EQ.2

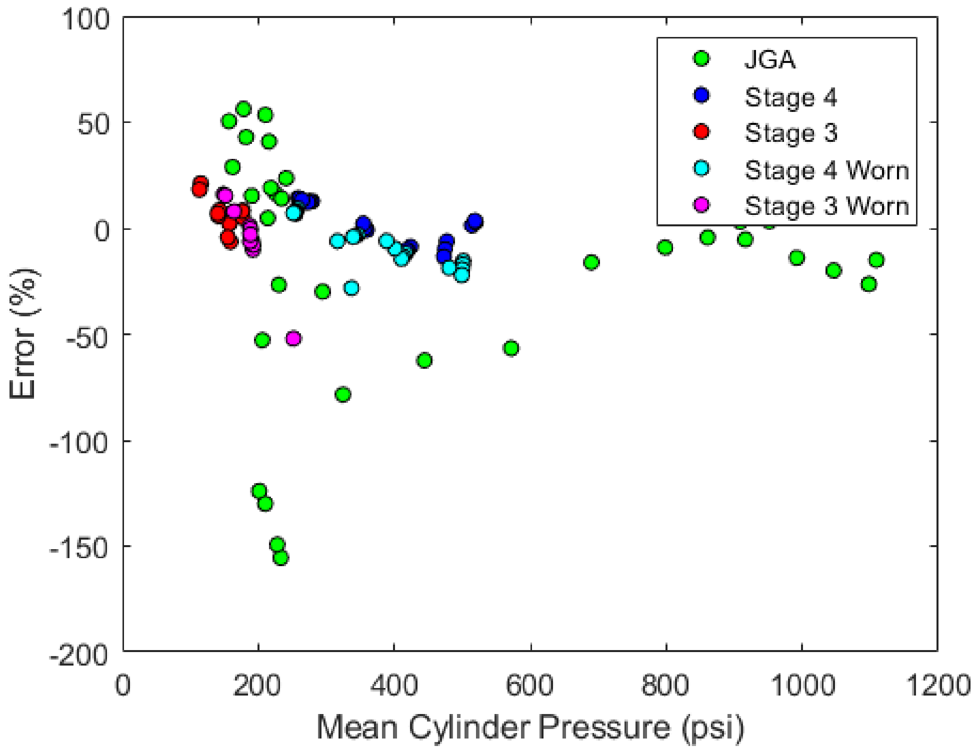


Figure 16. Error Using EQ.2

6.4 *Task 8.0: Final Data Analysis and Evaluation*

In conclusion, a large database of packing leakage was developed using a JGA/2 and JGT/4 compressor. A model was used to predict the packing leakage and compared to the collected data. The model captured the baseline and used packing within a 25% error compared to the measured data. The data collected represented wear rates ranging from 1 (baseline) to 10 (stage 4 used packing). Future testing campaigns could further investigate predicting the wear rate (W_r) to further improve the model. Such studies should include more time history on packing at field locations. Additionally, used packing could be installed with longer run times and more wear.

Future testing could include long-duration leakage measurements of packing as they wear. This will reduce the uncertainty that comes with testing the used packing in a different compressor than their operation. Additionally, leakage could be measured for multiple new packings in the baseline compressor. This would help to further validate the baseline data captured for this testing. Finally, incorporating more field data into the model would also aid in determining the correlation of operation conditions and wear rate.

Table 3. Data in the Raw and Reduced Form

Used Packing	Cylinder	Rod Size (‘’)	Speed (rpm)	Discharge Pressure (psi)	Suction Pressure (psi)	Discharge Temp (°F)	Suction Tempe (°F)	Mean Cylinder Pressure (psi)	Z_{avg}	n_{avg}	Mass Flow (lbm/s)	Leakage (SCFM)	Model Leakage (SCFM)
No	JGA	1.125	306	211.0	210.0	85.0	66.0	210.5	1.005	1.387	0.041	0.167	0.078
No	JGA	1.125	403	179.0	178.0	92.0	63.0	178.5	1.005	1.386	0.046	0.150	0.066
No	JGA	1.125	501	158.0	156.0	96.0	59.0	157.0	1.004	1.385	0.050	0.117	0.058
No	JGA	1.125	603	244.0	238.0	88.0	54.0	240.9	1.006	1.388	0.093	0.117	0.089
No	JGA	1.125	699	228.0	224.0	88.0	51.0	226.0	1.006	1.387	0.102	0.100	0.084
No	JGA	1.125	801	220.0	217.0	89.0	50.0	218.5	1.006	1.387	0.114	0.100	0.081
No	JGA	1.125	899	216.0	212.0	89.0	49.0	214.0	1.006	1.387	0.125	0.083	0.079
No	JGA	1.125	1,000	208.0	204.0	89.0	49.0	206.0	1.005	1.387	0.133	0.050	0.076
No	JGA	1.125	1,099	204.0	199.0	91.0	49.0	201.4	1.005	1.387	0.142	0.033	0.075
No	JGA	1.125	1,194	192.0	189.0	91.0	49.0	190.5	1.005	1.386	0.147	0.083	0.071
No	JGA	1.125	801	396.0	269.0	113.0	49.0	324.7	1.009	1.389	0.126	0.067	0.119
No	JGA	1.125	801	538.0	371.0	117.0	49.0	444.4	1.012	1.392	0.176	0.100	0.162
No	JGA	1.125	801	696.0	475.0	118.0	48.0	572.0	1.016	1.395	0.228	0.133	0.209
No	JGA	1.125	801	838.0	574.0	119.0	47.0	690.0	1.019	1.398	0.280	0.217	0.252
No	JGA	1.125	801	970.0	664.0	119.0	47.0	798.4	1.022	1.401	0.326	0.267	0.291
No	JGA	1.125	801	1,056.0	709.0	122.0	46.0	860.8	1.024	1.402	0.348	0.300	0.313
No	JGA	1.125	801	1,125.0	754.0	121.0	46.0	916.3	1.026	1.403	0.371	0.317	0.333
No	JGA	1.125	801	1,214.0	819.0	120.0	46.0	992.0	1.028	1.405	0.407	0.317	0.361
No	JGA	1.125	801	1,290.0	857.0	123.0	46.0	1,046.0	1.030	1.406	0.425	0.317	0.380
No	JGA	1.125	801	1,361.0	913.0	122.0	46.0	1,109.0	1.031	1.408	0.456	0.350	0.403
No	JGA	1.125	801	958.0	946.0	71.0	45.0	951.9	1.026	1.407	0.534	0.367	0.355
No	JGA	1.125	900	918.0	900.0	69.0	45.0	908.8	1.025	1.406	0.568	0.350	0.339

Used Packing	Cylinder	Rod Size (‘’)	Speed (rpm)	Discharge Pressure (psi)	Suction Pressure (psi)	Discharge Temp (°F)	Suction Tempe (°F)	Mean Cylinder Pressure (psi)	Z_{avg}	n_{avg}	Mass Flow (lbm/s)	Leakage (SCFM)	Model Leakage (SCFM)
No	JGA	1.125	306	286.0	164.0	103.0	66.0	215.7	1.006	1.386	0.026	0.133	0.079
No	JGA	1.125	403	244.0	137.0	109.0	61.0	182.1	1.005	1.385	0.029	0.117	0.067
No	JGA	1.125	501	214.0	124.0	110.0	58.0	162.2	1.004	1.385	0.033	0.083	0.059
No	JGA	1.125	603	313.0	209.0	110.0	52.0	254.4	1.007	1.387	0.072	0.100	0.093
No	JGA	1.125	699	302.0	288.0	107.0	51.0	294.7	1.008	1.388	0.131	0.083	0.108
No	JGA	1.125	801	286.0	194.0	108.0	51.0	234.3	1.006	1.387	0.090	0.100	0.086
No	JGA	1.125	899	285.0	188.0	111.0	50.0	230.3	1.006	1.387	0.097	0.067	0.084
No	JGA	1.125	1,000	315.0	174.0	122.0	50.0	233.3	1.006	1.387	0.092	0.033	0.085
No	JGA	1.125	1,099	318.0	164.0	124.0	50.0	227.9	1.006	1.386	0.092	0.033	0.083
No	JGA	1.125	1,194	296.0	150.0	126.0	50.0	210.3	1.006	1.386	0.090	0.033	0.077
No	JGA	1.125	900	1,341.0	908.0	117.0	45.0	1,097.8	1.031	1.412	0.512	0.317	0.400
No	4	2	1,175	852.1	305.1	251.2	118.4	514.2	1.017	1.391	1.084	0.103	0.102
No	4	2	1,175	861.8	307.4	253.3	115.6	519.2	1.017	1.391	1.099	0.106	0.103
No	4	2	1,175	860.6	307.1	252.8	115.2	518.5	1.017	1.391	1.098	0.107	0.103
No	4	2	1,175	761.9	296.1	251.3	130.4	477.3	1.016	1.389	1.173	0.089	0.094
No	4	2	1,175	758.7	293.7	250.5	130.2	474.4	1.016	1.389	1.155	0.085	0.094
No	4	2	1,175	757.1	292.4	249.1	123.2	473.0	1.016	1.390	1.147	0.083	0.094
No	4	2	1,175	647.4	277.0	245.5	117.4	424.0	1.014	1.389	1.209	0.078	0.084
No	4	2	1,175	639.3	275.2	245.5	117.0	419.8	1.014	1.389	1.197	0.076	0.084
No	4	2	1,175	636.2	273.2	245.1	120.1	417.4	1.014	1.389	1.186	0.075	0.083
No	4	2	1,175	510.0	255.7	237.6	120.2	359.8	1.011	1.388	1.267	0.071	0.072
No	4	2	1,175	505.9	253.4	236.4	133.4	356.8	1.011	1.387	1.247	0.071	0.071
No	4	2	1,175	503.1	251.5	234.3	132.7	354.5	1.011	1.387	1.233	0.072	0.070

Used Packing	Cylinder	Rod Size (")	Speed (rpm)	Discharge Pressure (psi)	Suction Pressure (psi)	Discharge Temp (°F)	Suction Tempe (°F)	Mean Cylinder Pressure (psi)	Z_{avg}	n_{avg}	Mass Flow (lbm/s)	Leakage (SCFM)	Model Leakage (SCFM)
No	4	2	1,175	337.1	234.1	210.8	118.0	279.2	1.008	1.387	1.496	0.065	0.056
No	4	2	1,175	332.5	231.7	199.7	113.6	275.9	1.008	1.388	1.474	0.064	0.056
No	4	2	1,175	329.9	228.9	193.9	111.7	273.1	1.008	1.388	1.451	0.063	0.056
No	4	2	1,175	297.5	227.2	182.5	117.4	258.6	1.008	1.388	1.536	0.062	0.053
No	4	2	1,175	299.5	228.9	184.6	114.8	260.5	1.008	1.388	1.549	0.062	0.053
No	4	2	1,175	307.9	229.3	188.6	112.4	264.3	1.008	1.388	1.533	0.062	0.054
No	3	2	1,175	291.6	106.8	314.4	131.1	177.7	1.006	1.381	1.045	0.036	0.034
No	3	2	1,175	290.7	106.7	312.6	133.3	177.4	1.006	1.381	1.050	0.037	0.034
No	3	2	1,175	289.2	105.9	312.3	131.8	176.3	1.006	1.381	1.043	0.037	0.034
No	3	2	1,175	249.4	100.8	295.3	137.9	159.0	1.005	1.381	1.319	0.029	0.031
No	3	2	1,175	246.3	100.4	293.7	139.9	157.6	1.005	1.381	1.322	0.031	0.031
No	3	2	1,175	242.7	98.8	294.0	136.2	155.3	1.005	1.381	1.302	0.029	0.030
No	3	2	1,175	220.0	92.5	283.2	137.1	142.8	1.005	1.381	1.352	0.030	0.028
No	3	2	1,175	217.7	91.5	281.3	135.2	141.4	1.005	1.381	1.340	0.029	0.028
No	3	2	1,175	215.8	90.7	280.3	135.1	140.1	1.004	1.382	1.331	0.029	0.027
No	3	2	1,175	154.7	87.0	246.9	134.9	115.4	1.004	1.382	1.692	0.029	0.023
No	3	2	1,175	152.7	85.3	238.6	134.4	113.5	1.003	1.382	1.663	0.028	0.023
Yes	4	2	1,175	824.1	300.4	228.2	129.4	501.4	1.017	1.391	0.965	0.864	0.999
Yes	4	2	1,175	823.5	299.9	229.4	130.1	500.8	1.017	1.391	0.961	0.851	0.997
Yes	4	2	1,175	822.8	299.0	229.9	128.8	499.9	1.017	1.391	0.955	0.833	0.995
Yes	4	2	1,175	822.8	298.0	230.3	125.4	499.2	1.017	1.391	0.947	0.815	0.995
Yes	4	2	1,175	775.5	294.4	228.4	126.4	480.6	1.016	1.391	1.009	0.807	0.959
Yes	4	2	1,175	641.8	269.1	223.6	126.5	416.3	1.014	1.389	1.012	0.744	0.833

Used Packing	Cylinder	Rod Size (")	Speed (rpm)	Discharge Pressure (psi)	Suction Pressure (psi)	Discharge Temp (°F)	Suction Tempe (°F)	Mean Cylinder Pressure (psi)	Z_{avg}	n_{avg}	Mass Flow (lbm/s)	Leakage (SCFM)	Model Leakage (SCFM)
Yes	4	2	1,175	636.9	266.8	222.0	129.0	413.0	1.013	1.389	1.005	0.728	0.826
Yes	4	2	1,175	634.7	264.8	220.8	127.3	410.8	1.013	1.389	0.996	0.718	0.822
Yes	4	2	1,175	601.5	267.1	218.6	123.1	400.8	1.013	1.389	1.074	0.734	0.804
Yes	4	2	1,175	569.5	265.9	217.1	123.5	388.5	1.012	1.389	1.119	0.736	0.780
Yes	4	2	1,175	497.1	242.2	212.2	121.1	345.9	1.011	1.388	1.050	0.676	0.697
Yes	4	2	1,175	491.2	239.7	209.8	119.6	342.1	1.011	1.389	1.040	0.666	0.691
Yes	4	2	1,175	487.2	237.8	208.9	121.7	339.3	1.011	1.388	1.032	0.658	0.685
Yes	4	2	1,175	484.0	236.3	208.8	123.9	337.2	1.011	1.388	1.025	0.530	0.680
Yes	4	2	1,175	429.8	235.4	204.3	123.6	316.4	1.010	1.388	1.160	0.603	0.639
Yes	4	2	1,175	334.3	201.1	197.1	119.6	257.7	1.008	1.387	1.044	0.577	0.523
Yes	4	2	1,175	332.6	199.0	196.4	119.9	255.7	1.008	1.387	1.029	0.565	0.519
Yes	4	2	1,175	330.8	196.9	193.5	120.3	253.6	1.008	1.387	1.018	0.559	0.516
Yes	4	2	1,175	328.4	195.2	192.9	117.3	251.7	1.008	1.387	1.014	0.552	0.513
Yes	3	2	1,175	224.9	98.7	228.3	114.1	251.7	1.005	1.384	1.485	0.033	0.051
Yes	3	2	1,175	230.4	99.7	244.3	116.8	149.0	1.005	1.384	1.477	0.035	0.030
Yes	3	2	1,175	251.6	107.0	257.6	120.5	151.7	1.005	1.383	1.395	0.036	0.030
Yes	3	2	1,175	295.3	121.7	273.7	126.4	164.2	1.006	1.383	1.462	0.035	0.032
Yes	3	2	1,175	297.5	122.5	279.0	130.3	190.0	1.006	1.383	1.465	0.035	0.037
Yes	3	2	1,175	299.1	122.7	286.2	133.2	191.3	1.006	1.382	1.456	0.035	0.037
Yes	3	2	1,175	299.3	122.8	292.5	134.7	192.1	1.006	1.382	1.457	0.034	0.037
Yes	3	2	1,175	295.9	118.5	296.7	135.4	192.2	1.006	1.382	1.296	0.035	0.037
Yes	3	2	1,175	309.6	113.6	306.2	135.4	187.9	1.006	1.382	1.041	0.034	0.036
Yes	3	2	1,175	308.8	112.4	309.7	135.4	188.9	1.006	1.381	1.014	0.036	0.036

Used Packing	Cylinder	Rod Size (‘’)	Speed (rpm)	Discharge Pressure (psi)	Suction Pressure (psi)	Discharge Temp (°F)	Suction Tempe (°F)	Mean Cylinder Pressure (psi)	Z_{avg}	n_{avg}	Mass Flow (lbm/s)	Leakage (SCFM)	Model Leakage (SCFM)
Yes	3	2	1,175	309.9	112.6	310.6	136.4	187.7	1.006	1.381	1.012	0.037	0.036
Yes	3	2	1,175	310.2	112.4	315.8	136.4	188.3	1.006	1.381	1.003	0.036	0.036
Yes	3	2	1,175	309.9	111.9	317.4	137.4	188.2	1.006	1.381	1.0	0.0	0.036

7. CONCLUSIONS

The two major goals of the project were to (1) demonstrate the potential for producing a packing seal that reduces methane emissions by a minimum of 95% of 1% of the total mass flow of the compressor with minimal wear to the seal, and (2) measuring the packing seal leakage of both baseline and used packing and developing an analytical model to predict the leakage. The first goal was accomplished through a detailed engineering design effort to develop a seal. The design was followed by a stringent testing campaign to test the leakage of the seal. The second goal was completed with the commissioning of a new test loop with a JGT/4 compressor capable of 700 HP. After commissioning, both baseline and used packing seals were tested to develop and improve the model.

The seal designed was tested statically and dynamically to determine the seal leakage. Static pressure holds up to 200 psi showed zero observable leakage. The required oil flow rate for sealing was 0.01-0.05 gpm. Dynamic testing up to 200 psi also showed no observable amount of leakage of gas into the oil or oil into the cylinder. Prolonged testing was performed to identify wear of the novel packing. No increase in wear to the seal was found when compared to the previous measurement taken after the static hold testing. The leakage showed a reduction of methane by a minimum 95% of 1% the total mass flow as no significant leakage was measured and additional testing showed minimal wear.

The leakage model was developed using a large database of packing leakage collected from a JGA/2 and JGT/4 compressor. The packing included both baseline and used packings for the model. A model was developed to predict the packing leakage and compared to the collected data. The model captured the baseline and used packing within a 25% error compared to the measured data. The data collected represented wear rates ranging from 1 (baseline) to 10 (stage 4 used packing). The model showed the largest error when compressor ratios were small. Both the used and baseline packing were measured with calipers and compared. The used packing did not show a significant difference from the baseline packing.

8. ACKNOWLEDGEMENT

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9. DISCLAIMER

10. REFERENCES

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