DEVELOPING & TESTING COMPONENTS FOR MORE RELIABLE LINEAR RECIPROCATING COMPRESSION OF HYDROGEN

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ABSTRACT

Southwest Research Institute® (SwRI®), ACI Services, Inc. (ACI), and Libertine FPE Limited collaborated to design and build a Linear Motor Reciprocating Compressor (LMRC) via a DOE-funded project with ACI cost share. The advanced compression system utilizes a novel concept of driving a permanent magnet piston assembly inside a hermetically sealed compressor cylinder through electromagnetic windings. The LMRC design minimizes the mechanical part count and has no process gas leakage to atmosphere. The LMRC has no "rod," rod packing, crankshaft, coupling, or separate motor/driver. In addition, the LMRC is able to improve the efficiency of the compression process by eliminating bearing losses and optimizing the piston speed profile to reduce fluid dynamic losses. The primary project objective was to meet the DOE goal of increasing the compression efficiency and reducing the cost of forecourt hydrogen compression; however, most of the associated technology developments can be applied to high-pressure natural gas, process gas, air, and other compressors. High pressures, electromagnetic fields, and a hydrogen environment (for the specific DOE vehicle refueling application) are the main design obstacles that had to be overcome to design a linear motor reciprocating compressor that can ultimately achieve a 12,700-psi final discharge pressure in the third stage.

Manufacturing of the first stage LMRC (first of three stages) was completed and tested in early-to-mid 2020. Solid model images and a photo of the LMRC that was built and tested is presented in Figure 1. The first stage LMRC has design suction and discharge pressures of 290 and 1,035 psi, respectively. After a failure caused the testing to end prematurely, SwRI internal research and development (IR&D) funding was sought to rebuild the LMRC using the lessons-learned from the 2020 testing to improve some of the key components of the design. The key components that were the focus of the IR&D project are as follows:

- Metal Coatings – Specifically, coatings for magnets. A new coating and process method was developed to protect magnets from hydrogen incursion.
- Valve Design – Based on the identified design improvements, a new valve design with minimal leakage for hydrogen service was developed and built.
- Motion Profile – Motion profile optimization efforts were performed with the rebuilt LMRC.

Testing of the above-noted components of the LMRC was completed in early-to-mid 2022; therefore, test data is included in this lecture. In addition to those component developments, further advances in the hermetic actuator platform technology are expected to yield efficiency and durability benefits for subsequent phases of development ahead of commercial product launch. The paper will include discussions of design, manufacturing, and testing aspects of some of the individual components and of the entire LMRC. In addition to being highly relevant to the hydrogen gas economy, the LMRC is considered relevant and applicable to most gas compression industries.

Figure 1. LMRC Solid Model Images and Photo of Tested LMRC

INTRODUCTION

Reciprocating and diaphragm compressors are the current state of the art in gas compression and in particular for the quickly growing hydrogen compression market. Considering the small size of the hydrogen molecule and its high diffusivity, being able to contain and compress hydrogen gas demonstrates a system that is capable of containing and compressing essentially any larger gas molecule.

In addition to hydrogen compression, highly efficient hermetically-sealed compressors could be applied in many applications such as natural gas compression, which would result in reduced greenhouse gas emissions. Any hazardous gas application is an application for a hermetically-sealed compressor, since containment of the hazardous gas is critical. Hermetically-sealed reciprocating compressor machinery is also of interest to non-hydrogen applications including closed cycles for refrigeration or power generation, where leakage from the process through primary machinery shaft seals impacts cycle performance and must be made up through an external supply. These applications include supercritical carbon dioxide power cycles, mixed refrigerant or nitrogen-based cycles for cryogenic refrigeration, and high-pressure air or helium cycles considered for grid-scale energy storage and advanced nuclear power applications. Therefore, the development of key components of a hermetically sealed compressor will lead to advancements in reducing gas emissions.

The team of Southwest Research Institute, ACI Services, Inc., and Libertine FPE Limited designed, built, and tested the stage one Linear Motor Reciprocating Compressor (LMRC) during the 2014-2020 DOE-funded project #DE-EE0006666. The LMRC was designed to compress hydrogen for refueling stations and to meet the Department of Energy's (DOE) goal of increasing the efficiency and reducing the cost of forecourt hydrogen compression. The advanced compression system utilizes a novel concept of driving a permanent magnet piston inside a hermetically sealed compressor cylinder through electromagnetic windings. The LMRC is an improvement over conventional reciprocating compressors as it minimizes the mechanical part count for high reliability, reduces leakage paths, allows for optimized motion profiles, and is easily modularized for simple field installation. A patented concept [U.S. Patent 8,534,058] was conceived, which eventually lead to the idea of the LMRC. The LMRC has the following advantages over conventional reciprocating compressors:

- System Complexity – Conventional state-of-the-art reciprocating compressors utilize double-acting pistons, each connected to a rod, crankshaft, coupling, and separate motor/driver. This arrangement is mechanically complex and less efficient, as it consists of multiple moving parts that require bearings, seals, and lubrication, which can require frequent maintenance intervals. The fundamental piston actuation of the LMRC is achieved through magnetic forces. Since the LMRC replaces a crankshaft-type piston design with a sealed cylinder, deterioration of the wear bands is minimized and piston rod packing is not required. Therefore, component wear and associated maintenance should be significantly reduced.
- Mechanical Performance – Due to the many moving parts of a conventional reciprocating compressor, speed variation and flow capacity control make it difficult to avoid vibration problems. Each moving part has its own natural vibration frequency and

high-cycle fatigue limitation. The LMRC uses fewer moving parts, and thus, it is easier to design the system to avoid coincidence with component mechanical natural frequencies.

In addition to the advantages over conventional reciprocating machinery noted above, the LMRC is able to improve the efficiency of the hydrogen compression process by using low-friction bearings and optimized piston motion control.

The existing LMRC system uses low-pressure-drop contoured compressor valves, low-speed, piston motion control (no piston-crank mechanism) and inter-stage cooling to minimize parasitic losses. The LMRC was designed to meet an isentropic efficiency target of greater than 95%. That efficiency can be compared with current state-of-the-art technology that typically has an efficiency of closer to 73% [Deffenbaugh, 2005].

Stage one of the three stages was built and tested in 2020 (but hydrogen testing was not yet final at that time) with a single compression chamber design. Figure 2 is a screen shot of the configuration from a video/animation of the LMRC.

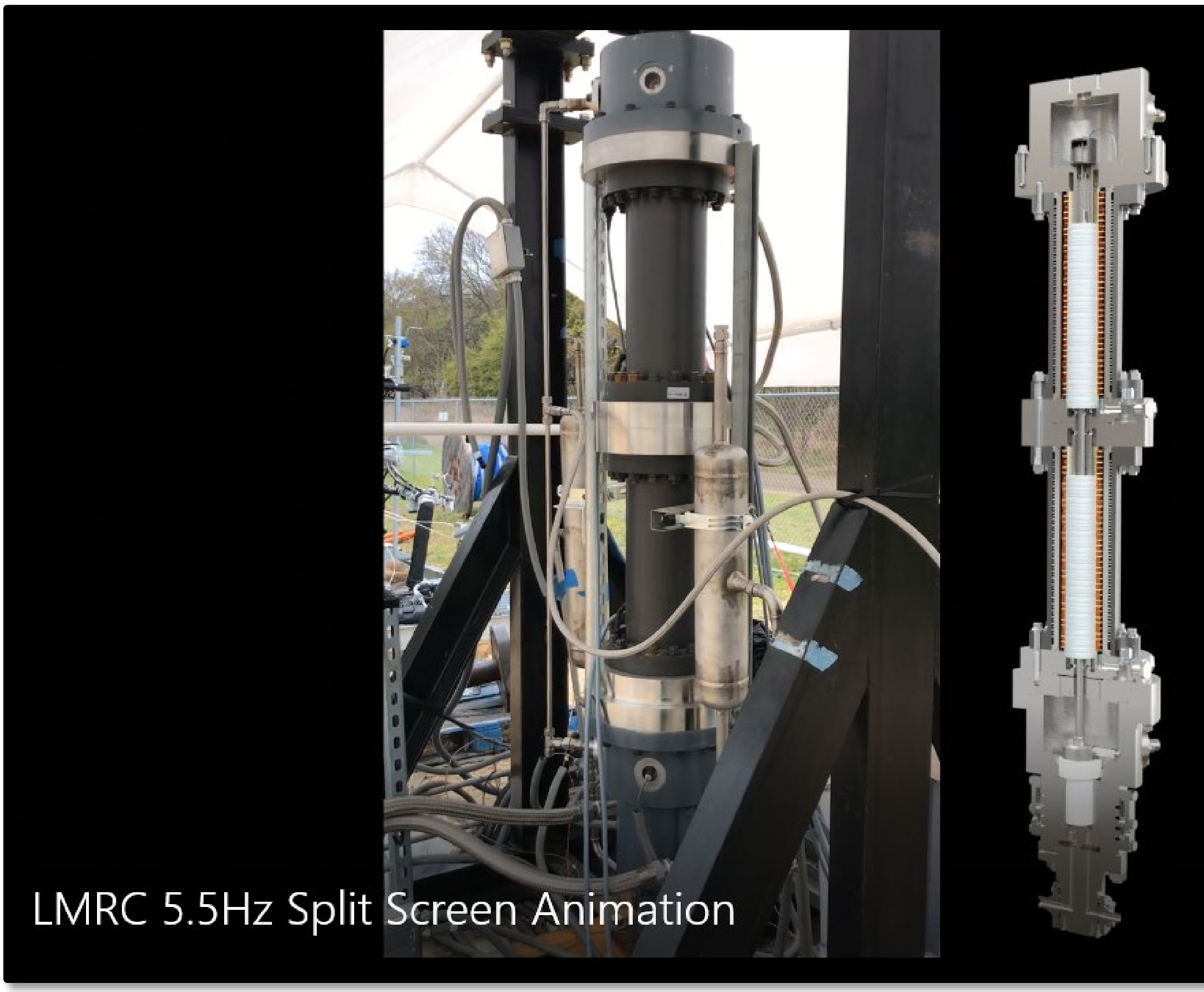

Figure 2. LMRC Mounted on Steel Frame at the Research Institute Test Facility [Shade, 2020]

Testing of helium and hydrogen gases was accomplished during the 2014-2020 LMRC research project, but the test plan was cut short due to failure of some of the permanent magnets in the linear motor. Upon investigation of the physical system and the available data from the relatively short test period, it was found that four main components of the LMRC design needed improvement or still needed to be evaluated. The magnet coatings and compressor valves needed improvement, and the ceramic-on-ceramic seal and the motion profile optimization needed to be evaluated. Unfortunately, the ceramic-on-ceramic seal testing was not completed prior to the completion of this paper, but sufficient testing of the other three components was complete in time to be included in this paper.

MAGNET COATINGS / PLATINGS

As noted previously, testing during the 2014-2020 LMRC research project was cut short due to failure of some of the permanent magnets in the linear motor. Coating/plating technology for magnets was challenged during the 2014-2020 project prior to the failure. A nickel-copper-nickel (Ni-Cu-Ni) coating (sometimes referred to as simply a nickel coating) is a standard coating for a conventional magnet. It was found during some pressurized hydrogen tests (at least 5,200 psi hydrogen at room temperature for at least three days) that hydrogen will not destroy a magnet that is thoroughly and completely coated with the nickel coating, which is why nickel-coated magnets were specified for the motor build that was tested in 2020. After encountering the magnet failure, sample nickel-coated ring magnets from the same batch of magnets that were used to build the motor were tested in a pressurized hydrogen gas chamber up to 1,100 psi (76 bar) at a temperature of 125°F (52ºC) for approximately 24 hours or more. All ring magnets failed the test. Each ring was approximately 3-inches (76 mm) in diameter, 0.5-inches wide (13 mm), and 0.25-inches (6 mm) thick. A microscopic exam was performed at SwRI for some of the not-tested magnets from the same batch of magnets that failed the testing, and the exam identified some areas of the magnets that were insufficiently coated or missing parts of the specified coatings, as noted in Figure 3. The bare surface was not visible to the naked eye.

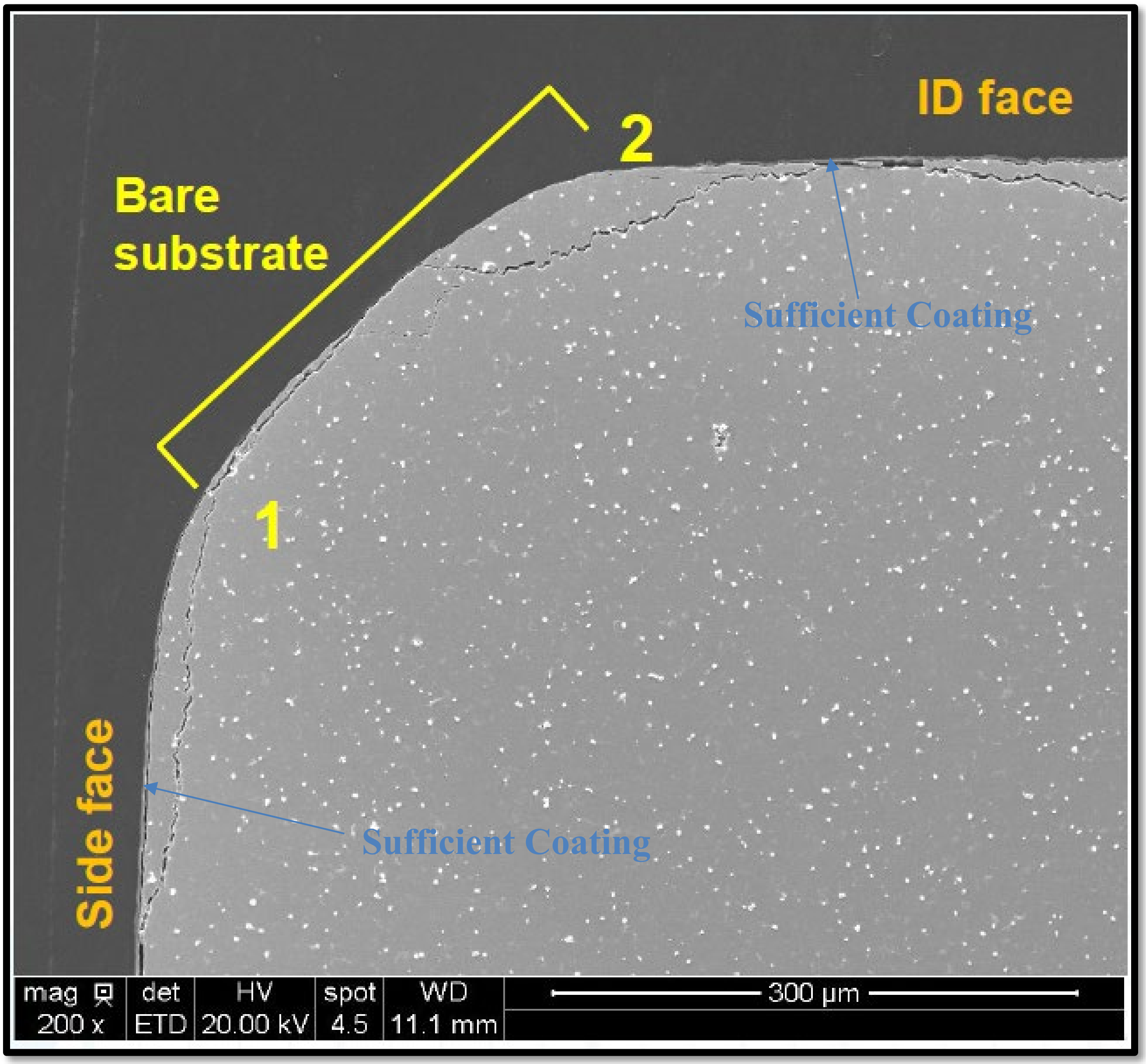

Figure 3. Magnified Image of Sectioned Magnet to Show Missing Coating (Bare Substrate)

Alumina Coating

It is known that alumina (Al_2O_3) is an excellent hydrogen barrier that can be applied as a coating on various materials, attributed to its exceedingly low hydrogen diffusivity for well consolidated, crystalline films. To test the likelihood of being able to use alumina as a magnet coating, two bare (uncoated) ring magnets were coated with approximately 2 μm of alumina using plasma enhanced magnetron sputtering (PEMS) of pure aluminum with an oxygen plasma (see example image in Figure 4), yielding stoichiometrically correct Al_2O_3.

Figure 4. Image of the plasma enhanced magnetron sputtering (PEMS) process for depositing refractory coatings

One of the magnets was placed in pressurized hydrogen, and the other was sectioned and prepared for a microscopic examination. The magnet placed in the pressurized hydrogen environment did not survive, and the microscopic examination observed areas of the other magnet that were not coated. It is known that alumina can be an excellent hydrogen barrier, but the coating process needs to be refined to ensure coating uniformity with no defects. Indeed, Nd readily forms hydride phases at modest temperatures that must be abated through application of a robust, defect-free coating.

Another ring magnet was coated with two layers of alumina in an effort to avoid any holidays (uncoated areas). The double alumina-coated magnet was immersed in pressurized hydrogen and found to once again fail the test. The result of the testing was a typical result that is shown in Figure 5.

Figure 5. Photo of Ring Magnet in Pieces (in a plastic bag) After Testing in a Pressurized Hydrogen Gas Environment

A final ring magnet, which was already nickel-coated, had two layers of alumina added to the magnet coating in an effort to avoid any holidays (uncoated areas) associated with the nickel-coating. This test also provides an evaluation of whether the alumina bonds better with the nickel than the bare magnet material. The nickel-coated and double alumina-coated magnet has not yet been immersed in pressurized hydrogen, so the effectiveness of this coating combination is not yet known.

Coating Process

In parallel with the new coating development, the coating process was investigated and developed. It was determined from hydrogen pressure test results that the larger nickel-coated magnets typically do not survive the tests, but the smaller nickel-coated magnets typically do survive the tests. An example arc magnet (see left side of Figure 6) that was destroyed (failed) as a result of the hydrogen testing is pictured on the right side of Figure 6. After discussing this issue with the magnet manufacturer, it was discovered that there are different coating processes for the different size magnets. The processes are either a barrel plating process (smaller arc magnets) or spray deposition plating process (larger ring magnets). Knowing this issue existed based on the plating/coating process, the magnet array design for the new translators was modified to only include smaller arc magnets to avoid using the significantly less reliable spray deposition plating process. The new magnet array design included six different styles/models of magnets. Magnets were ordered, which are long-lead items, with at least a 10% excess order for each of the six magnet models, in hopes that at least 90% of the magnets would survive the pressurized hydrogen gas environment.

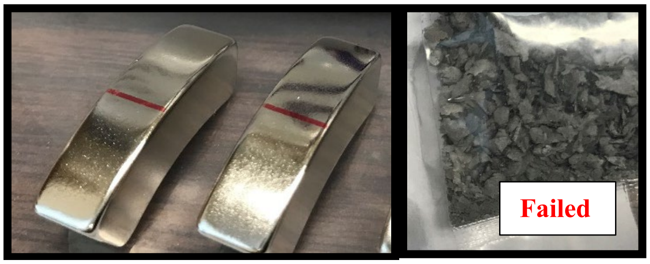

Figure 6. Photo of Magnets Before (left) and After (right; Failed) Testing in a Pressurized Hydrogen Gas Environment

After the magnets arrived, testing of the magnets included an approximately 24 hours test in approximately 1,100 psi pressurized chamber of hydrogen gas maintained at a temperature of approximately 125°F. Initial tests in the pressurized hydrogen environment included just a few magnets. If an insufficient number of magnets did not survive, the plan would be to focus on the new coating development, which could then be applied to the large quantity of magnets that are needed for the translators. However, the initial test results were encouraging. Subsequent tests included larger batches of magnets, and the later rounds of testing included hundreds of magnets. It was found that 90.3% to 100% of each magnet model survived the pressurized hydrogen environment. Photos of some of the magnets before and after the testing are included in Figure 7. Some tarnishing of the magnet coatings can be seen, but the magnets remained intact. It was concluded that the nickel coating is a sufficient magnet coating, so the rebuild of the translators was performed with the nickel coated magnets.

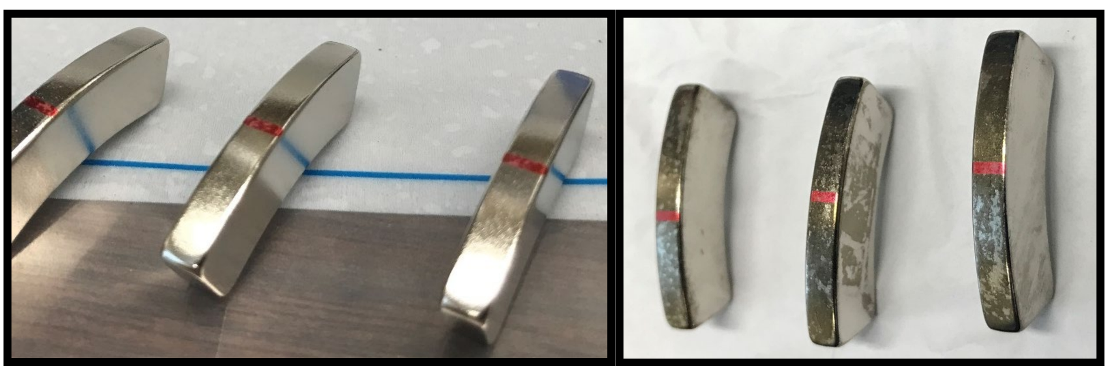

Figure 7. Photo of Magnets Before and After Surviving Testing in a Pressurized Hydrogen Gas Environment

To be able to perform additional testing of the magnets in the pressurized hydrogen environment, ten magnets of each magnet model were kept at SwRI while the magnet count that was needed to build the translators was shipped to the motor manufacturer (in the United Kingdom). Additional testing included 21 cycles of pressurized and de-pressurized hydrogen. Each pressurized phase of the cycle lasted approximately 24 to 72 hours. The cycling was done primarily to see if or when any of the magnets failed, but it was also a good test to see if the magnets will have issues with the pressurization and depressurization of the compressor. All sixty magnets surviving the 21 cycles, which amounted to 711 hours in pressurized H2. To conserve funding, further testing of the magnets was halted after this successful result.

VALVES

Evaluating data from one of the hydrogen tests in 2020 (prior to the period when the compressor seemed to be operating with a significant influence on the magnet failures), it was calculated that the compressor was operating at a pressure ratio of approximately 2.2, with suction and discharge pressures of approximately 311 psia (21 bar) and 686 psia (47 bar), respectively. Flow rate during this period reached a maximum of 0.14 lb_m/min (or 3.9 kg/hr), and compressor cycle speed was approximately 208 cpm. The calculated isentropic compression efficiency of a measured PV card was approximately 84%. It should be noted that the operating pressures and pressure ratio were not at the project goals. After analyzing the data, it was determined that part of the deviation from an ideal compressor performance was the result of excessive leakage of the compressor valves, which was also observed during benchtop testing of the valves with a simplified leakage test rig.

Valve design, particularly aspects that will impact leakage while the valves are closed, was seen as a key to improving the compressor performance. Valve design modifications in 2021 focused on reducing valve leakage and improving gas flow aerodynamics. Design changes to reduce valve leakage were developed based on experience and knowledge gained from recent testing. Specifically, from a comparative study of the suction and discharge valves, it was identified that the discharge valve had significantly better sealing performance than the suction valve. Therefore, where issues were identified on the suction valve, it was redesigned and modified to more closely match the discharge valve design.

First, from initial observations of the previous suction valve design it was determined that there was an alignment issue between the seat and the poppet. This mis-alignment was caused by an error in placement of an alignment pin. To address this issue, the design was modified to remove the alignment pin, and instead more closely resemble the discharge valve design for assembly, which maintained alignment of the two components through concentric design features, including use of a threaded connection of the guard and seat.

Next, a comparison of the design features between the two valves identified that the sealing surfaces on the seats of each valve were different. That is, on the suction valve, the poppet would seal against a chamfer surface on the seat, whereas on the discharge valve the sealing surface of the seat was a radius or fillet. As such, it was decided that modifying the suction seat to have a radius or fillet surface should lead to a better and more consistent seal.

Design changes to both of the above areas is expected to improve the overall sealing efficiency of the suction valve. In order to improve the flow performance of the valves, additional gas flow aerodynamic improvements were developed with the help of CFD tools. One of the aerodynamic modifications that was made included rounding the shoulder of the poppets in both valves (as shown in Figure 8), to reduce the sharp corner that gas would have to flow around.

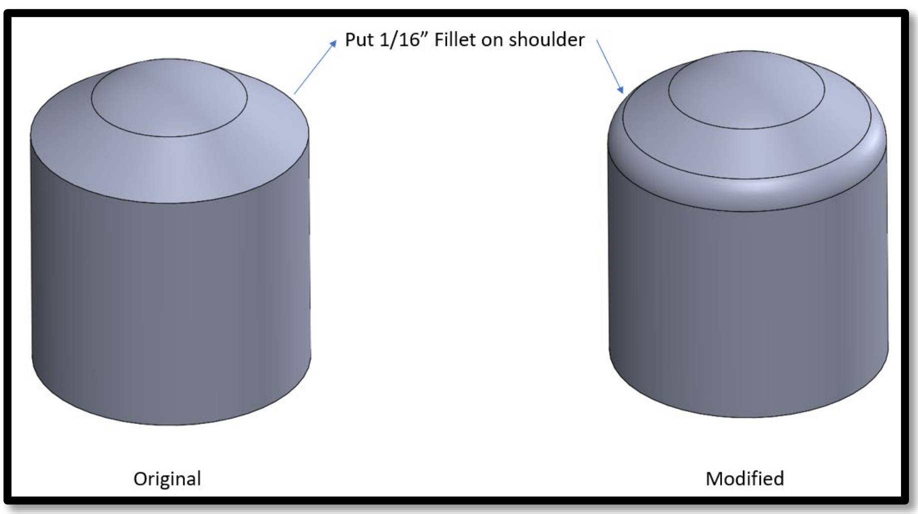

Figure 8. Poppet Shoulder Modification

On the discharge valve, two additional modifications were also implemented. First, it was determined that as the discharge poppet opened, the choke position (the location of smallest flow area) would transition from the area between the poppet opening to the inlet throat of the valve. It was decided that this movement of choke location could be leading to flow instabilities and valve flutter. Therefore, the inlet throat area was increased so that the choke location remains at the valve opening regardless of poppet position.

Next, it was determined that with the previous design, the flow area immediately downstream of the poppet opening actually went through a rapid expansion, followed by a contraction as the flow went around the shoulder of the poppet to the annular flow area between the walls of the poppet and the seat. To improve the aerodynamics in this region, in addition to rounding the shoulder of the poppet (as discussed earlier), a change to the valve seat was made that kept the flow area in this region to a consistent, smooth expansion from the poppet area to the annular space. An image of the previous/initial design and modified design is shown in Figure 9. The final design iteration of the discharge valve is shown in Figure 10, which indicates the velocity contours on a slice of the valve’s axial flow profile.

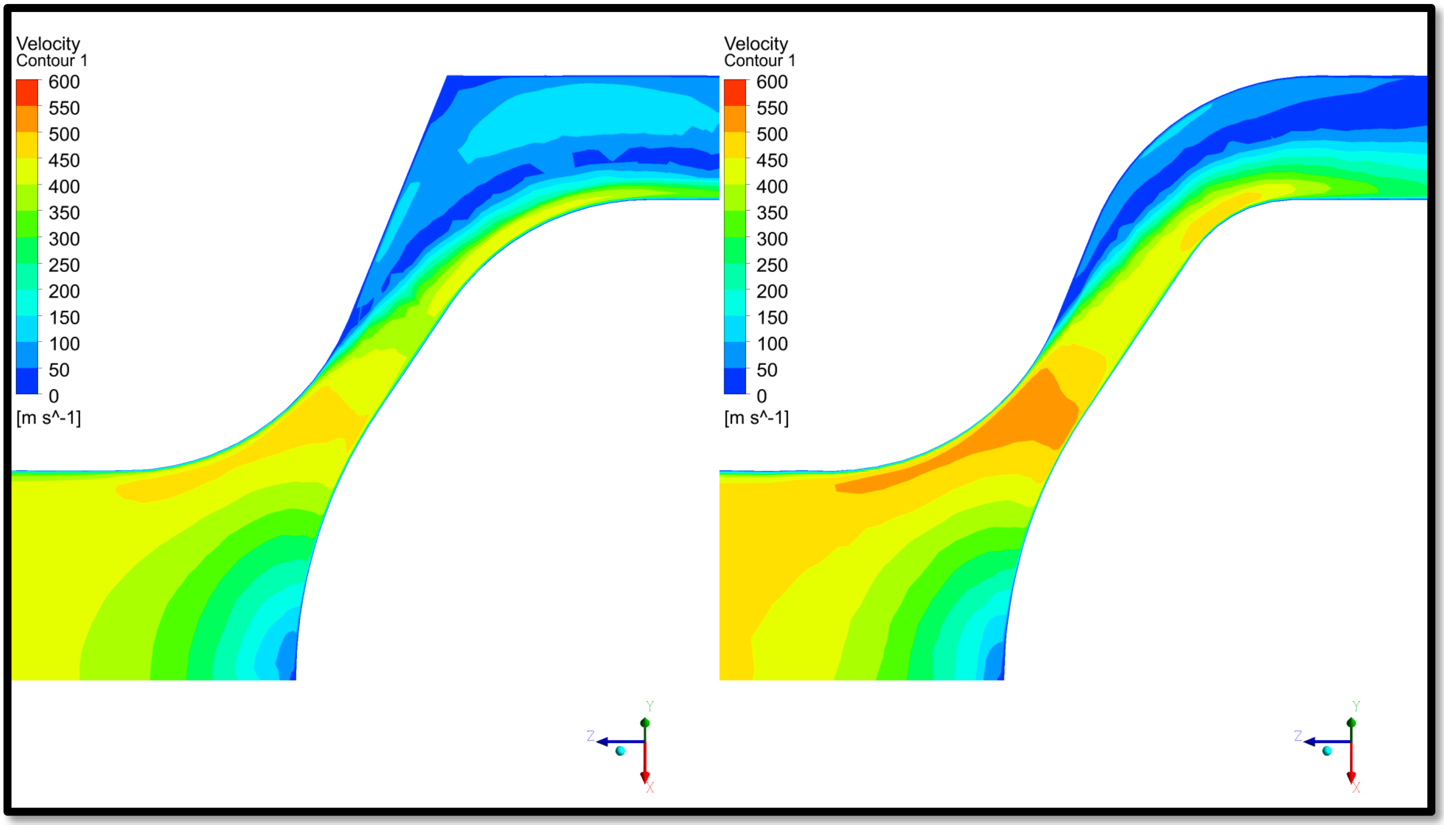

Figure 9. Discharge Valve CFD Velocity Contour Plots for Initial (left) and Final (right) Valve Designs

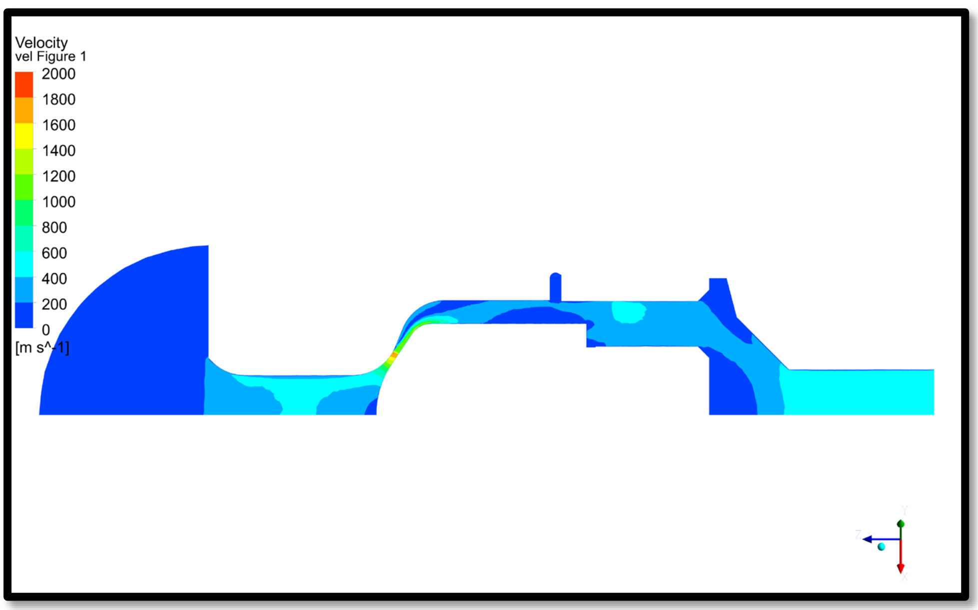

Figure 10. Predicted Velocity Flow Contour for Final Discharge Valve

MOTION PROFILE DEVELOPMENT & TESTING

Testing in 2020 was cut short, so motion profile optimization did not occur. However, it was determined at the time that a customized profile would be possible using the linear-motor design. This customized profile would differ from conventional reciprocating compressor profiles, as shown in Figure 12, to reduce the speeds of the piston during the suction and discharge events, thereby reducing the energy losses resulting from high velocity flow through the valves.

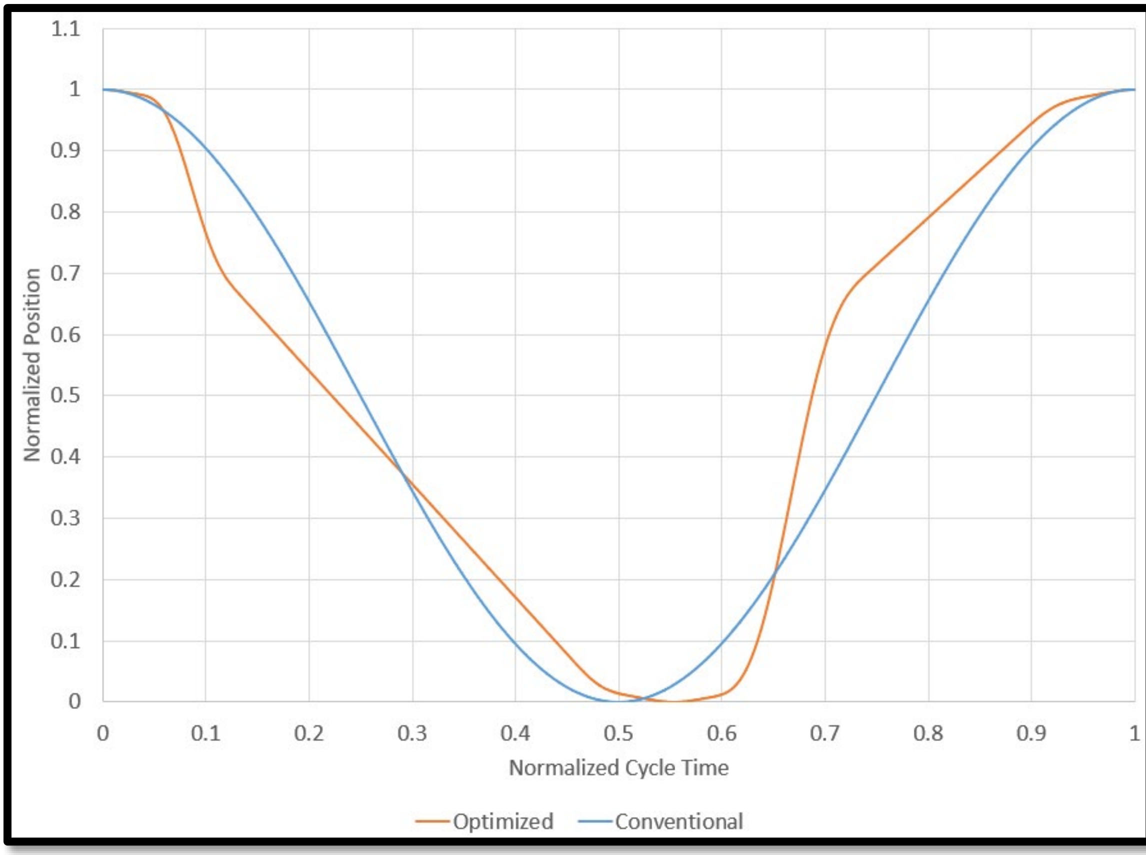

Figure 11. Comparison of Optimized to Conventional Reciprocating Motion Profiles

In the 2020 testing, this profile was proven possible, although at the time, it was not met exactly, as shown in Figure 12 for Test 2662. In this earlier test, the velocities of the suction and discharge events were not met exactly, and the system dwelled too long at the end points. This led to lower than desired system speed, as well as much higher electrical demand.

Improvements made to the PID algorithms, and the software feed-forward definitions have resulted in more reliable operation. In the latest testing campaign, these improvements have allowed for better matching of the desired velocities as shown by the Test 2828 curve, in Figure 12. It was, however, determined that trying to maintain the dwell times at the end of the strokes was not ideal for electrical operation, so they have been effectively eliminated from the profile by allowing the system to turn around sooner than originally desired.

In terms of the performance gain using the optimized profile, both the conventional and optimized profiles shown in Figure 11 were used as target profiles of the LMRC. The comparison of the resulting PV cards is shown in Figure 13 below. In this comparison, some of the benefits obtained are demonstrated. In particular, during the actual suction and discharge events, the profile is much flatter in the optimized profile as compared to the conventional profile. This is a result of the piston speed during these events being controlled to a constant velocity. This also leads to lower peak and mean pressure differences across the valves because of the selected velocities. Additional modification to the optimized profile could result in even lower discharge pressure differences.

The performance of these PV cards is quantified in terms of the isentropic efficiency, which compares the work indicated by the ideal curves compared to the corresponding actual measured curves. In this case, the conventional profile has an isentropic efficiency of approximately 93.6%, whereas the optimized profile was calculated to have a 97.5% efficiency. Both efficiencies are considered high compared with conventional reciprocating compressors, and are largely considered a result of the low speed of operation used in these cases [Deffenbaugh, 2005]. The efficiency measured in both tests are considerably higher than the 84% efficiency measured during the 2020 operation of the LMRC [Broerman, 2021]. In both of these 2022 tests, the speed of the unit was approximately 420 cpm. New standard reciprocating compressor packages have speeds of twice this or more, and the actual target speed of the LMRC was 330 cpm.

During these two tests, even though the cycle speeds of both tests were similar, the gas flow rate in the test loop was marginally higher for the optimized profile. Flow when running the optimized profile reached 0.155 lbm/min (70.3 g/min), but the flow maxed out at 0.149 lbm/min (67.6 g/min) when running the conventional profile. Unfortunately, this flow rate, when adjusted to the target speed of 330 cpm, is below the original target rate, which seems to indicate higher than anticipated leakage rates across the dynamic seal and/or cylinder valves.

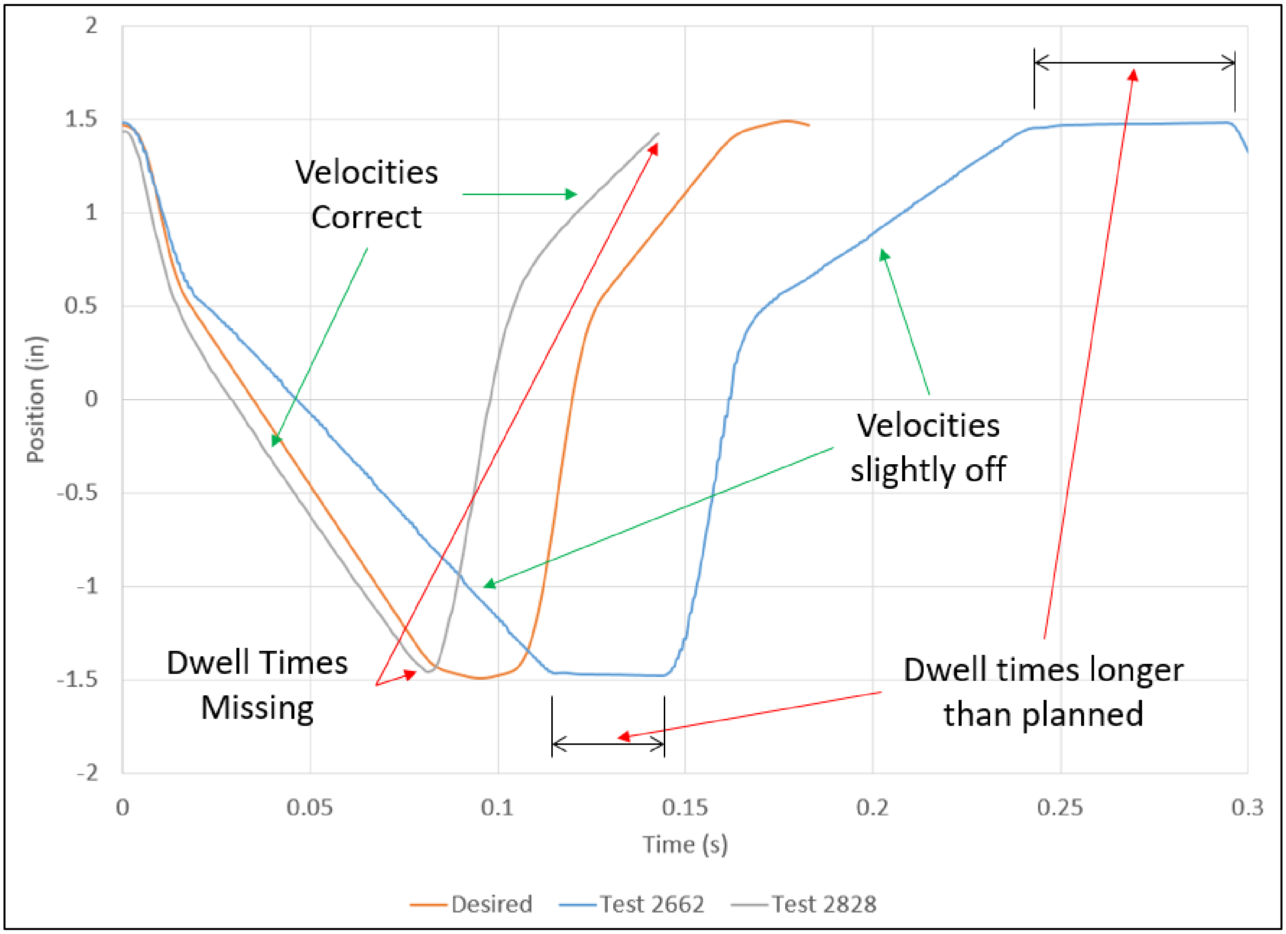

Figure 12. Comparison of Desired to Actual Operating Motion Profiles

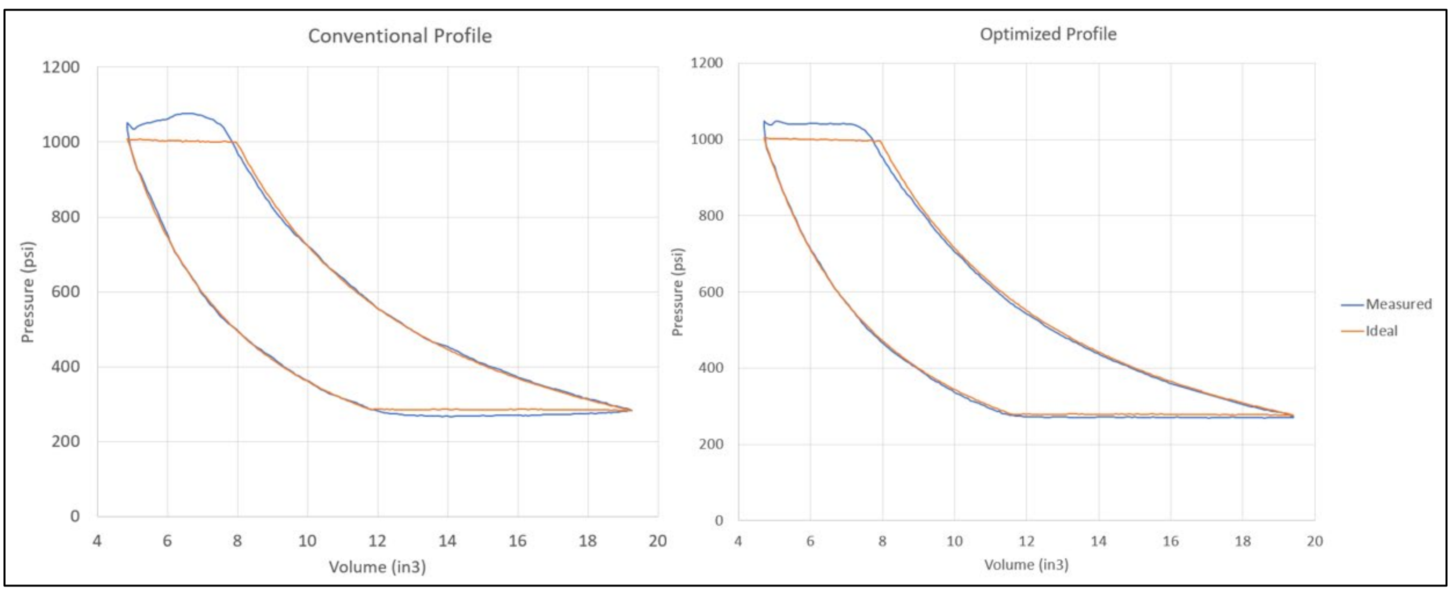

Figure 13. Comparison of Conventional and Optimized Profile Performances

CONCLUSIONS

Improvements were made to the LMRC magnets coating, valves re-design, and motion profile development. Testing in mid-2022 resulted in successful operation of the compressor even when compressing hydrogen, which means the magnets did not fail in the pressurized hydrogen environment. The key improvement that allowed additional compressor operation time and will allow future refinement of system challenges was the development of a magnet coating that has successfully kept the magnets intact throughout hours of testing with hydrogen gas. Valve design alterations showed reduced leakage during static bench testing and helped achieve isentropic efficiency better than the 95% target. Motion profile development and optimization also helped improve the efficiency to a value beyond the 95% target. Test measurements indicated a compression efficiency of 93.6% to 97.5% efficiency, depending on the chosen motion profile. Both efficiency values are greater than the 84% efficiency measured during the 2020 operation of the LMRC, which is likely a combined result of improvements on the valve designs and better control leading to more accurate matching of the target piston profiles. Optimizing the motion profile was observed to provide nearly a 4% efficiency advantage over a conventional reciprocating compressor. The 2022 testing has confirmed that hermetically sealed linear motor reciprocating compressor (LMRC) can be designed and developed to efficiently compress hydrogen gas.

Future development plans of the linear motor include:

1. A high-force, high-efficiency "slotted stator" EM design enabling each LMRC cylinder to be constructed using a single stator assembly, and offering a reduction in system mass, size and cost.
2. Integrated gas bearing systems making use of the LMRC's working gas to eliminate the friction and wear associated with sliding contact bearings.
3. A simplified housing and sealing construction for improved thermal performance, cost and compactness.
4. A new, flexible, and more powerful Drive Control Unit (DCU) architecture comprising separate Motion Control Unit (MCU) and ServoDrive Unit (SDU) control cabinets powering LMRC systems with up to four movers.

Additional development of the LMRC could include dynamic seal re-design to minimize leakage, durability testing of the dynamic seal and compressor valves, and advanced optimization of the motion profile. In addition to being highly relevant to the hydrogen gas economy, the LMRC is considered relevant and applicable to most gas compression industries.

For accomplishing the future application of the LMRC for hydrogen compression aimed at heavy-duty commercial hydrogen refueling for fuel-cell vehicles (compression of hydrogen from 435 psia (30 bara) to 13,320 psia (918 bara)), four identical modules each comprised of four inter-cooled stages of double-acting compression would be proposed. Calculations using a speed of 990 CPM and a compression ratio of 2.37 for each stage, indicate that the first stage of compression will utilize the same first stage cylinder bore as the system described in this paper, with the stroke increased to 6.0-inches. This stage sizing allows the LMRC to meet the heavy-duty commercial hydrogen refueling flow goal of greater than or equal to 10 tons/day. One potential layout for the entire 10+tons/day system could be as depicted on the left side of Figure 14. Each circled number in Figure 14 represents a double-acting, single-stage, and vertically-mounted LMRC. Transverse stage manifolds serve each 4-stage LMRC module. Modular heat exchanger packs are associated with each 4-stage LMRC module. There are common power, control and cooling services. Construction could facilitate swap-out of individual modules. Being able to swap-out individual modules would minimize downtime and allow custom system scaling for varying site needs, as depicted by the three options in Figure 14.

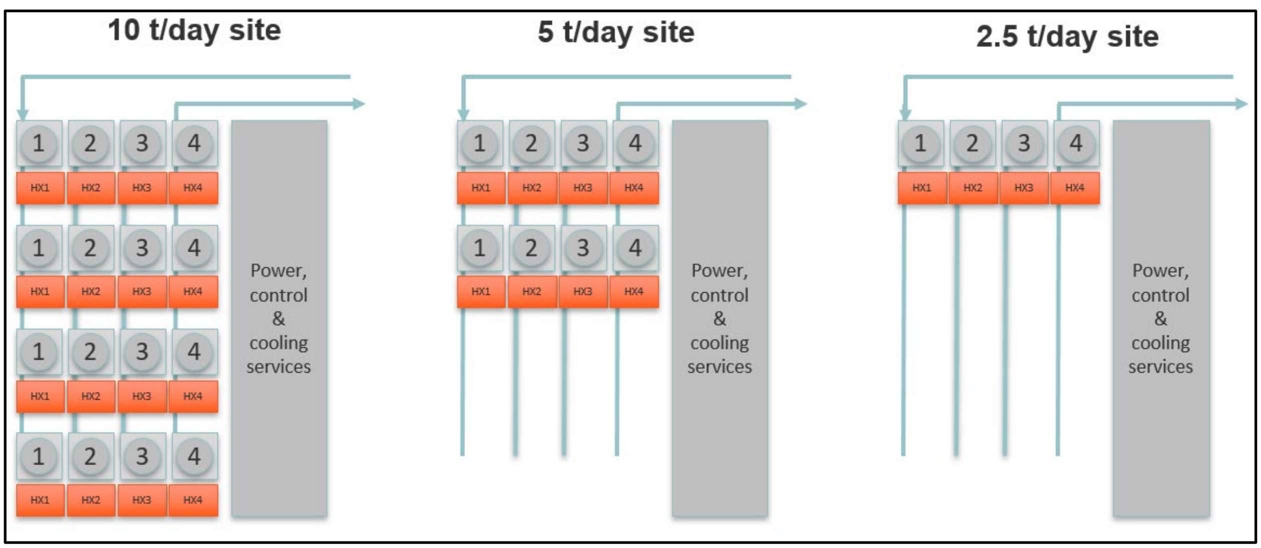

Figure 14. Modular Architecture can be Scaled Per Site

Application of the LMRC for other gas compression applications can also be accomplished with a similar approach. The design bore and stroke would need to be altered to fit the specific application, but the general design would remain unchanged. The envisioned modularization aspect of the design is also a beneficial characteristic that can result in efficient capacity control, ease of maintainability and relatively lower cost resulting from higher production quantities of standard components..

NOMENCLATURE

ACI	= ACI Services, Inc.
Al_2O_3	= alumina
CFD	= Computational Fluid Dynamics
cpm	= cycles per minute
DOE	= Department of Energy
LMRC	= Linear Motor Reciprocating Compressor
Ni-Cu-Ni	= nickel-copper-nickel
PEMS	= plasma enhanced magnetron sputtering
PID	= Proportional-Integral-Derivative
SwRI	= Southwest Research Institute

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