
Hydrogen Compression Application of the Linear Motor Reciprocating Compressor

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Subcontractor:
ACI Services, Inc., Cambridge, OH

Project Start Date: September 5, 2014
Project End Date: September 4, 2020

Overall Objectives

- Demonstrate the linear motor reciprocating compressor (LMRC) by integrating individually developed Technology Readiness Level 4 or higher components.
- Demonstrate that the compressor portion of the LMRC has improved compression efficiency and a reduced capital and maintenance cost compared to conventional reciprocating compression technology.
 - 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 bara) to 12,690 psia (875 bara) 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 bara) to 1,030 psia (71 bara) 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 test requirements for the first stage of compression: compress hydrogen from 290 psia (20 bara) to 1,030 psia (71 bara) with flow rates greater than 22 lbm/h (10 kg/h) and an overall system specific energy of 1.6 kWh/kg or lower.

Fiscal Year (FY) 2019 Objectives

- Develop an adapter section to mate the Libertine linear motor design with the existing compression chamber.
- Modify the Libertine linear motor design to be suitable to contain pressurized hydrogen.
- Rebuild the compression chamber such that it is confirmed to be ready for the future testing.
- Fabricate and purchase the necessary parts to assemble the newly designed Libertine linear motor with the rebuilt compression chamber.
- Commission the motor at Libertine.
- Commission and start up the demonstration test loop at Southwest Research Institute (SwRI).
- 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) Plan¹:

- 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.

This project is developing and testing a new compressor designed to compress hydrogen more efficiently, reliably, and cost effectively in an effort to meet the following DOE hydrogen compression targets:

- Compressor specific energy with a 100-bar inlet pressure: 1.6 kWh/kg
- Availability: $\geq 85\%$

- Uninstalled capital cost with a 100-bar inlet pressure: \$275,000
- Annual maintenance cost: $<4\%$ of installed capital cost.

FY 2019 Accomplishments

- Developed an adapter section to mate the Libertine linear motor design with the existing compression chamber.
- Modified the Libertine linear motor design to make it suitable to contain pressurized hydrogen.
- Rebuilt the compression chamber such that it is confirmed to be ready for future testing.
- Fabricated and purchased the necessary parts to assemble the newly designed Libertine linear motor with the rebuilt compression chamber. The only part that is not yet complete, due to manufacturing delays, is the translator shaft that will have permanent magnets fastened to it.

¹ <https://www.energy.gov/cere/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 H₂/h peak flow)

Characteristic	Units	2012 MYRDD Target for 2020	2015 MYRDD Target for 2020	LMRC 2020 Status (Predictions)
Reliability		High	NA	High
Availability	%	NA	≥85	TBD
Compressor efficiency	Isentropic %	80%	NA	80%—all 3 stages
Compressor specific energy	kWh/kg	100-bar inlet: NA 500-bar inlet: NA	100-bar inlet: 1.6 500-bar inlet: 1.4	20 bar to 875 bar: 1.8 (compressor only) 9.4 (LMRC) 100-bar inlet pressure: 1.45 (optimized LMRC)
Losses of H ₂ throughput	% of flow	<0.5%	0.5%	<0.4%
Uninstalled capital cost (based on 1,000 kg/d station [~100 kg H ₂ /h peak compressor flow])	\$	\$240,000 (one compressor, no backup)	NA	20 bar to 875 bar: \$284,000 (one compressor, no backup)
Uninstalled capital cost (based on 750 kg/d station [~100 kg H ₂ /h peak compressor flow])	\$	NA	100-bar inlet: \$275,000 500-bar inlet: \$90,000 (one compressor, no backup)	100 bar to 875 bar: \$195,000 500-bar inlet: \$105,000 (one compressor, no backup)
Annual maintenance cost	% of installed capital cost	2.0%	4%	1.2% of uninstalled capital cost
Outlet pressure capability	bar	860	950	875
Compression power	kW	240 (20 bar at inlet)	NA	170 (20 bar at inlet) (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

SwRI, ACI Services, Inc. (ACI), and Libertine FPE Limited are developing an LMRC to meet the DOE 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 (U.S. Patent 8,534,058) [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. It will have 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 is operable 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 in 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 of closer to 73%. The improved isentropic efficiency and reduced mechanical losses result in an increase in overall efficiency for the LMRC system.

RESULTS

Phase 3 of the project involves a significant change from the original project plan. Phase 3 originally called for building the medium-pressure and high-pressure stages and testing all three stages in series concurrently. However, recognizing the need to significantly improve the electrical efficiency and to overcome the control and position measurement issues encountered in Phase 2, the development team stepped back to explore better alternatives for success. After weighing alternatives, the preferred path forward was determined to be collaboration with Libertine FPE Limited, a UK company with a core business of supplying linear power systems to developers of free piston engines, actuators, and gas expander/compression systems. Libertine has developed and built a number of high-force-density linear electrical machine prototypes for dynamic test actuator programs, and one of these prototypes was determined to be adaptable to the LMRC application.

Phase 3 was changed to mate a more efficient and lower risk Libertine electric motor, including motion controller and motor drive, with the existing low-pressure stage compressor and test loop. This approach is intended to result in higher overall efficiency (much closer to the 2015 MYRDD target for 2020 of achieving an overall specific energy of 1.6 kWh/kg) and a prototype that is closer to commercialization. A cross-section view of the Libertine motor design mated with the existing compression chamber is depicted in Figure 1.

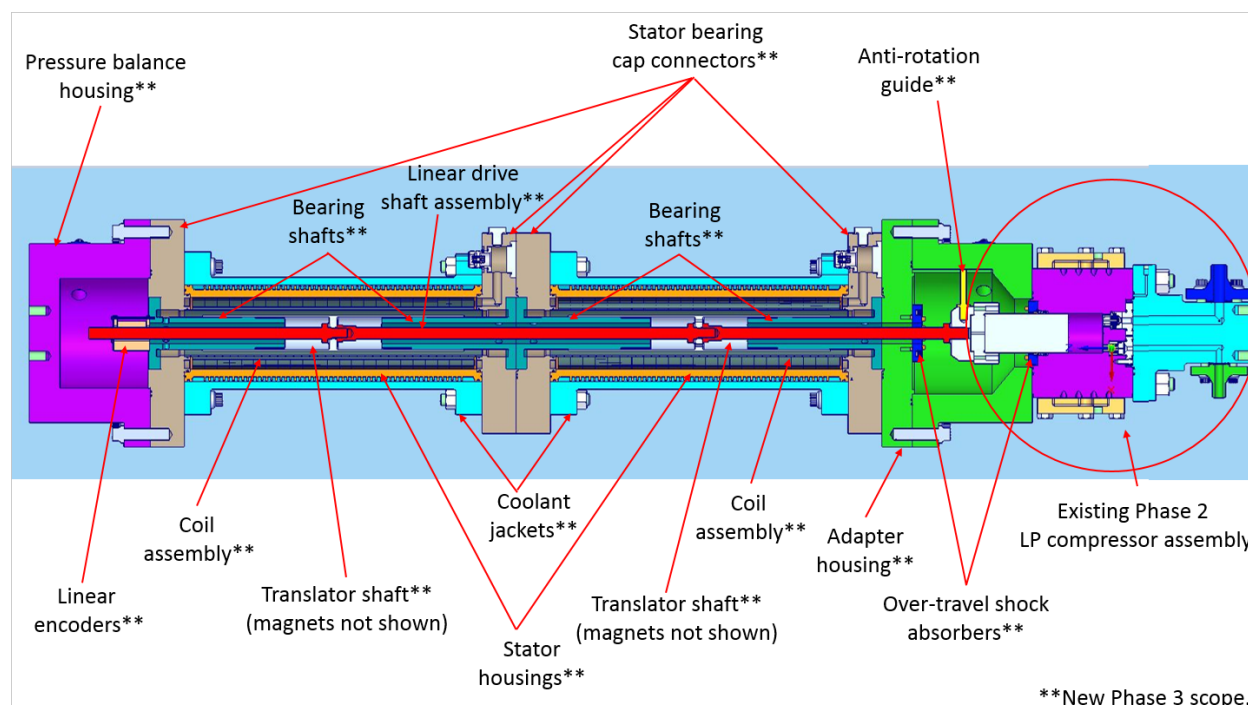


Figure 1. Cross-section of Phase 3 LMRC identifying major components

Many design changes were needed to make the Libertine motor design suitable for operation within a pressurized hydrogen environment. Several analyses were performed to evaluate and adequately alter the motor design for this new application. Figure 2 includes a meshed model of the stator assembly housing that was evaluated using a finite element analysis.

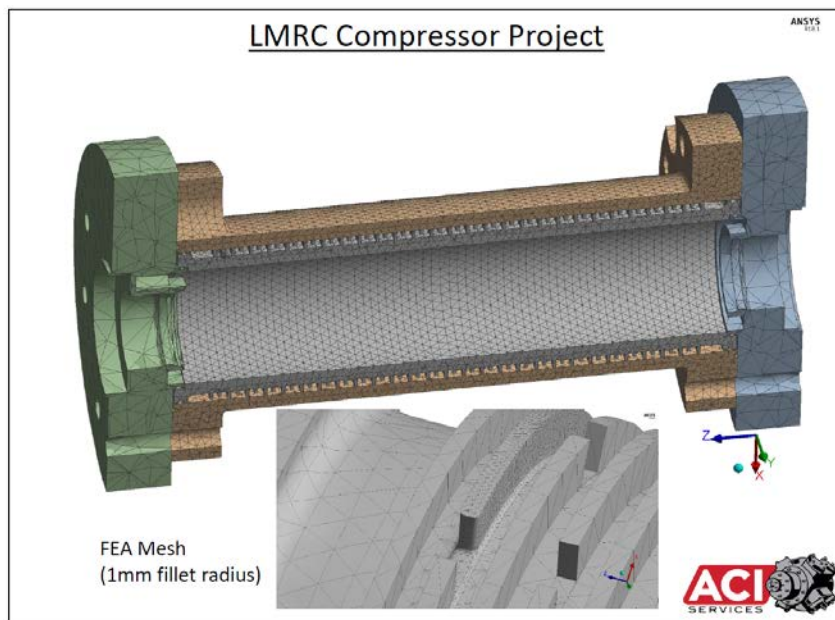


Figure 2. Meshed model of stator assembly housings

Delivery of the 4-drive electrical cabinet to SwRI for initial layout measurements occurred in late March 2019, as scheduled. The 4-drive cabinet, depicted in Figure 3, was uncrated and temporarily placed in the location where it will be more permanently installed during final testing. After the measurements and in-place observations were made, the 4-drive cabinet was shipped to Libertine for some initial testing of the new LMRC motors.



Figure 3. Photo of 4-drive electrical cabinet

Manufacturing of the motor stator and translator parts is complete. The stator portions of the motors are shown in Figure 4. Assembly of the translators should be complete by the end of this year (2019).

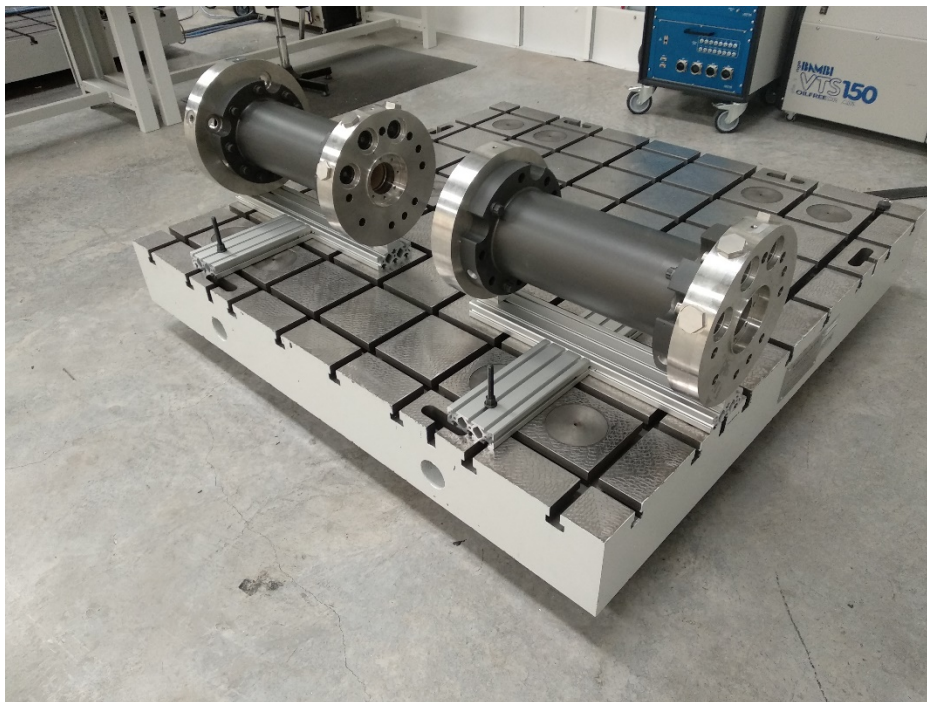


Figure 4. Photo of assembled motor stators

CONCLUSIONS AND UPCOMING ACTIVITIES

Conclusions derived from the work conducted in FY 2019 are:

- Modifying the Libertine linear motor design to be suitable to contain pressurized hydrogen was not an insignificant task. Many details needed to be considered to get it ready for operation in a hydrogen environment.
- Testing of the initially proposed magnet coating in a pressurized hydrogen environment resulted in failure of the magnets. A much more hydrogen-resistant and more standardized magnet coating was required, which resulted in a delay of the project timeline.
- The existing compression chamber was salvaged and reconditioned such that it is now ready for the future testing.

Future work in Project Year 6 (FY 2020; Budget Period 3) will include:

- Commission the motor at Libertine.
- Commission and start up the demonstration test loop at SwRI.
- Test the bench-scale system.
- Analyze the single-stage test results.

REFERENCES

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