III.4 Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)

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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 flow and pressure requirements: compress hydrogen from 290 psia (20 bara) to 12,690 psia (875 bara) with flow rates greater than 22 lbm/hr (10 kg/hr).

Fiscal Year (FY) 2016 Objectives

The overall objective for FY 2016 is fabrication and testing of the LMRC.

- Perform detailed mechanical design.
- Estimate cost projection for full-scale version of LMRC compressor.
- Develop test matrix for bench-scale testing, design compressor test stand for low pressure (LP) stage; develop plans for commissioning, safety, and operation of test stand.
- Fabricate and assemble LP stage compressor parts.
- Construct the test stand and integrate the compressor.
- Commission and start-up the demonstration model.
- 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.

(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 2016 Accomplishments

- Finalized the detailed mechanical design of the compressor.
- Calculated and estimated the cost to manufacture a full-scale version of the LMRC.
- Developed a test matrix for bench-scale testing.
- Designed the compressor test stand for the LP stage.
- Developed plans for commissioning, safety, and operation of the test stand.

TABLE 1. Progress towards Meeting Technical Targets for Hydrogen Delivery with Small Compressors: Fueling Sites (~100 kg H_2/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) 9.2 (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 (1 Compressor, No Backup)	NA (1 Compressor, No Backup)	20 bar to 875 bar: $284,000 (1 Compressor, No Backup)
Uninstalled Capital Cost (Based on 750 kg/d Station, [~100 kg H_2/h Peak Compressor flow])	$	100-bar inlet: NA 500-bar inlet: NA (1 Compressor, No Backup)	100-bar inlet: 275,000 500-bar inlet: 90,000 (1 Compressor, No Backup)	100 bar to 875 bar: $195,000 500-bar inlet: $105,000 (1 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

- Fabricated and assembled many of the LP stage compressor parts.
- Construction of the test stand is underway.

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INTRODUCTION

SwRI® and ACI Services, Inc. are developing a 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 is comprised of 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

The detailed mechanical design, including all detailed manufacturing drawings, assembly drawings, and bills of material (material lists), were completed for the first-stage LMRC. The first-stage LMRC assembly drawing is shown in Figure 1. Detailed mechanical design efforts included design of the skid to support the LMRC during testing. That skid was designed to meet the American Petroleum Institute 618 [3] requirements for reciprocating compressors. The separation margin requirement was verified with a modal analysis, and the steady-state response requirements were verified with a forced-response analysis of the system. Figure 2 shows a computer assisted design model of the skid design, constructed of structural steel beams.

Cost of a full-scale version of the LMRC compressor based on supplier quotes for the bench-scale version was estimated to be $284,000 when designed to compressor gas from 20 bar to 875 bar. Strategies were identified to meet the capital and operating and maintenance targets in the MYRDD Plan for 2020 of $240,000 per compressor with an operating and maintenance cost of less than $4,800 per year in high-volume production. Full-scale was defined by DOE during the project proposal phase as a compressor that can produce a flow rate of 100 kg/h of hydrogen while achieving the goal of compressing the gas from 20 bar to 875 bar. Another MYRDD target is to deliver the required pressures and flow rates with an isentropic efficiency of greater than 73%. Summaries of the cost and capabilities of the LMRC as compared with the 2020 targets are listed in Table 1.

The LMRC test loop was designed, and plans were developed for testing and safety. A schematic showing the approximate location of the LMRC test loop in relation to the existing building can be seen in Figure 3.

In order to complete the LMRC parts fabrication, all components were ordered and entered into production. Machining of the pressure containing components—central casing, cylinders, heads, and manifold—commenced and are complete. Component machining photos can be seen in Figure 4. Also depicted in Figure 4 are pistons and bushing seals deliveries from third parties that were received.

Significant progress has been made for the LMRC test stand construction. The concrete foundation has been poured,

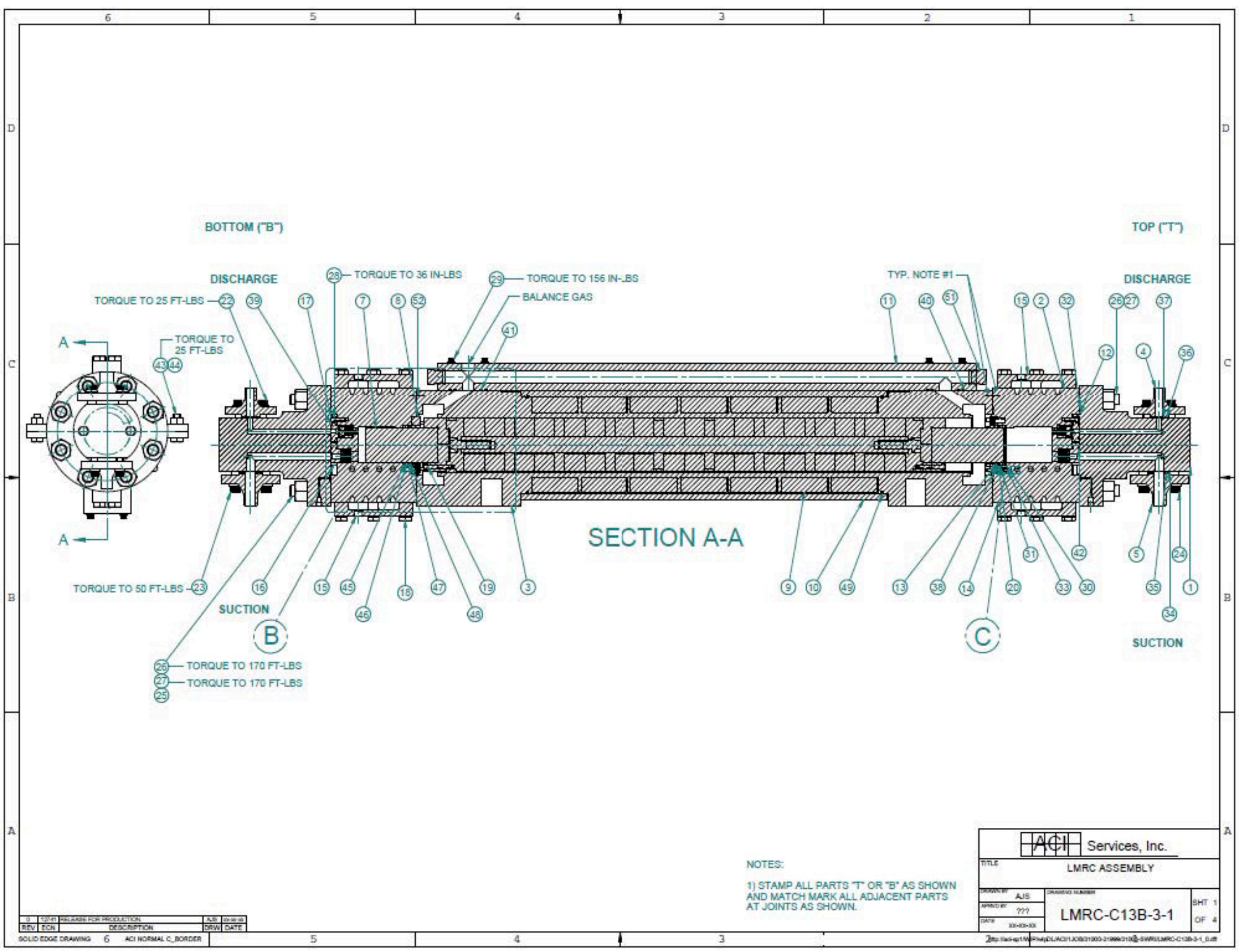

FIGURE 1. First-stage LMRC assembly drawing

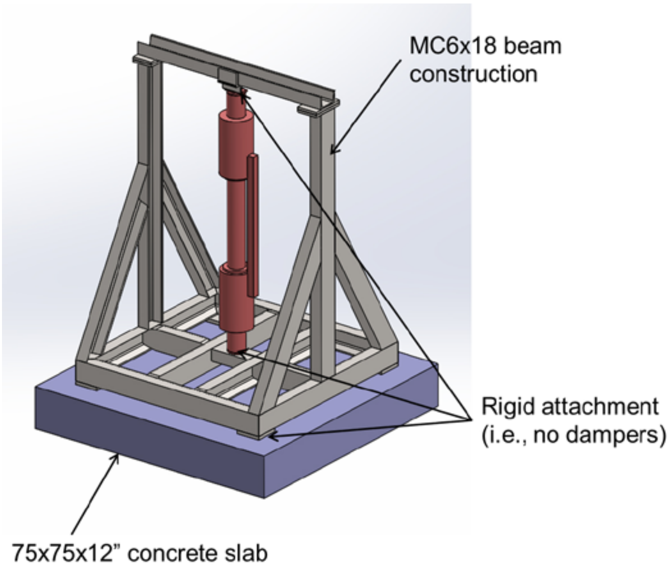

FIGURE 2. Computer assisted design model of the LMRC skid design

and the compressor test frame and connecting brackets have been delivered. The two chillers, electrical panel and filter, water tank, and gas cylinders rack have been moved into position. Additionally, electrical wiring has been laid underground and run to the necessary locations. While the compressor manufacturing is being finished by ACI Services, SwRI is focused on preparing all systems to support the testing.

CONCLUSIONS AND FUTURE DIRECTIONS

Conclusions derived from the work conducted in FY 2016 are:

- Hydrogen embrittlement and powerful magnetic forces add a significant degree of difficulty to the design of a compressor system.
  - The potential for hydrogen embrittlement was considered for all of the LMRC parts that will come in contact with hydrogen, and material selection was limited for some parts due to the application.
  - Lower cost, high strength magnetic materials cannot be used for the central case for the LMRC, where high strength is required.
  - Special tools were designed to safely assemble the magnets on the central shaft without damaging the magnets or other parts.
- The cost of $284,000 to manufacture the full-scale LMRC is higher than the 2012 MYRDD goal for 2020 when the LMRC is designed for a pressure range of 20 bar to 875 bar. However, when using a higher compressor inlet pressure (100 bar or 500 bar), a stage or two of compression is removed and the cost of the LMRC is significantly reduced to approximately $200,000 or less.
- Updated predictions still indicate that highly efficient hydrogen compression is possible with an LMRC used for the compression process.

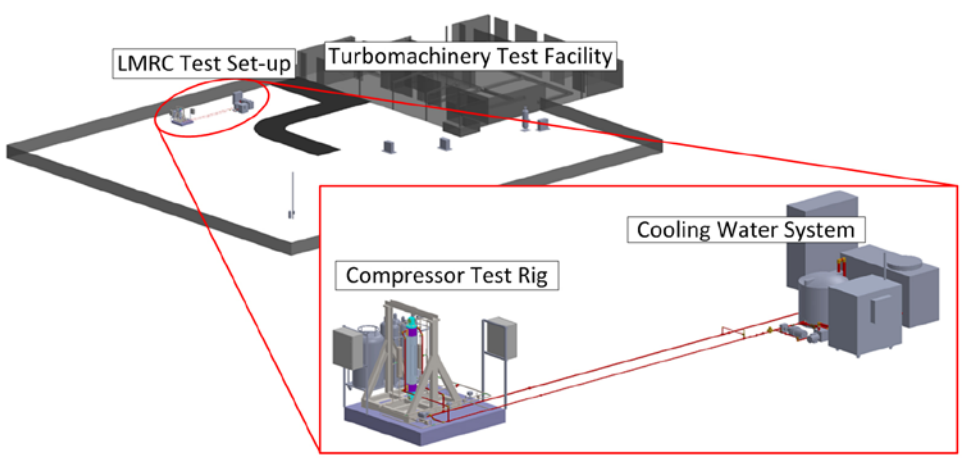

FIGURE 3. Location of the LMRC test loop in relation to the existing building

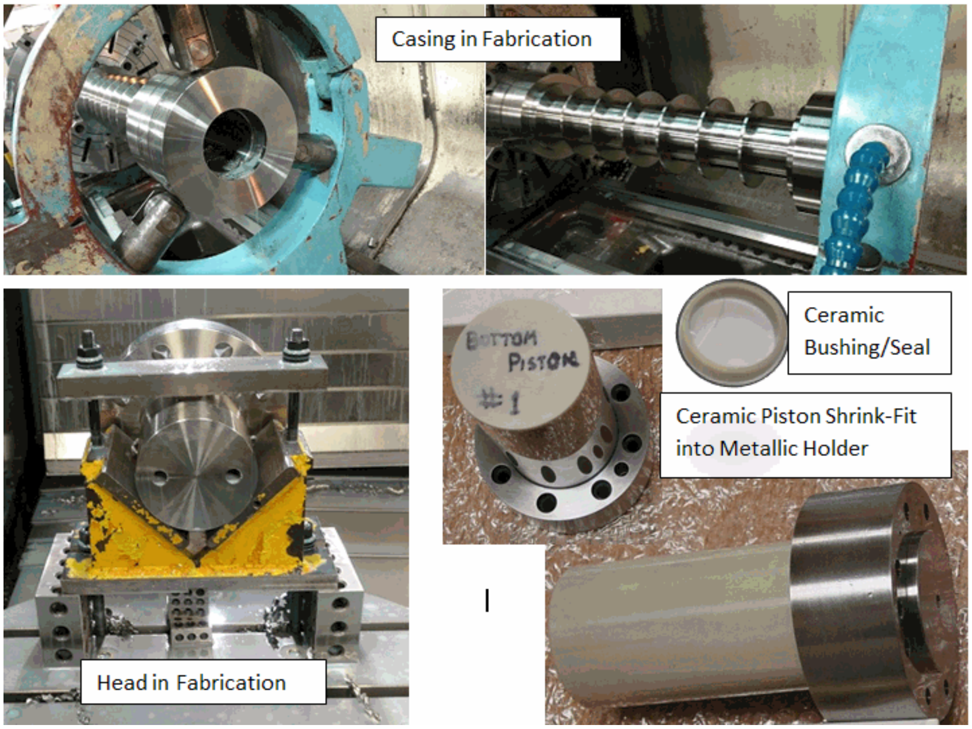

FIGURE 4. Major component photos: items delivered and items being machined or assemble

Future work in Project Year 3 (FY 2017) will include:

- Develop and check fabrication and manufacturing drawings for compression stages two and three. Identify vendors and obtain quotes for the fabrication of the various components.
- Develop a test matrix for the full three-stages system testing. Design test fixtures and select instrumentation needed to test the compressor and measure the system performance.
- Fabricate and assemble the other two compressors and the associated supporting components.
- Select and purchase hardware and fabricate the extended test stand.
- Commission the test bench using an inert gas and following the plan previously defined.
- Complete testing of the LMRC system according to the defined test matrix with hydrogen.
- Analyze the results from the full system testing (20 bar to 875 bar pressure range).

FY 2016 PUBLICATIONS/PRESENTATIONS

1. Broerman, E.L., J. Bennett, K. Brun, N. Shade, L. Chordia, "Designing a Linear Motor Recip Compressor to Achieve 12,700 psia (875.6 bara) Outlet Pressure." COMPRESSORtech^2, July 2016.

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. Deffenbaugh, D., et al., "Advanced Reciprocating Compression Technology," DOE Award No. DE-FC26-04NT42269, SwRI Contract No. 18.11052, December 2005.

3. American Petroleum Institute 618, 2007, "Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services," Fifth Edition, American Petroleum Institute, Washington, D.C.