# Hydrogen Compression Application of the Linear Motor Reciprocating Compressor

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## Overall Objectives

- Develop and evaluate the linear motor reciprocating compressor (LMRC) by integrating individually developed components.
- Achieve a higher efficiency than conventional reciprocating compression using an LMRC that also has lower capital and maintenance costs.
    - Improve isentropic efficiency above 73% by minimizing aerodynamic losses and using low-friction bearings (goal is above 95%).
    - Reduce capital costs to half those of conventional reciprocating compressors by minimizing part count.
    - Reduce required maintenance by simplifying the compressor design to eliminate common wear items.
- Meet the design requirements for all three stages of compression: compress hydrogen from 290 psia (20 bar) to 12,690 psia (875 bar) with flow rates greater than 22 lbm/h (10 kg/h) and an isentropic efficiency of compression above 73%.
- Meet the test requirements for the first stage of compression: compress hydrogen from 290 psia (20 bar) to 1,030 psia (71 bar) with flow rates greater than 22 lbm/h (10 kg/h) and an isentropic efficiency of compression above 73%.
- Meet the Fiscal Year (FY) 2018 additional test requirement for the first stage of compression: achieve an overall system specific energy of 1.6 kWh/kg or lower.

## FY 2018 Objectives

- Commission bench-scale system.
- Test the bench-scale system.
- Analyze the single stage test results.

## Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRDD) Plan[1]:

(B) Reliability and Costs of Gaseous Hydrogen Compression.

## Technical Targets

During the proposal phase and kick-off of the project, the DOE technical targets were based on the 2012 MYRDD Plan. A 2015 MYRDD Plan was updated in August of 2015. Table 1 compares the predicted characteristics of the LMRC design with 2020 targets from both MYRDD reports.

## FY 2018 Accomplishments

- Commissioned bench-scale system.
- Tested the bench-scale system.
- Analyzed the single stage test results.

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

Table 1. Progress Toward Meeting Technical Targets for Hydrogen Delivery with Small Compressors: Fueling Sites (~100 kg $H_2$/h peak flow)

| Characteristic | Units | 2015 MYRDD Target for 2020 | LMRC 2020 Status (Predictions) |
|---|---|---|---|
| Reliability | | NA | High |
| Availability | % | ≥85 | TBD |
| Compressor Efficiency | isentropic % | NA | 80% – all three stages |
| Compressor Specific Energy | kWh/kg | 100 bar inlet: 1.6<br>500 bar inlet: 1.4 | 100-bar inlet pressure:<br>1.45 (projected to be achievable given optimizations to LMRC) |
| Loss of Hydrogen Throughput | % of flow | 0.5% | <0.4% |
| Uninstalled Capital Cost (based on 750 kg/d station, ~100 kg $H_2$/h peak compressor flow) | $ | 100-bar inlet: $275,000<br>500-bar inlet: $90,000<br>(1 compressor, no backup) | 100-bar to 875-bar inlet: $195,000<br>500-bar inlet: $105,000<br>(1 compressor, no backup) |
| Annual Maintenance Cost | % of installed capital cost | 4% | 1.2% of uninstalled capital cost |
| Outlet Pressure Capability | bar | 950 | 875 |
| Compression Power | kW | NA | 170 (20 bar at inlet)<br>(compressor required power) |

NA – not applicable

TBD – to be determined

100-bar inlet – pipeline delivery of gas to the compressor

500-bar inlet – tube trailer delivery of gas to the compressor

## INTRODUCTION

Southwest Research Institute and ACI Services, Inc. are developing an LMRC to meet DOE's goal of increasing the efficiency and reducing the cost of forecourt hydrogen compression. The proposed advanced compression system utilizes a novel and patented 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, reduces leakage paths, and is easily modularized for simple field installation [1].

## APPROACH

The LMRC is a novel concept compared to conventional reciprocating compression technology. The compression system replaces the functions of an electric motor drive and reciprocating compressor with an integrated, linear, electrically actuated piston. The LMRC design includes a magnetic piston within a cylinder and a gas compression chamber at each end of the piston. The compressor cylinder comprises an electromagnetic coil that operates with the piston to convert an input of electrical power to a reciprocating movement of the piston. This uses the same technology seen in magnetic bearings of turbomachinery and does not require oil for lubrication. Since the driver and compressor are integrated into the same hermetically sealed component, there is a significant reduction in the number of parts and materials needed to construct this device. In addition, the simplicity of the design reduces required maintenance, minimizes seal leakages and wear, and allows for oil-free operation.

The LMRC system minimizes parasitic losses by using: reduced piston speeds, low-pressure-drop contoured valves, and inter-stage cooling manifolds. Working at low reciprocating speeds of approximately 300 cycles per minute (5 Hz), the LMRC prototype is expected to meet an isentropic efficiency goal of greater than 95% per stage [2]. That efficiency can be compared with current state-of-the-art technology that typically has an efficiency closer to 73%. The improved isentropic efficiency and reduced mechanical losses result in an increase in overall efficiency for the LMRC system.

## RESULTS

Initial commissioning efforts revealed that due to a hardware change in the control circuitry made to protect the electric driver, the ability to switch the polarity of the current flows was limited to no faster than ~10 ms. Regardless, a timed sequence of duty cycles was successful in generating cyclic motion of the LMRC. Initial tests with this sequence compressing nitrogen gas rarely ran for more than 2–3 simultaneous cycles before the piston was unable to move far enough past the zero-force point near the middle of the stroke to successfully complete the stroke, and the piston would subsequently become stuck. One example of this issue is shown in Figure 1.

The next test step used helium as the test gas instead of nitrogen. Results revealed that the piston traveled much more freely than with the nitrogen, such that greater lengths of travel would occur for similar inputs of energy. Alternatively, the same amount of travel could be achieved with lower inputs of energy. This is due to the flow performance of the compressor valves and other flow-restricting devices with the smaller molecular size of the helium gas. As a result, longer continuous operation (i.e., a greater number of simultaneous cycles) could be obtained. Subsequent testing was performed to improve the performance of the LMRC by optimizing the performance of the electrical controls and timing of the software controls system.

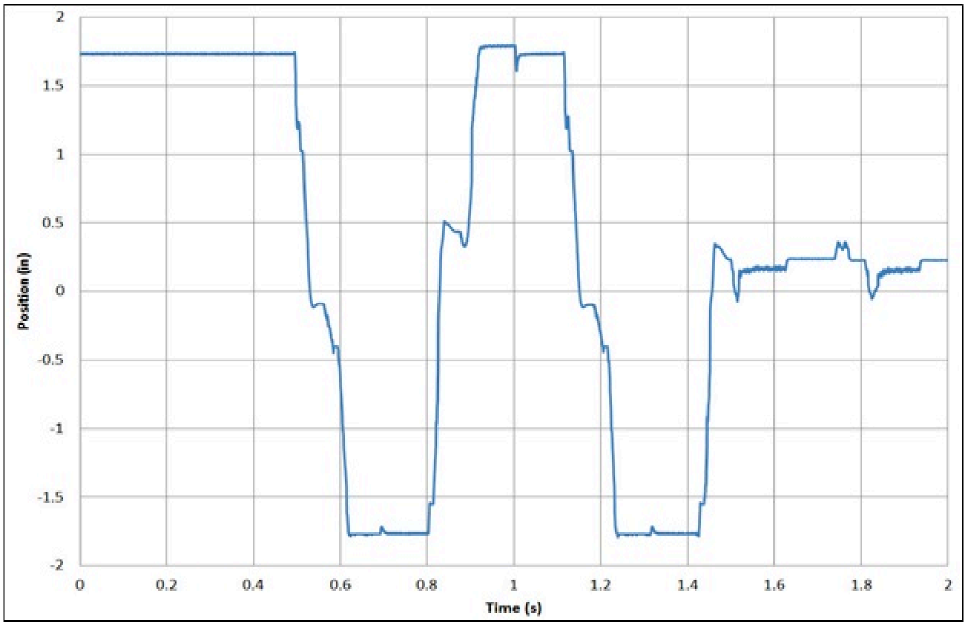


Figure 1. Commissioning issues: failed continuous cycle

Successful operation of the compressor was achieved with the use of helium as the working fluid after performing the numerous modifications to the system to resolve or improve the commissioning issues. One example of these tests in shown in Figure 2. At this point, the compressor was running at about 280 cycles per minute, with a compression ratio of 3.76 (suction line pressure of 73 psia and discharge line pressure of 274 psia).

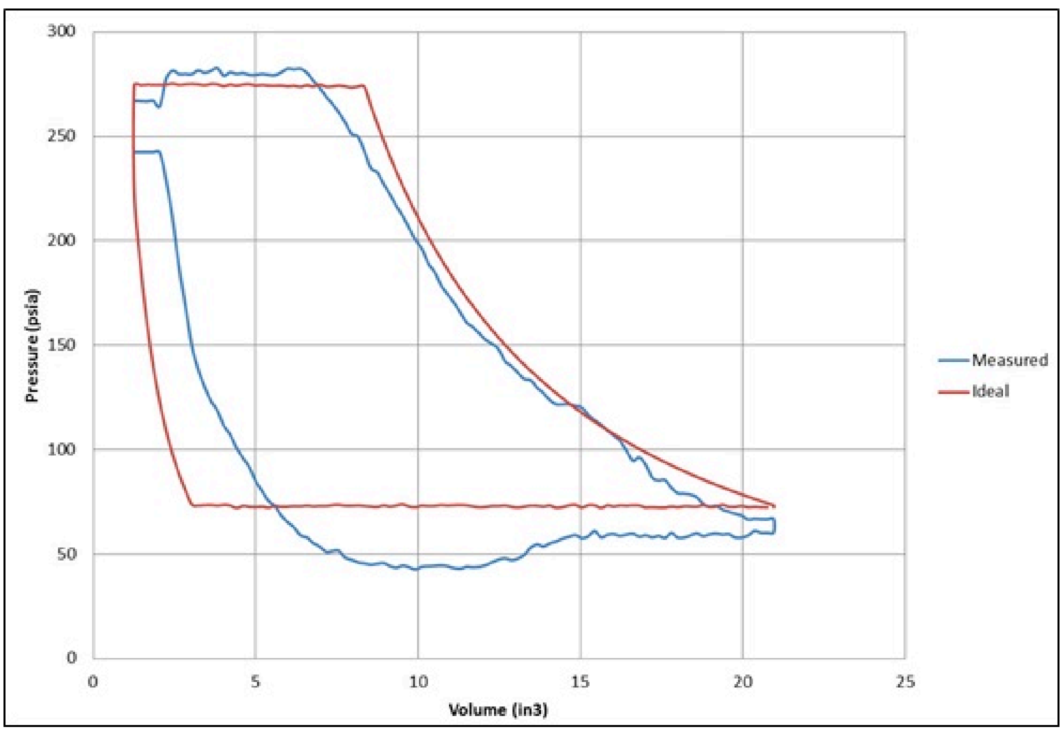


Figure 2. Pressure-volume (PV) card for helium

Of the testing performed with hydrogen gas, the test case that came the closest to the design conditions is presented in Figure 3. For this test, the compressor was operating at 456 cycles per minute, a compression ratio of 3.5 (suction pressure at 137 psia and discharge pressure at 478 psia), and flow rate of approximately 8.2 kg/h.

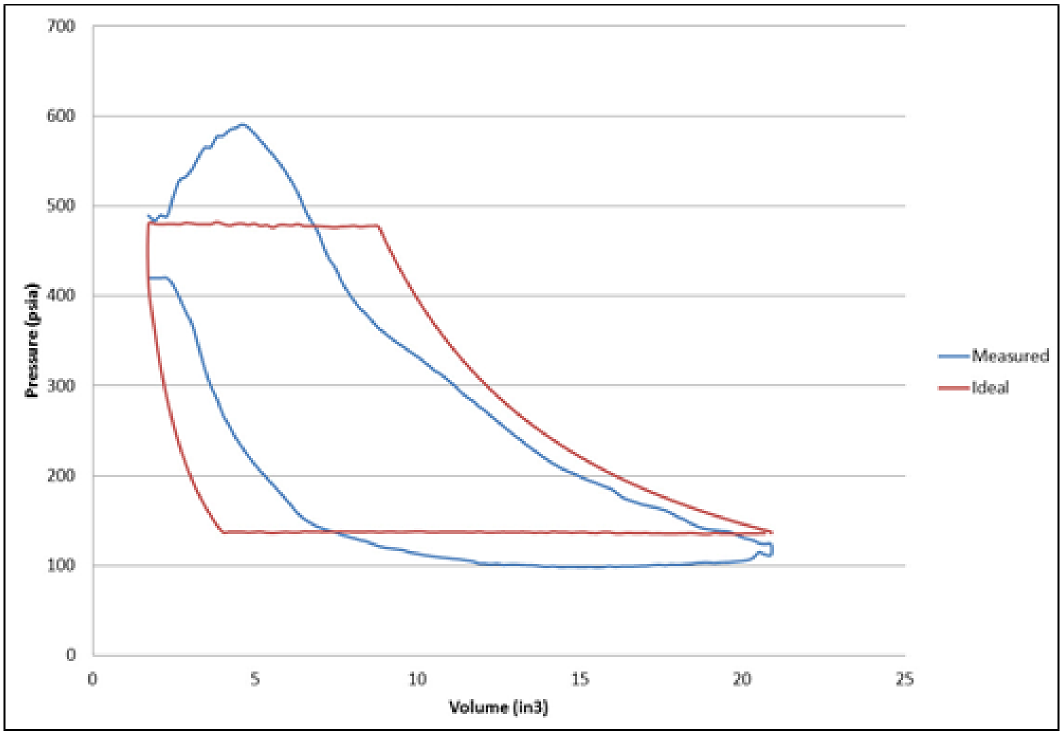


Figure 3. PV card for hydrogen

## CONCLUSIONS AND UPCOMING ACTIVITIES

Conclusions derived from the work conducted in FY 2018 are:

- Testing indicates that high-efficiency hydrogen compression is possible with an LMRC used for the compression process. Modifications to the LMRC will be needed to achieve target efficiencies.
- Inconsistent currents, “slow” switching speeds (due to performance issues with the electronics controller), and inaccurate position measurements led to inaccurate motor control.
- Inaccurate motor control prevented the LMRC from achieving the goals.

Future work in Project Year 5 (FY 2019; Budget Period 3) will include:

- Redesign the motor portion of the low-pressure LMRC such that the overall system will have a specific energy significantly closer to 1.6 kWh/kg
- Fabricate and assemble the more efficient low-pressure LMRC
- Commission the test bench using an inert gas and following the plan previously defined
- Complete testing of improved LMRC system according to the defined test matrix with hydrogen
- Analyze the results from the improved low-pressure system testing.

## REFERENCES

1. U.S. Patent 8,534,058. Issued Sept. 17, 2013. "Energy Storage and Production Systems, Apparatus and Methods of Use Thereof." Patented in United States of America.
2. D. Deffenbaugh, et al. "Advanced Reciprocating Compression Technology." DOE Award No. DE-FC26-04NT42269, Southwest Research Institute Contract No. 18.11052, December 2005.