

## III.7 Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)

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Project End Date: October 4, 2017

### Overall Objectives

The primary project goal/objective is to demonstrate the linear motor reciprocating compressor (LMRC) by integrating individually developed technology readiness Level 4 or higher components and to demonstrate that the compressor has improved compression efficiency and a reduced capital and maintenance cost compared to conventional reciprocating compression technology. Another project goal is to meet the flow and pressure requirements in the Multi-Year Research, Development, and Demonstration (MYRDD) Plan tables. The success of these goals will be measured based on the metrics below.

- 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
- Design a system using the LMRC to compress hydrogen from 290 psia (20 bara) to 12,690 psia (875 bara) with flow rates greater than 22 lbm/h (10 kg/h)

### Fiscal Year (FY) 2015 Objectives

The overall objective for FY 2015 was to perform the primary design steps needed to develop the LMRC to the stage at which detailed mechanical design is necessary. Design steps taken to develop the LMRC were as follows.

- Stage sizing: provide cylinder size for each stage and accompanying calculations
- Basic mechanical design: provide finite element analysis (FEA) results and analysis, basic structural design, and material selection
- Linear motor design: provide linear motor design, including required magnet size and configuration of windings
- Bearing and seal design and analysis: provide selected bearing and seal technology and supporting calculations
- Valve selection: provide the valve type/design that will be used for the proposed system
- Pulsation control design: provide pulsation control design and/or techniques such that the predicted piping system pulsations are at or below the amplitudes specified in the American Petroleum Institute (API) Standard 618
- Cooling system design: provide cooler sizes and cylinder cooling specifications (if needed)
- Materials and coatings selection: deliver material specifications and manufacturer availability
- Performance predictions and comparison: deliver performance predictions and final computational fluid dynamics (CFD) calculations

### Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies Office 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 published recently. Table 1 compares the predicted characteristics of the LMRC design with 2015 targets from both MYRDD reports.

**TABLE 1.** Progress towards Meeting Technical Targets for Hydrogen Delivery with Small Compressors: Fueling Sites (~100 kg H<sub>2</sub>/h peak flow)

Characteristic	Units	2015 Target per 2012 MYRDD / 2015 Target per 2015 MYRDD	LMRC 2015 Status (Predictions)
Reliability		Improved/NA	Improved
Availability	%	NA/70–90	TBD
Compressor Efficiency	Isentropic %	73%/NA	99% for Stage 1
Compressor Specific Energy	kWh/kg	100-bar pipeline delivery: NA/1.6 250-bar tube trailer delivery: NA/1.5	TBD
Losses	% of H <sub>2</sub> throughput	0.5%/0.5%	<0.4%
Uninstalled Capital Cost (based on 1,000 kg/day station, [~100 kg H <sub>2</sub> /hr peak compressor flow])	\$	400,000/NA (Two compressors at \$200,000 each. Both at 50% throughput each, no backup) or \$360,000/NA (one compressor, no backup)	TBD
Uninstalled Capital Cost (based on 750 kg/day station, [~100 kg H <sub>2</sub> /hr peak compressor flow])	\$	100-bar pipeline delivery: NA/275,000 (Three compressors, no backup) 250-bar tube trailer delivery: NA/250,000 (One compressor, one backup)	TBD
Annual Maintenance	% of Installed Capital Cost	2.5%/8%	TBD
Outlet Pressure Capability	bar	860/950	875
Compression Power	kW	260 (20 bar at inlet)/NA	~20 per 10 kg/h (required for compression process— all 3 stages; 20 bar at inlet)
Contamination		Varies by design/NA	TBD
Lifetime	years	NA/–	TBD

NA – Not Applicable  
TBD – To Be Determined

### FY 2015 Accomplishments

Accomplishments during the current project period include:

- Compressor stage sizing identified the approximate sizes and forces/power that would be necessary for the H<sub>2</sub> compression process up to 875 bar. Based on the approximate size requirements, a three-dimensional (3D) model was developed that could be used to refine the design.
- FEA was used to determine the appropriate LMRC casing thickness and material type.
- A linear motor/actuator was designed to provide sufficient forces needed for the compression process.
- A high-pressure piston dynamic seal between the cylinder compression chamber and the magnets chamber was identified and analyzed. Predictions indicate a seal leak rate that is below the losses target of 0.5% of H<sub>2</sub> throughput identified in Table 1.
- Compressor valves were designed for the first stage LMRC.
- System pulsation characteristics were modeled, and predictions were found to be acceptable.
- System cooling was evaluated and modeled. Inter-stage cooler manufacturers were identified, and the LMRC internal cooling was designed to maintain the temperatures at adequately low levels for the various parts of the system.
- Appropriate system materials and coatings were identified based on the criteria of strength, hydrogen embrittlement characteristics, magnetic properties, coefficient of expansion, and Young’s modulus.
- A performance prediction software package was developed to account for the unique motion of the compressor. Isentropic efficiency predictions indicate 99% efficiency for the first stage of compression.



## INTRODUCTION

Southwest Research Institute® (SwRI®) and ACI Services, Inc. (ACI) 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

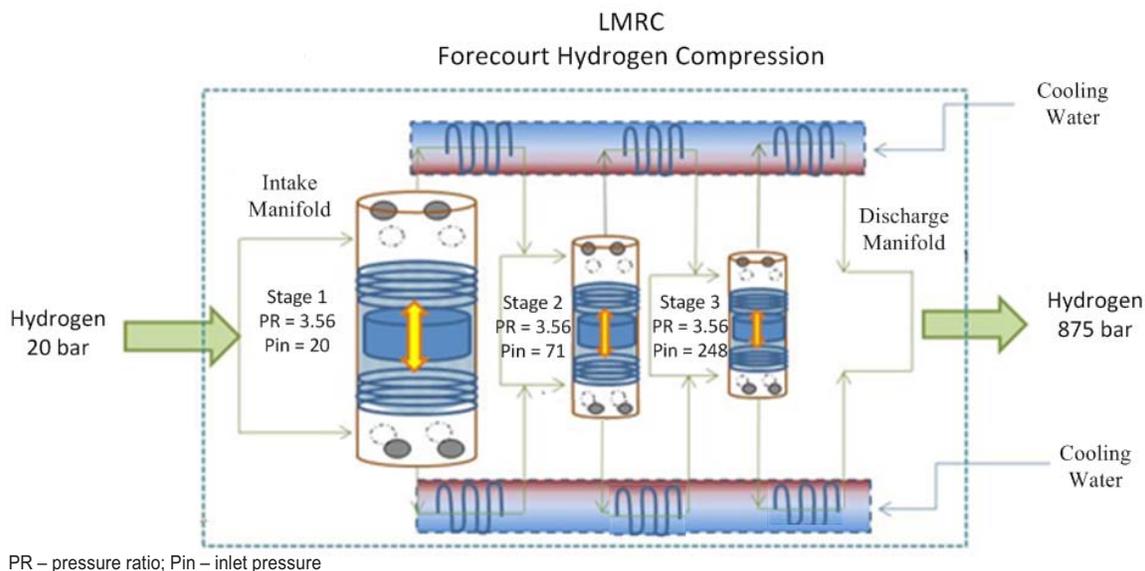
The LMRC is a novel concept compared to conventional reciprocating compression technology. The basic principles of reciprocating compressor design have shown that lower piston speeds and gas flow velocities are necessary to maintain isentropic efficiencies within five percentage points of the isentropic limit. In a low-speed reciprocating compressor, the piston imparts energy on a stationary gas resulting in minimal aerodynamic losses, especially when recirculation and friction losses are well controlled. Utilizing inter-stage cooling reduces the initial enthalpy of the gas per stage, which keeps the gas at a lower energy state and requires less compression power. The LMRC system uses these principles to keep parasitic losses minimized, 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 (CPM) (5 Hz), the LMRC is expected to meet an isentropic efficiency target of greater than 95% [2]. That efficiency can

be compared with current state-of-the-art technology that typically has an efficiency of closer to 73%.

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. As mentioned previously, the isentropic efficiency is improved with the LMRC design and mechanical losses are reduced by reducing secondary systems. This results in an increase in overall efficiency for the system.

## RESULTS

The proposed process will follow a near isentropic thermodynamic path. To achieve this, the hydrogen will remain in the gas phase, and the system will include inter-stage cooling. The reciprocating motion of the piston is sufficient to compress the hydrogen gas to elevated pressures. The compression of the hydrogen from 290 psia (20 bara) to 12,690 psia (875 bara) will be accomplished through three stages of compression, as depicted in Figure 1. Using a speed range of 300–330 CPM and a compression ratio of



**FIGURE 1.** LMRC three stage compression system concept with inter-stage cooling manifolds

approximately 3.6 for each stage, calculations indicate that the three stages of compression would be approximately 3.0-inch stroke and 2.6-inch bore, 1.5-inch bore, and 0.9-inch bore for stages one, two, and three, respectively. This stage sizing will allow the LMRC to meet the flow requirement of greater than or equal to 22 lbm/h (10 kg/h).

Basic mechanical design efforts have included LMRC 3D modeling and FEA. System modeling and FEA is in progress, and those tasks include modeling and analyses for each of the three stages of compression. Upon completion of the magnet and coil design, a 3D computer assisted design (CAD) model was developed for each of the three stages. A representative sample of the first-stage model is shown in Figure 2, and an expanded cross-section of one end of first stage is shown in Figure 3 with the significant components labeled.

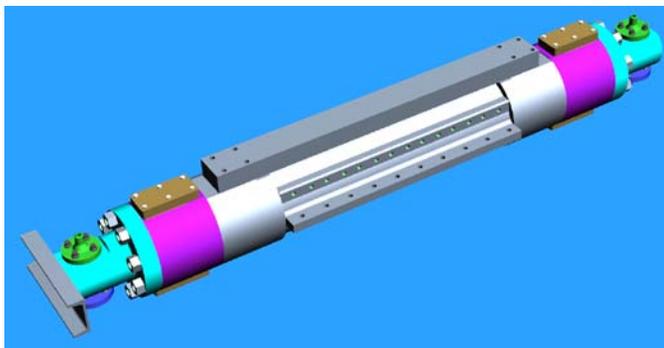


FIGURE 2. Representative screen shot of the first stage 3D CAD model

structural design of the central casing was completed by performing an extensive finite element stress analysis with ANSYS 16.0 on the complete first and second stage pressure containment assemblies. Overall, the stress levels are acceptable. In addition to the structural design of the central casing, bolting design calculations were performed, piston shock absorbers were designed, a magnets assembly fixture is being designed, and a failure modes analysis was performed to thoroughly evaluate the LMRC mechanics.

It was determined that no linear motor design existed that could be used for the LMRC; therefore, a linear motor/actuator was designed based on a traditional moving-magnet-type actuator. The design uses a stack of between seven and 10 actuators/coils (depending on the stage of the compressor) on a shaft. These coils can achieve the required actuation force while maintaining acceptable power dissipation per unit volume. The current-carrying coils are situated outside the pressure vessel where water cooling can easily be used to keep the coil temperatures within an acceptable range. A fully coupled dynamical model was developed that describes the piston action to better understand the linear motor dynamics and to feed critical system dynamic information to the system performance and controls model.

A high-pressure piston dynamic seal (polymeric seal on sapphire piston) between the cylinder compression chamber and the magnets chamber was identified by project partner, Thar Energy, for the LMRC system design. A leak rate analysis was performed on the seal that focused on bounding the leak rate and ensuring the leak rate is sufficiently small relative to its impact on machine performance. The analysis

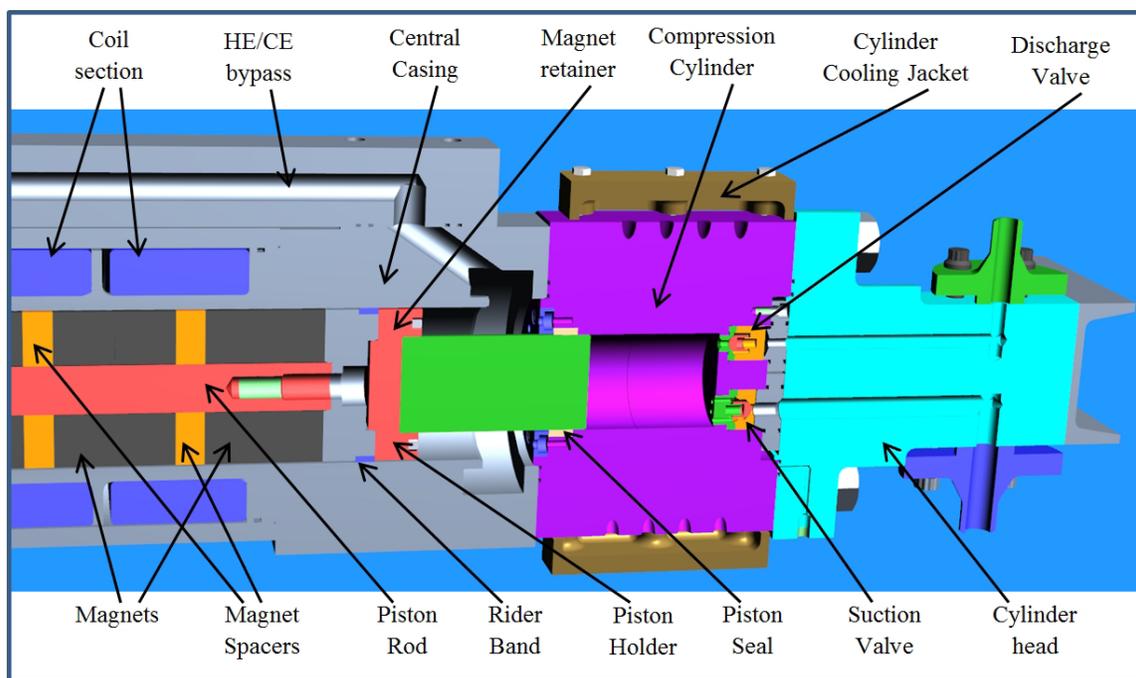


FIGURE 3. Cross-section of one identical end of the first stage LMRC

combined the static pressure load, assembly preload, and linear spring model to determine the likelihood of gap formation due to static loading only, and it was determined that the seals are adequate in terms of static-only conditions. Then dynamic loading was evaluated using the compressible Reynolds equation that governs fluid flow in thin films, and it was determined that the seal leak rate will be less than 0.4% of  $H_2$  throughput per stage. In addition to the dynamic seal design, appropriate static seals were identified for the multiple areas of the LMRC where static sealing is necessary.

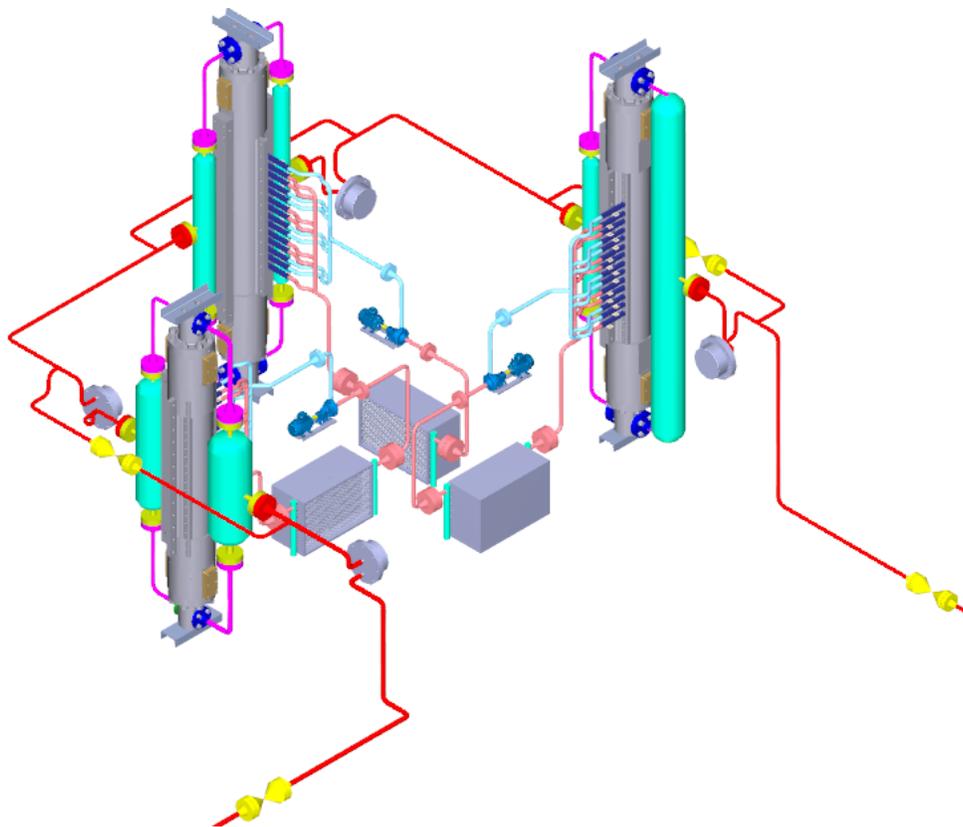
It was determined that no compressor valve manufacturers had existing valves or valve designs that could be used in the LMRC; therefore, valves are being designed. Utilizing a modified version of an internally developed valve design code and CFD modeling, initial valve designs conceptualized by ACI Services for each stage of compression are being optimized. First stage suction and discharge valves are designed, and second and third stage valve designs are in progress.

A pulsation analysis was performed to ensure that the inherent pulsating flow leaving the compressor does not cause any operational issues, such as high vibrations. Based on initial vessel sizing per API Standard 618 and a preliminary system layout as shown in Figure 4, SwRI

utilized a proprietary acoustical simulation software, the Transient Analysis Pulsation Solver design tool (full Navier-Stokes solution in one-dimension which can be analyzed in the time or frequency domain), to perform the pulsation analysis for the LMRC piping system, and all pulsation amplitudes were predicted to be acceptable.

System inter-stage, first suction, and final discharge cooling requirements were identified, and cooler manufacturers were identified that could provide the necessary equipment. In addition to process gas cooling, the LMRC internal cooling was evaluated using a conjugate heat transfer analysis. Simulations were performed to predict steady-state temperatures and pressures, and system modifications were implemented to design the system such that each component will be maintained at acceptable temperature and pressure ranges during continuous operation.

The phenomenon of hydrogen embrittlement was one of the primary factors considered when determining the appropriate materials. Hydrogen embrittlement of high-strength NdFeB magnets is a severe problem if inadequate coatings are applied to the magnets. Appropriate system materials and coatings were identified based on the criteria of



**FIGURE 4.** 3D model of LMRC piping system

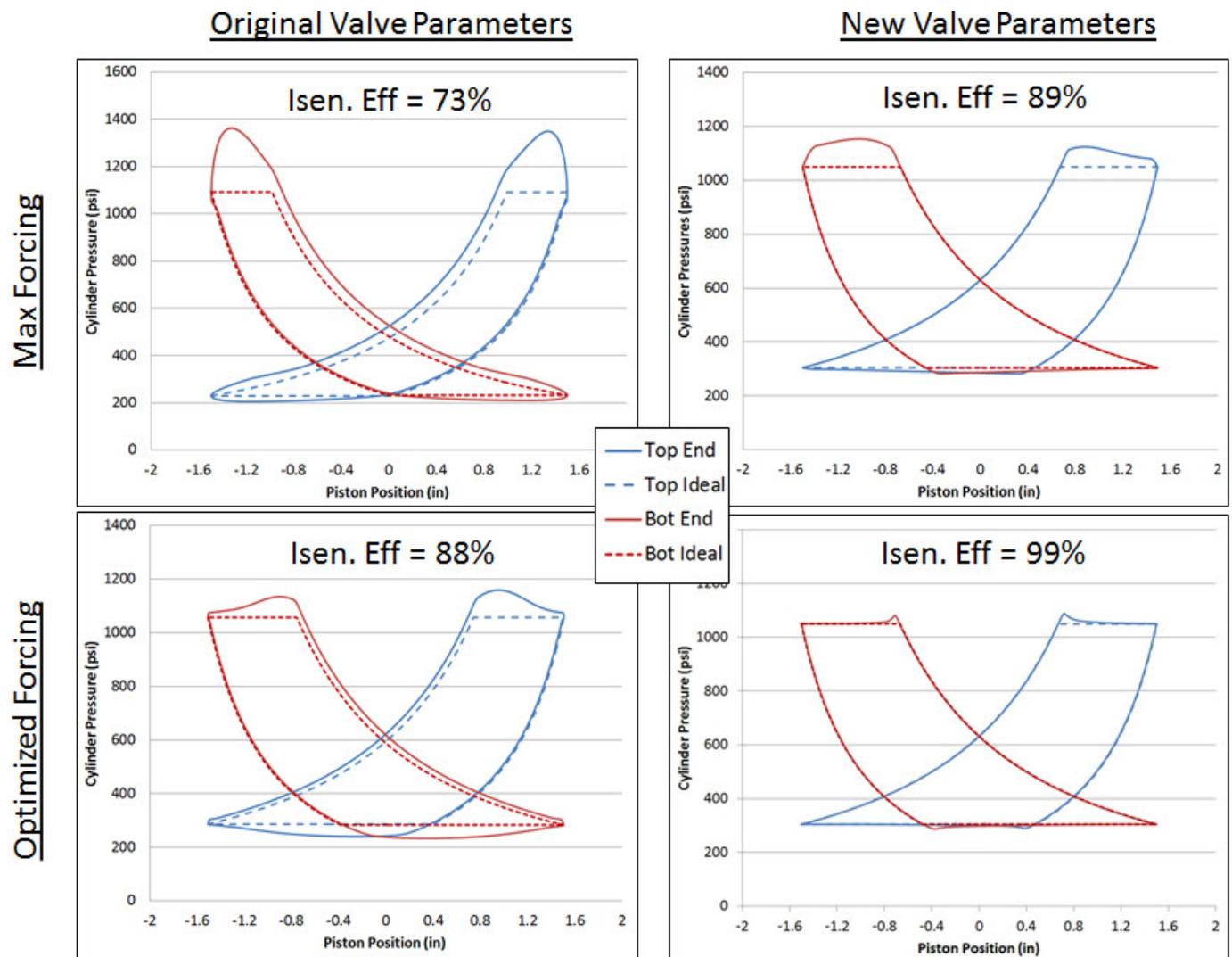


FIGURE 5. Predicted efficiencies

strength, hydrogen embrittlement characteristics, magnetic properties, coefficient of expansion, and young’s modulus.

A system performance and controls model was developed to predict the compressor performance and to develop strategies for control of the compressor. This model was created as a software tool and incorporates the various compressor characteristics, such as the piston velocity and acceleration, valve losses, and magnet performance. The unique motion of the compressor emphasized the need for a unique performance prediction and controls simulation software package. Isentropic efficiency predictions indicate 99% efficiency for the first stage of compression after implementing an optimized control scheme. Predictions are depicted in Figure 5.

### CONCLUSIONS AND FUTURE DIRECTIONS

Conclusions derived from the work conducted in FY 2015 are:

- Hydrogen embrittlement and powerful magnetic forces add a significant degree of difficulty to the design of a compressor system.
- The predicted leak rate of the selected dynamic seal is adequately low.
- Sufficient water cooling of the current-carrying coils, clearance volumes, bypass lines, optional recycle lines, and inter-stage gas cooling are predicted to maintain the LMRC system temperatures at acceptable levels.
- Valves and linear actuators that meet the criteria of the LMRC design are not readily available in industry; however, the project team is capable of designing and manufacturing sufficient components for the LMRC.

- It is predicted that highly efficient hydrogen compression is possible with an LMRC used for the compression process.

Future work in Project Year 2 (FY 2016) will include the following.

- Develop and check fabrication and manufacturing drawings; identify vendors and obtain quotes for the fabrication of the various components
- Estimate the cost of a full-scale version of the LMRC compressor based on supplier quotes for the bench-scale version; identify strategies to meet the capital and operating and maintenance targets in the MYRDD Plan for 2020
- Develop a test matrix for single-stage testing (low-pressure stage) and for testing the full compressor, design test fixtures and select instrumentation needed to test the compressor and measure the system performance, and develop a personnel and environmental safety plan for testing
- Fabricate and assemble the compressor and its supporting components
- Select and purchase hardware and fabricate the test stand
- Commission the test bench using nitrogen 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 single-stage (low-pressure stage) testing

## FY 2015 PUBLICATIONS/PRESENTATIONS

1. Broerman, E., J. Bennett. "Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)," Joint Codes & Standards Tech Team (CSTT) and Hydrogen Delivery Tech Team (HDTT) Meeting, Sacramento, CA, January 21, 2015.
2. Broerman, E., J. Bennett, K. Brun, N. Shade, L. Chordia. "Designing a Linear Motor Recip Compressor to Achieve 12,700 psi Outlet Pressure," Abstract accepted and paper being reviewed by Gas Machinery Research Council (GMRC) for October 2015 GMC.

## 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.