

Final Report to



Hybrid Rotor Compression for Multiphase and Liquids-Rich Wellhead Production Applications

OsComp Systems Inc. – 11123.15.Final

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Abstract

This paper presents the results of work performed under RPSEA's Small Producer Program, Subcontract number 11125-15. The award was presented to OsComp Systems to continue development of a new compressor concept that could be used for small producers to operate wet gas and multiphase wells without the need for wellhead separation.

Over the course of the project, two successive compressor prototypes were developed and tested. The testing shows very strong conceptual proof of concept, with the compressor being able to successfully accommodate multiphase flow through the machine without experiencing hydrolock conditions expected with conventional compression technologies. Challenges were encountered during testing with achieving sufficient reliability of the machine, and so the initially planned field trials were pushed out in favor of additional lab testing and redesign efforts. The project culminated with significant strides made in working through many of the problematic components and subsystems of the compressor. In addition, private funds have been secured to allow development to continue, the successful completion of which will lead to future commercialization of the technology.

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3. Executive Summary

OsComp Systems received Subaward number 11123-15 through RPSEA's Small Producer Program to continue development of a wet gas compressor technology. The project commenced in January 2013 and concluded in September 2014.

The focus of the project was to develop and test OsComp's new compression technology. The technology can best be explained by focusing on three aspects— thermodynamics, mechanical design, and multiphase capabilities. The thermodynamics of compression are such that gas heats up as it is compressed. The hotter the gas gets, the harder it becomes to compress, which further leads to more and more heat generation. This effect realistically limits most compressor technologies to compression ratios of 5:1. OsComp has developed a cooling technology in which an atomized liquid coolant is injected directly into the compression chamber. The manner of injection results in extremely rapid heat transfer from the gas to the liquid, keeping the gas cool. This cooling effect not only makes the compression process more efficient, but also allows compression ratios of 40:1 or higher.

Conventional compression equipment is not capable of utilizing this type of cooling technology because liquids cannot be tolerated in the compression chamber. OsComp's unique hybrid rotary design allows liquids to be swept out of the compression chamber, eliminating the hydrolock conditions seen with liquids in traditional compressors. This unique mechanical design not only enables the thermodynamic enhancements, but also allows for compression of wet gas, or gas that contains liquid content.

At many natural gas wellheads, liquids—typically heavier hydrocarbons and water—are present in the gas stream. In fact, with the recent pricing trends with natural gas and other hydrocarbons, wet gas is actually more desirable to producers due to the higher value of the liquid hydrocarbons. However, since traditional compressors cannot accommodate liquids, the gas and liquid have to be separated at the wellhead and dealt with separately. This presents significantly higher costs to operators. With OsComp's technology, the gas and liquid can go directly from the wellhead through the compressor and on to a single multiphase pipeline, leading to a centralized processing facility and dramatically lower costs.

Over the course of this 21 month project, the OsComp team has developed two successive prototypes of its compressor technology, each improving on the last. The first prototype developed under this project, known as "unit 2", was designed and built at the start of the project, coming online for testing in May 2013. Testing of the unit verified the conceptual breakthroughs of the design, with multiphase flows being successfully accommodated and the cooling technology working well. However, some design issues were encountered, leading to the decision that additional lab testing would need to be conducted before entering into field trials and that a new design would need to be completed to correct for some of the issues experienced with unit 2.

The unit 3 design was developed over the fall of 2013 and built through the winter, coming online for testing in April 2014. Unit 3 initially appeared much more robust than unit 2, performing well in early tests and continuing to show further proof of the technological breakthroughs inherent to the design. However, issues with reliability continued to plague the testing efforts, with tests under more extreme

conditions or for extended time periods typically leading to some type of failure. It was determined that the complexity of the system was too high to expect to be able to improve on this performance when only testing at a full system level, so a new plan of component and subsystem level testing was put into place.

This component level testing proved to be very successful, with many more hours of testing successfully completed and performance improved on several critical subsystems. Testing at the component level will continue after the culmination of the RPSEA subcontract, with plans for further units and eventual field trials and commercialization to follow.

A deep understanding of the challenges associated with developing a breakthrough industrial machinery technology has been developed over the course of the project. While the project did not progress as far as initially scoped, the current understanding of the problem allows for a much more accurate prediction of future success of the development. The team remains confident in a successful outcome, with private funding in place to help continue development into the future.

4. Introduction

OsComp Systems sought out to design a compressor that could help to make the production and transportation of natural gas more cost effective for producers, particularly small ones. Along the way, the technology has evolved into a revolutionary concept that enables dramatic simplification of wellhead infrastructure, lower capital and operating costs, and significant reductions in environmental impact.

It was with the early stages of this vision in mind that OsComp applied for and received Subaward number 11123-15 through the Research Partnership to Secure Energy for America (RPSEA) and its Small Producer Program. The work performed under that contract kicked off in January 2013.

This paper documents the work performed under this RPSEA subcontract during its 21-month period. The paper will first present an introduction to OsComp's technology, followed by an overview of the key progress made during the project. It will then review some key elements of the design of the prototypes developed under the contract and results of the testing conducted. The paper concludes with a review of technology transfer activities performed under the contract and next steps for the further development and commercialization of the technology.

5. Technology Introduction

There are three key components of OsComp's compression technology—thermodynamic enhancements, mechanical design, and multiphase capabilities.

5.1. Thermodynamic Enhancements

In a basic compression process, gas temperatures rise as the gas is compressed. In this scenario, temperatures rise quickly during the compression process. As temperatures rise, compression of the gas becomes more and more energy intensive. On the opposite end of the spectrum, an isothermal compression process is one in which the temperature of the gas is held constant during compression. This requires offloading heat into the outside environment to keep internal temperatures low. The energy required for each of these compression processes can be represented graphically in a pressure-volume (PV) plot, in which the work required for compression is represented by the area under the curve.

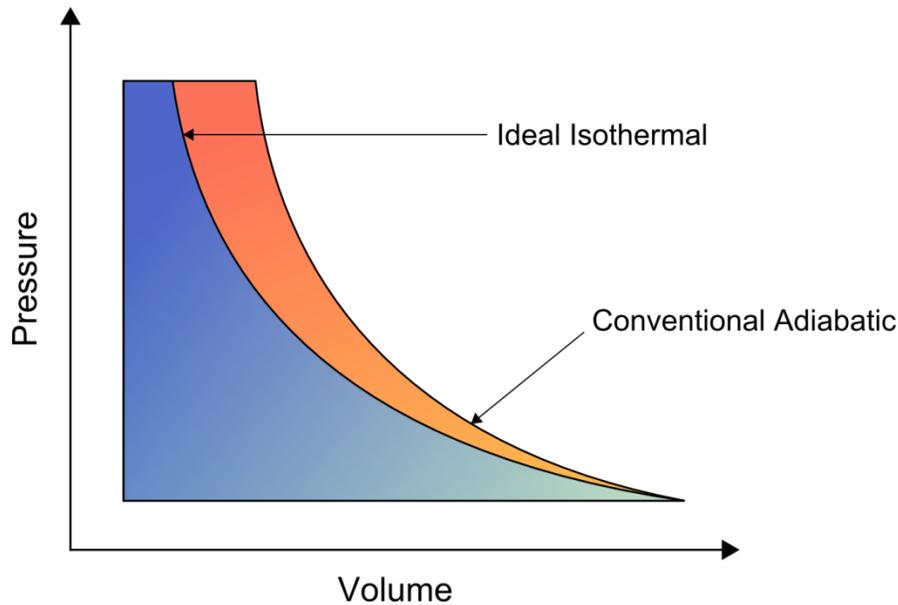


Figure 1 - PV plot of adiabatic versus isothermal compression

As seen in Figure 1, the isothermal curve, represented in blue, is an ideal compression process. The adiabatic process, shown in red, demonstrates the additional work required to achieve the same amount of compression. Despite the adiabatic process being known to be less efficient, many conventional compression technologies, such as reciprocating piston compressors, exchange little or no heat with the outside environment and essentially follow an adiabatic process due to the complexity in maintaining lower temperatures.

OsComp has solved this problem by cooling the gas as it is being compressed. An atomized liquid coolant is injected directly into the compression chamber during the compression process. Because the heat capacity of a liquid coolant can be more than a thousand times higher than that of a gas, the heat is transferred to the liquid and only results in minimal temperature rise, keeping gas temperatures low. The process is further enhanced by the atomization of the liquid, enabling extremely rapid heat transfer between the liquid and gas. By injecting a liquid coolant in this manner, OsComp is able to achieve a near isothermal compression process with improved efficiency over traditional compression.

An added benefit of this type of cooling is the ability to achieve extremely high compression ratios. The temperatures generated during a traditional compression process typically limit compression ratios to no more than 5:1. With OsComp's cooling technology, temperature rise is less than 10% of that seen in an adiabatic process, allowing compression ratios of 40:1 or higher. This can simplify a complete compression package, enabling many applications to be accomplished with a single stage of compression, where other technologies would have required 2 or 3 stage compressors.

5.2.Mechanical Design

A major enabling feature of OsComp's compressor is designing a machine that is capable of handling liquids in the compression chamber. Typical compressors, such as reciprocating pistons, will fail when any significant amount of liquid is allowed into the machine. OsComp not only created a design that

allows liquids to pass through, but also produced an elegantly simple machine with high power density, fewer moving parts, and lower vibration and noise.

OsComp's design is a hybrid rotary design as seen in Figure 2. A concentrically spinning, balanced rotor spins in line with the main drive shaft. A vertically moving vane is driven by external cams such that it maintains contact with the rotor as all times, sealing between the high and low pressure portions of the chamber. As seen in Figure 2, gas (shown in blue) enters the compressor at the bottom left. The leftmost image represents the maximum gas volume. As the rotor sweeps around counterclockwise, the gas is compressed between the rotor and vane. Once internal pressures exceed those of the downstream piping, valves at the lower right of the compressor open and allow the gas to exhaust.

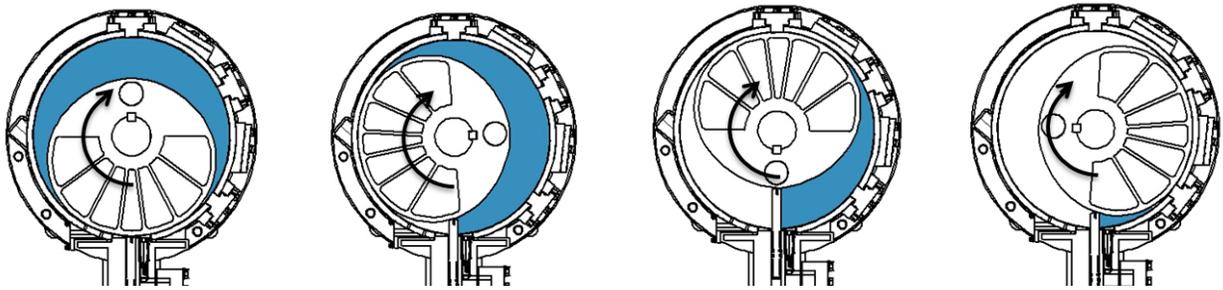


Figure 2 - Schematic of OsComp compression process

The sweeping motion of the rotor ensures that all of the liquid is fully exhausted from the cylinder during each rotation, preventing buildup of liquid and eventual hydrolock experienced with conventional pistons compressors. Special valves are designed with extremely high orifice volume, allowing the mixed phase fluid to easily exhaust. In addition, the location of the outlet at the bottom of the compressor ensures that gravity will help to force liquids from the chamber.

This design not only enables liquid injection and the thermodynamic benefits described in §5.1, but has a number of other key features. The rotary nature of the machine allows the compression chamber to be built directly around the main drive shaft, dramatically reducing the size of machine required for a given compression process as compared to piston type machines with the compression occurring normal to the drive shaft. This also simplifies the design and number of moving parts since no motion transferring components such as tie rods are required, ultimately resulting in lower costs and improved reliability. The balanced nature of the rotary motion also ensures low vibration and noise during operation.

5.3. Multiphase Capabilities

A significant added benefit of the machine's ability to pass liquids through the compression chamber is that not only can cooling liquids be injected, but wet gas can also be passed directly through the compressor without need for pre-separation.

Many natural gas wells produce not only gas, but also contain liquid hydrocarbons, such as propane and butane, known as natural gas liquids (NGLs). These NGLs are of significantly higher value than the primarily methane gaseous portion of the stream. Unfortunately, capturing these NGLs with

conventional compression technology can be both difficult and expensive. As shown in Figure 3, conventional compressors require gases and liquids to be separated before entering the compressor. The gas and liquid streams must then be dealt with separately. Depending on the volume of each, liquids will often be stored at the wellhead and periodically removed via truck. Other scenarios involve operating two separate pipelines or even flaring the gas and only capturing the liquids.

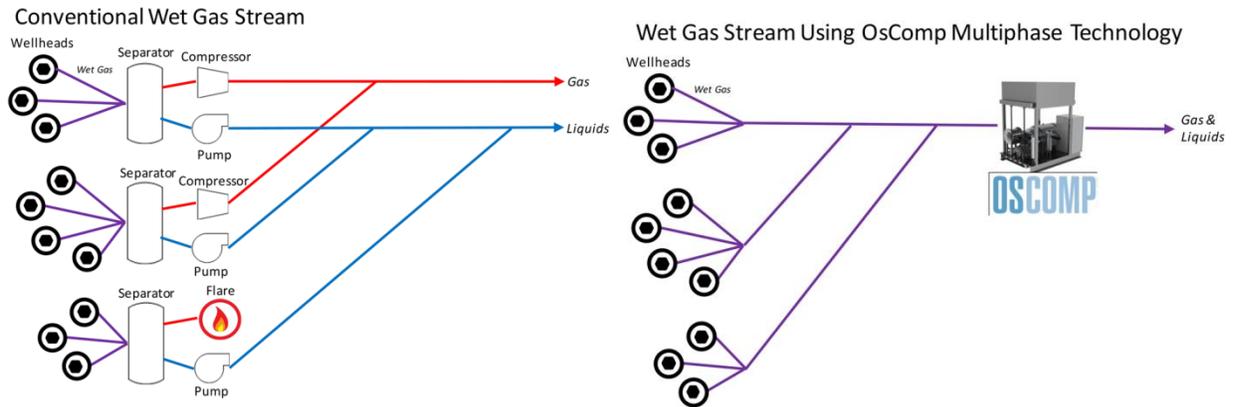


Figure 3 - Schematic of conventional (left) versus OsComp (right) wet gas stream

With OsComp technology (right schematic in Figure 3), the multiphase flow can be passed directly through the compressor, and transported in a single multiphase pipeline. Separation can then be handled in a centralized facility. Figure 4 demonstrates the dramatic simplification of the wellhead achieved by using OsComp multiphase technology.



Figure 4 - Wellhead with conventional technology versus OsComp technology

6. Project Summary

6.1. “Unit 2” Design

The project kicked off with the team building on initial compressor designs to create a “unit 2” design. Manufacturing partners were engaged to machine all the components of the machine and it was then built at OsComp’s Houston office and test facility.

6.2. “Unit 2” Testing

In parallel with designing and building the unit 2 compressor, the OsComp team was also constructing a fully featured test cell (outside the scope of the RPSEA project). Unit 2 testing began in May 2013 and proceeded through the rest of the year. The unit remains operational in a limited capacity and testing continues as time permits.

6.3. “Unit 3” Design

Unit 2 testing revealed some promising results, however it also revealed some shortcomings in the design. These shortcomings were used to inform a redesign effort for a new prototype, known as “unit 3.” Designs were released through late 2013 and early 2014. A manufacturing engineer added to the team since the unit 2 build led the sourcing effort, helping to control processes and ensure parts were delivered to specification. Unit 3 parts were received in-house and the compressor first assembled in April 2014.

6.4. “Unit 3” Testing

In addition to the build of unit 3, the OsComp team also completed a second, more functional test cell (also outside the scope of the RPSEA project). Unit 3 testing commenced in the new test cell in April 2014 and has proceeded to date. A number of promising results have been achieved and will be presented in §8.2.

6.5. Evolution of OsComp

Over the course of this project, OsComp has made large strides as a company. The team has expanded and added significant capabilities, with a senior manufacturing engineer, senior analysis engineer, senior test engineer, and a test technician added to the team. An initial series A venture capital fundraising round, raised before the start of this project, was augmented by a \$6M series B investment in December 2013.

As a final mark of the company’s progress, a rebranding effort has been completed. OsComp Systems is transforming into Hicor Technologies as of the completion of the project, to avoid confusion with a spinoff company, also called OsComp, delivering virtual pipeline natural gas solutions.

7. Design Review

7.1. Unit 2

The unit 2 design was discussed in detail in a previous RPSEA deliverable, “Design Overview Update.” Details of those improvements will be omitted here, however a summarized list of some of the key design improvements are below:

- Cast rotor casing and manifolds
- Improved countersurfaces
- Lubrication
- Focus on materials
- New rotor profile
- Rotor endcaps
- Smaller cam

7.2. Unit 3

The transition from the unit 2 to unit 3 design was much more subtle than the transition from unit 1 to unit 2, but no less impactful. On the surface, unit 2 and unit 3 appear nearly identical, whereas unit 1 appears significantly different. However, much of the challenge in engineering and technology development comes in getting the details right. In addition to the design updates, a massive effort was put into working with suppliers to develop good manufacturing processes, ensuring that the parts are delivered to print. Some of the noteworthy improvements in the unit 3 design are summarized below and shown in Figure 5:

- Increased focus on materials and coatings
- Larger shaft for improved strength and bending resistance
- New bearing arrangement to reduce axial play and improve rigidity
- Hardened cams and yoke style cam follower
- Graphite face seals bonded to stainless steel backing
- Single piece valve cartridge with reduced clearance volume

Item	Unit 3	Unit 2
Shaft/rotating assembly	4" shaft 25% deflection	3" shaft
Cams/followers	Yoke style follower Hardened cam. No offset loading	Stud style follower Hardened coating
Bearings	Opposed tapered rollers. Rigid, longer life.	Spherical roller
Seals	Graphite bonded to SS backing. Increased life	Polymers
Valve system	Single piece 3 rows. Low clearance volume	Multi-piece 2 rows

Figure 5 - Summary of design changes between unit 2 and unit 3

8. Test Results

8.1. Unit 2

Unit 2 came online in May 2013. A comprehensive test plan was created for the unit consisting of the following steps:

- Test Series 01 - Debugging
- Test Series 02 – Low speed, low pressure
- Test Series 03 – Low speed, high pressure
- Test Series 04 – High speed, low pressure
- Test Series 05 – High speed, high pressure
- Test Series 06 – Performance benchmarking
- Test Series 07 – 8 hour test
- Test Series 08 – 24 hour test

Early testing immediately proved out much of the conceptual work behind the technology. Liquids were passed through the compressor without any damaging effects, with gas volume fractions (GVFs) successfully tested down to 92%. This enabled the cooling technology to be tested, with very successful results. Figure 6 shows a small snippet of data from one such test. In this test, ambient inlet pressures were compressed to 250psig outlet pressures, a ratio of 18:1. The cooling technology held the temperature increase to only 20°C. An equivalent 18:1 compression ratio conducted without cooling, known as isentropic compression, would expect to yield a temperature of 390°C, far hotter than realistic given material limits, not to mention extremely inefficient.

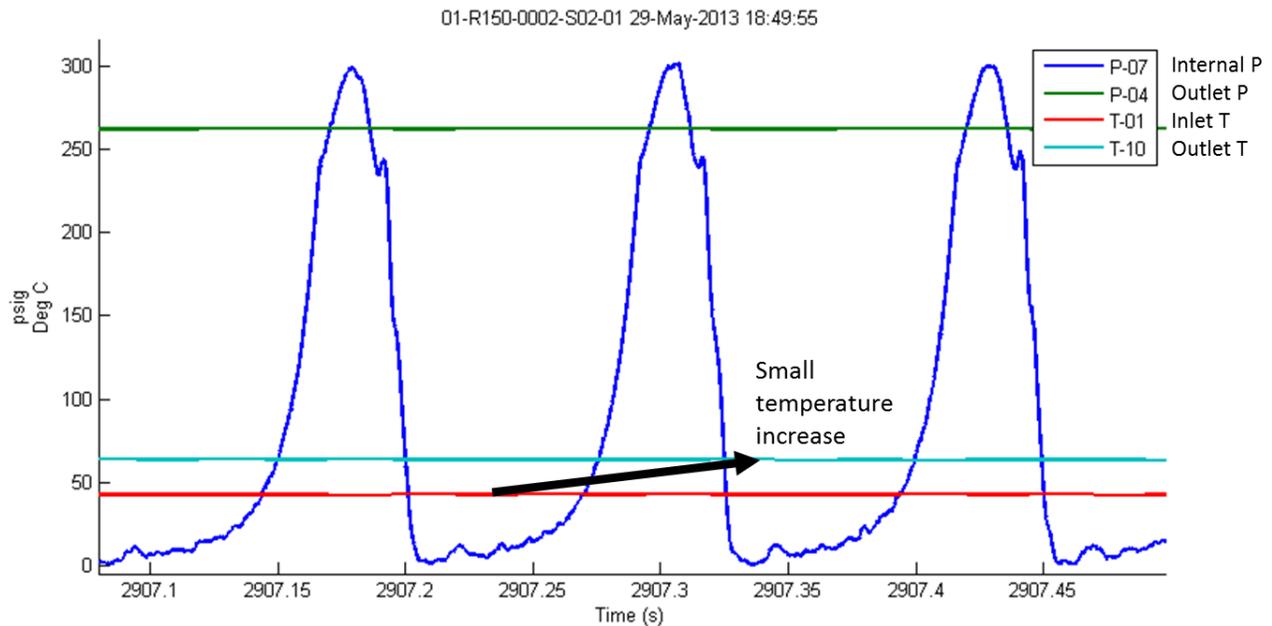


Figure 6 - Test data showing temperature rise with 18:1 compression ratio

Unfortunately, early testing also showed that achieving the milestones laid out in the initial development plan would be much more difficult than originally anticipated due to issues with component failures and reliability. Test plans were revised to proceed through slow ramp up of speed and pressure to identify maximum achievable specifications of the compressor.

Issues were identified with the shaft strength and bearing configuration that limited maximum differential pressures to approximately 250psig. It was also established that the system ran better at speeds around 700RPM as opposed to the full design speed of 900RPM. Further testing identified various other design shortcomings discussed in the unit 3 design overview in §7.2.

After establishing performance limits, testing transitioned to a focus on reliability. A plan was established for working towards a 24 hour continuous run test. The first step in that process was to achieve a 4 hour continuous run test. The system ran fairly well for the first 2 hours, at which time one of the two main drive springs fractured, immediately terminating the test (see Figure 7). Further investigation identified that the vendor had not delivered a spring designed to achieve the cycle life requested of them. The springs were replaced and the team moved forward with plans for a 24 hour test.



Figure 7 - Fractured spring from unit 2 4 hour test

Preparation for the 24 hour test involved several more upgrades to the compressor as well as the test stand. The test was attempted in December 2013. The test proceeded well initially and was uneventful. After about 18 hours, slow degradation in pressure and flow rate was observed. After another 45 minutes, an exterior plug on the casing was breached and steam began to exit the machine, so the test was terminated at that time. Figure 8 shows the results of the 24 hour test. The pressure line, shown in blue, can be seen dropping after 18 hours before the test is terminated at 19 hours.

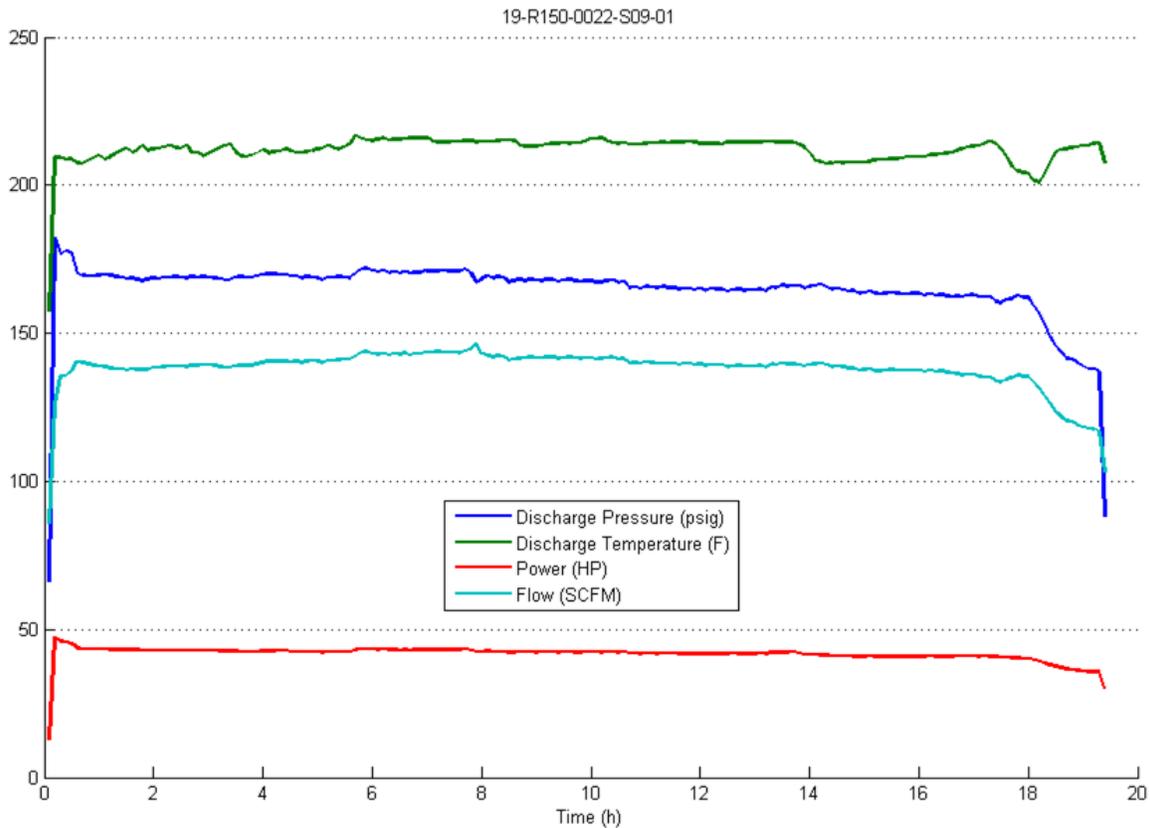


Figure 8 - Results of unit 2 24 hour test

A post-test teardown of the unit revealed a catastrophic failure of the rotor’s outside lip as shown in Figure 9. Working with fracture mechanics experts, it was determined that the failure was likely induced by impacts sustained to the rotor during earlier testing, with the high number of cycles sustained during the 24 hour test extending the initial damage to the point of fracture.

Despite the failure experienced at the end of the test, it was still a very valuable milestone to achieve. The test proved that the system could run for sustained periods of time and continue operating well after all components achieved thermal equilibrium and the system fully stabilized. The nature of the failure itself was due to early testing issues and not an inherent design flaw, creating a clear path towards eventual commercial levels of reliability.

With the results of that successful test in hand, and unit 2 out of commission for an extended period to repair the damaged rotor, the team moved forward with design release and build of unit 3.

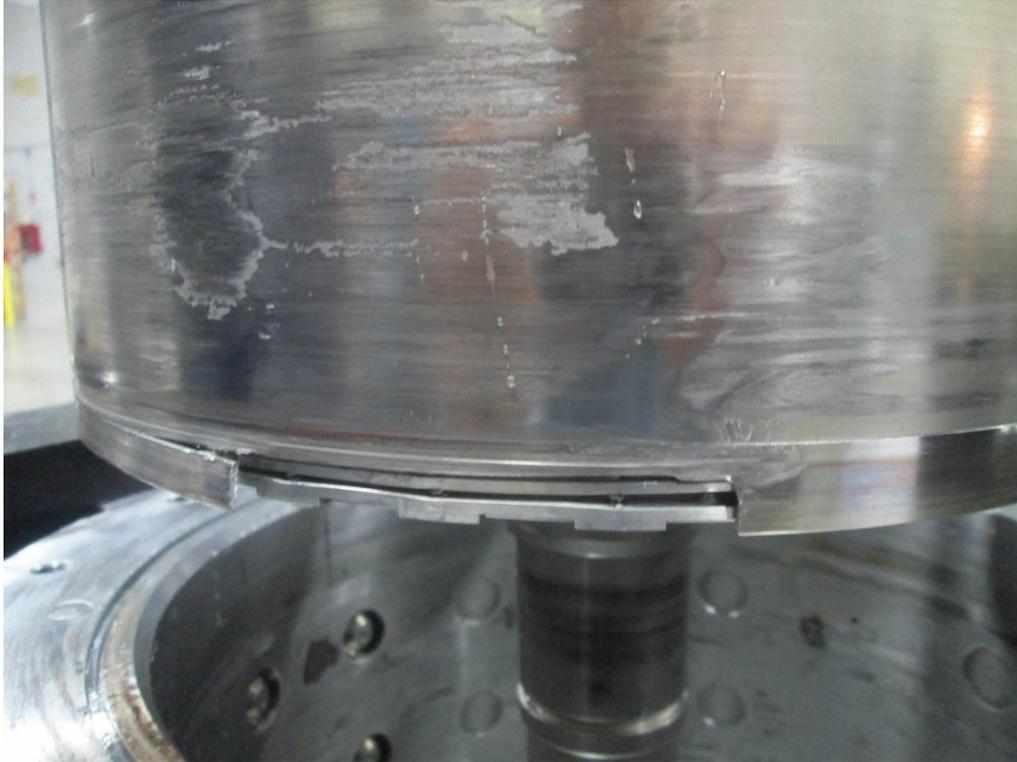


Figure 9 - Unit 2 rotor lip failure

8.2.Unit 3

Unit 3 came online in April 2013 with a slightly more conservative test plan than originally laid out for unit 2. The plan consisted of the following:

- Test Series 01 - Debugging
- Test Series 02 – Low speed, low pressure
- Test Series 03 – High speed, no pressure
- Test Series 04 – High speed, low pressure
- Test Series 05 – 4 hour test
- Test Series 06 – 24 hour test

Given earlier success in technological proof of concept, unit 3 testing was aimed more at reliability and working towards a commercially viable machine. The initial goal of unit 3 was to focus on achieving sustained run times and not immediately seeking to achieve higher pressures and validate full design specifications. Testing began in a very positive fashion with initial tests resulting in sustained runs at conditions never achievable with unit 2. Figure 10 shows the results of this initial run, with the full test sequence of running the compressor up to 450RPM and 250psi being successfully completed before shutting the unit down for examination.

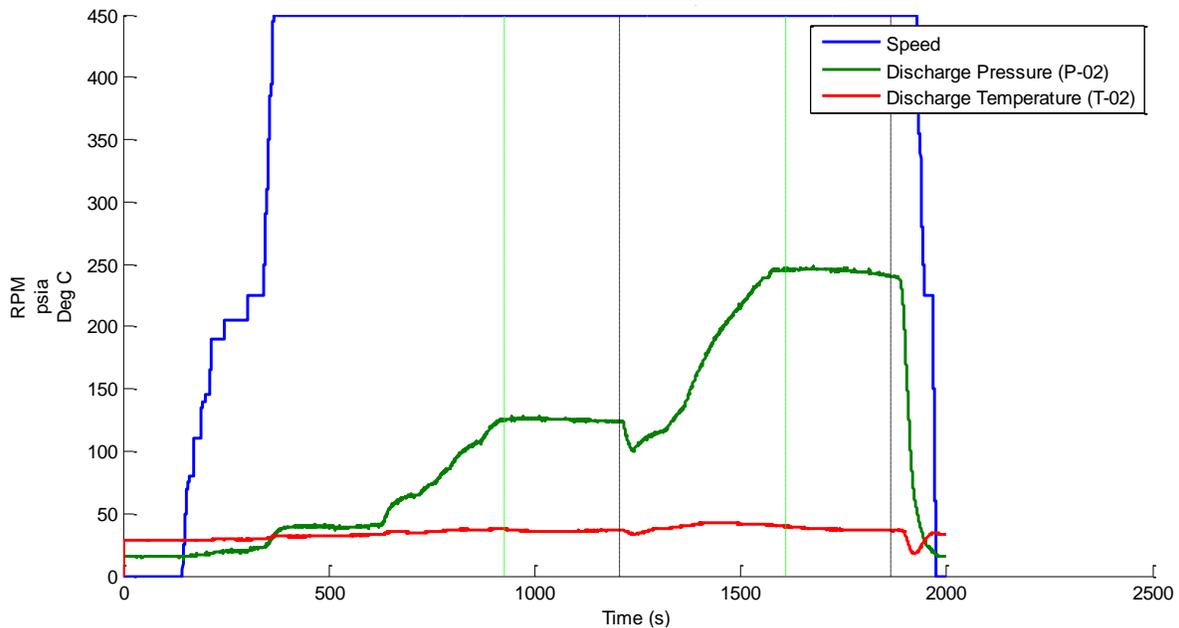


Figure 10 - Initial low pressure low speed test run of unit 3 prototype

However, further testing indicated that the initial test plan would be difficult, if not impossible, to follow. As testing of the full unit progressed, various components would fail or otherwise become problematic, but diagnosing the root cause when running the entire compressor was exceedingly difficult. As a result, the engineering and test team made the decision to take a step back and begin systematically testing various components and sub-systems of the compressor, working through one sub-system at a time to eliminate any design or implementation flaws, before moving on to the next test.

The results of this component testing were very successful. It allowed the team to work through and solve many of the component level issues in the design, which may have not yet appeared in full unit testing if other issues presented themselves first. In addition, the transition to a component focused test plan allowed for the compressor and test cell to log many more hours. This allows for validation of the support components such as springs and bearings that remain in place for many of the tests, as well as allows the team to ensure full functionality of most of the support equipment and test cell.

Figure 11 shows a summary of testing hours completed over time for the three compressor prototypes built to date. As seen here, the initial unit 1 prototype, built and tested prior to this project, only achieved a total of 11 hours of testing. Unit 2 was more successful, slowly accumulating hours over time, and culminating in the 19 hour test described previously. (The unit has recently been brought back online to fill gaps in testing while unit 3 is down.) Unit 3, as seen in Figure 11, started out slowly accumulating hours similar to unit 2. However, the transition to component testing has allowed a dramatic increase in completed testing hours with five successful 24 hour tests having been completed as of the end of this project. These tests have allowed the team to make significant strides in understanding and optimizing many of the components in the system.

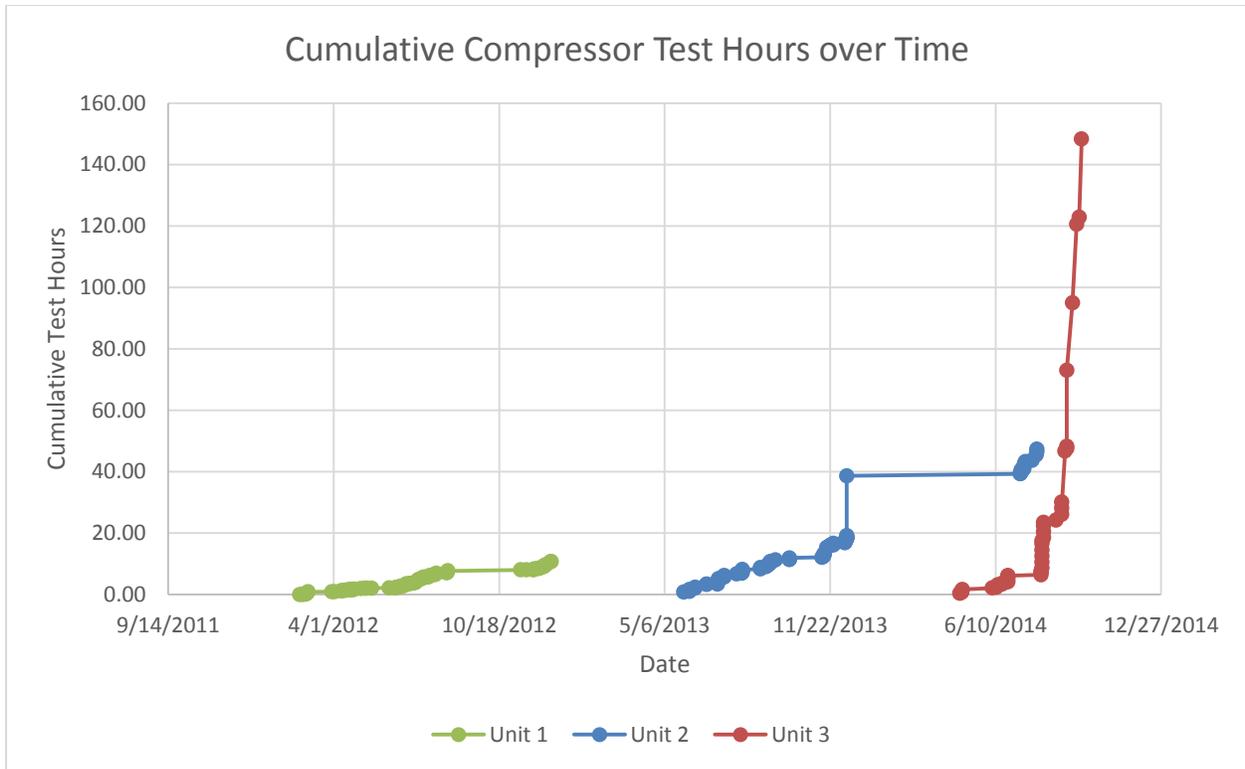


Figure 11 - Summary of testing hours for successive compressor prototypes

9. Technology Transfer Activities

OsComp recognizes that creating a revolutionary new compression technology is a worthless activity without educating relevant stakeholders. To that end, the team has spent a significant amount of effort on technology transfer activities. Along with countless informal conversations with compression packagers, equipment manufacturers, and natural gas producers, formal presentations were given at the following conferences:

- RPSEA Onshore Production Conference – Wichita, KS – June 27, 2013
- RPSEA Onshore Production Conference – Houston, TX – September 25, 2013
- ASME Shale Development and Fracturing Conference – San Diego, CA – March 18, 2014
- RPSEA Onshore Production Conference – Houston, TX – June 17, 2014

In addition to the speaking engagements, OsComp worked with Epic Software to create a video demonstrating the capabilities of the new compression technology. This video will ultimately be displayed prominently on the OsComp (Hicor) website and used in future presentations and tradeshows to help spread the word about OsComp’s breakthrough technology. The video is available online at <https://www.youtube.com/watch?v=VD8LkOcUqZE>.

10. Next Steps and Conclusion

The conclusion of this project comes at a time when, as described in §8.2, the team has begun to make significant strides in testing of unit 3 and beginning to solve many of the lingering problems in the system. The team's progress while working under RPSEA funding has been successful enough to obtain private funding to continue working on developing the product and hopefully making it commercially available to producers in the next few years.

The team's plan is to continue working through the system at a component level, validating and troubleshooting individual components of the design until the full compressor is well understood. In addition, design work on the next generation, "unit 4", compressor is underway with learnings from the unit 3 testing worked into the design and additional design updates to continue to be made after unit 4 comes online.

Further testing of unit 3, unit 4, and potentially additional units will continue in the lab through much of 2015, with field testing likely beginning in late 2015 or early 2016. The timeline has extended significantly from what was presented in the initial proposal for this project. However, one of the successful outcomes of the project has been a detailed understanding of how difficult the scope of work is in creating a new and breakthrough piece of industrial machinery. While physical progress in building a better prototype has been made during this project, the team's understanding of the problem, which is difficult to quantify and document, is perhaps where the most progress has been made.

Securing funding through RPSEA's small producer program has been critical in allowing OsComp and now Hicor to work through the enormous challenges inherent to early stage technology development, when private funding sources can often be difficult to secure. This project has allowed the team to make enough progress and get enough people excited about the technology being developed, that the team has been able to secure private funding and continue the development. Despite not achieving the initial milestones set out in the scope of work for this project, the Hicor team remains committed to developing this breakthrough technology and is confident that it will eventually be commercialized for the benefit of producers, both small and large.