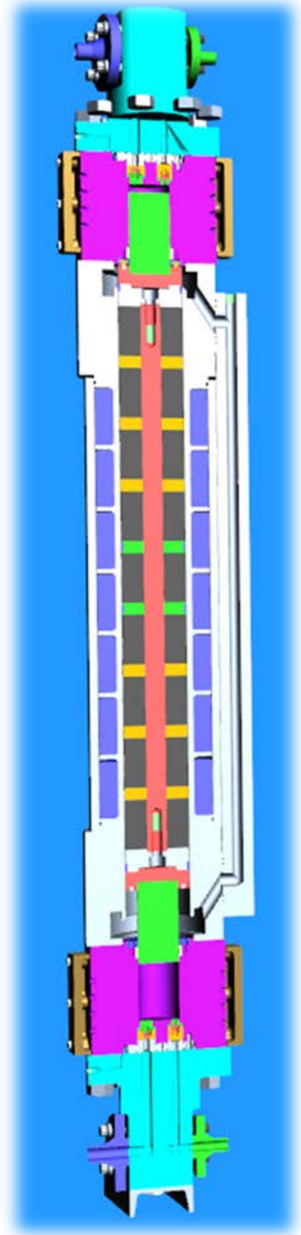
Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)



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ACI Services

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ACI Services, Inc.

Project ID # PD108

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Overview

Timeline

Description	Date / Timeframe
Project Start Date	9/5/14
Project End Date	4/4/19
Project Duration	4.5 years
Project Progress	3.5 years

Budget

- Total Project Budget: $2,294,553
  - Total Cost Share: $469,160
  - Total Federal Share: $1,825,393
  - Total DOE Funds Spent*: $1,143,005

* As of 3/30/18 (includes ACI's funds spent through Feb 2017)

Barriers

Barriers	Targets
Low Compressor Efficiency	>73% Isentropic Efficiency*
Capital Cost	<$240,000 per compressor**
O&M Costs	<$4,800 per year**

* DOE Project Target

** Targets in the 2012 MYRD&D for 2020

Partners

- **US DOE**: Project Sponsor and Funding
- **SwRI**: Project Lead
- **ACI Services**: Project Partner & Cost Share

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Relevance

- Project Objectives:
  - Improve **isentropic efficiency above 95%** by minimizing aerodynamic losses
    - Low speed
    - High valve area ratio

$$\eta_C = \frac{Isentropic\ compressor\ work}{Actual\ compressor\ work} = \frac{w_s}{w_a}$$

  - **Reduce capital costs** to half that of conventional reciprocating compressors by minimizing part count
  - **Reduce required maintenance** by simplifying the compressor design to eliminate common wear items

- BP1: Analyzed and Designed LMRC to be tested in BP2 & BP3

- Current Budget Period (Fiscal Year 2017, BP2):
  - Fabricated and assembled the LP Stage LMRC
  - Fabricated/assembled compressor test stand for LP Stage
  - Testing is planned for near future
  - Testing of stage 1 compressor completed

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Approach / Milestones

Fiscal Year 2015 – Design All 3 Stages

Task Title	Milestone Description (Go/No-Go Decision Criteria)	% Complete
Stage Sizing	Provide cylinder size for each stage and accompanying calculations.	100
Basic Mechanical Design	Provide FEA results and analysis, basic structural design, and material selection.	100
Linear Motor Design	Provide linear motor design, including required magnet size and configuration of windings.	100
Bearing and Seal Design and Analysis	Provide selected bearing and seal technology and supporting calculations.	100
Valve Selection	Provide the valve type that will be used for the proposed system.	100
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 API Standard 618.	100
Cooling System Design	Provide cooler sizes and cylinder cooling specifications	100
Materials and Coatings Selection	Deliver material specifications and manufacturer availability	100
Performance Predictions and Comparison	Deliver performance predications and final CFD calculations	100

Approach / Milestones

Fiscal Year 2016-mid2018 – Fabricate and Test LP Stage

Task Title	Milestone Description	% Complete
Detailed Mechanical Design	Provide final fabrication drawings of each compressor component & manufacturing/assembly drawings of the components	100
Estimate Cost Projection for full-scale version	Deliver cost estimate and calculations for a full-scale version	100
Design of Compressor Test Stand for LP Stage	Test Matrix for Bench Scale Testing. Plans for Commissioning, Safety, and Operation of Test Stand. Provide final compression system and test stand design.	100
Low Pressure (LP) Stage Compressor Parts Fabrication	Order or fabricate the compressor parts in accordance with the detailed design.	100
LP Compressor Assembly	Complete assembly of compressor based on detailed design.	100
Test Stand Construction, Compressor Integration	Manufacture the test stand using the drawings and details created in the previous budget period.	100
Commissioning & Startup	Verify & report operability of compressor and test stand.	100
Bench Scale Testing	Report on the completion of the single-stage testing.	100

Go/No-Go Decision Criteria -- Flow rate of 10 kg/hr of Hydrogen ±10%, discharge pressure of ~71 bara (1030 psia) ±10%, and an isentropic efficiency of > 73%. If any performance goals are not met, the ability to achieve the goals will need to be explained/justified by proposed design modifications and the DOE may choose to continue the final year of the project based on the predicted improved performance of the LMRC associated with the proposed design modifications. If it is predicted that the performance goals of the compressor cannot be met even with design modifications, the final year of the project is a no-go.

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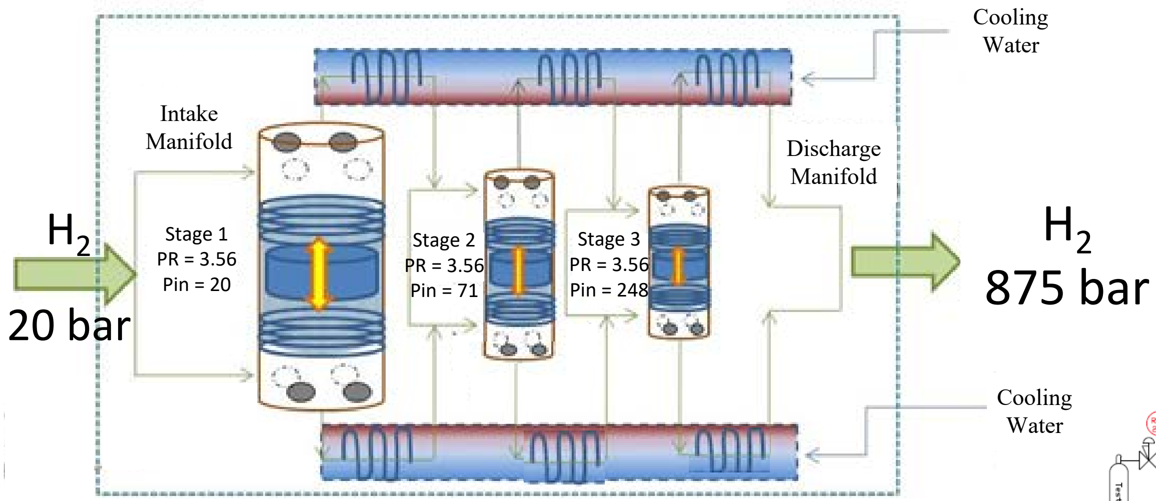
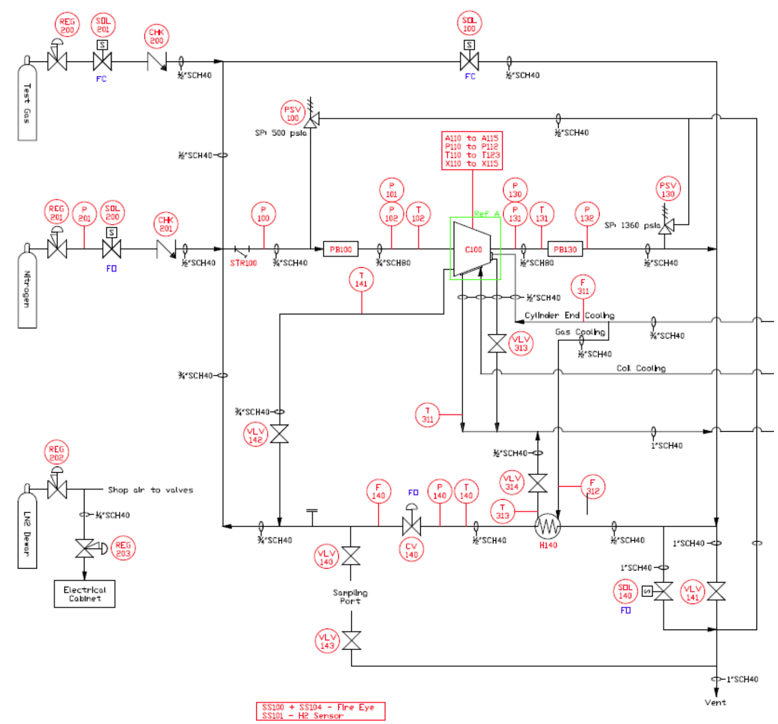
Accomplishments and Progress:
Overall Concept & Test Loop

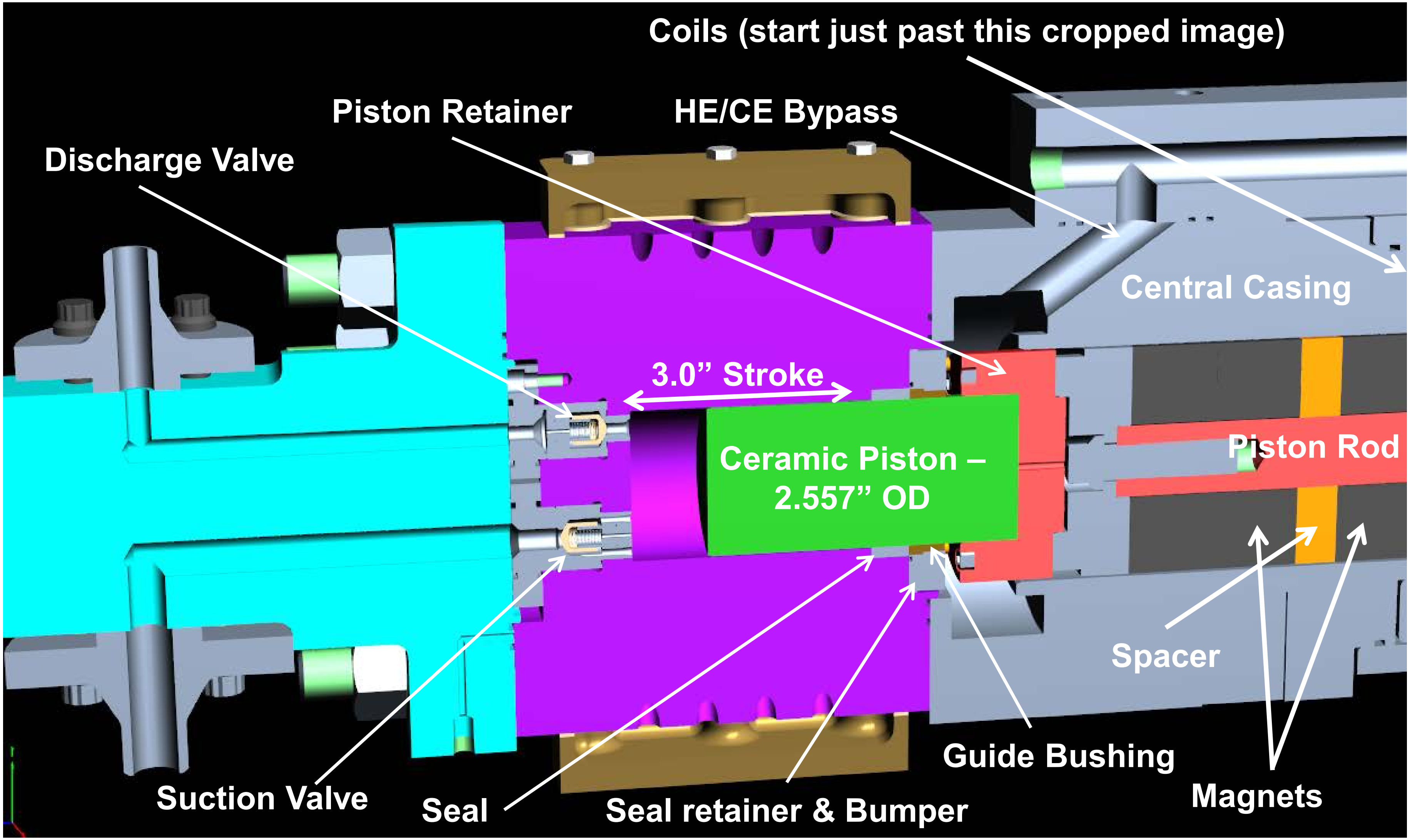


Test Loop for BP1, 2, and BP3 – Stage 1 Test Loop P&ID



Overall Concept = Compress H_2 in 3 stages with 3 LMRCs

Accomplishments and Progress:
3D Model: Piston Close-up

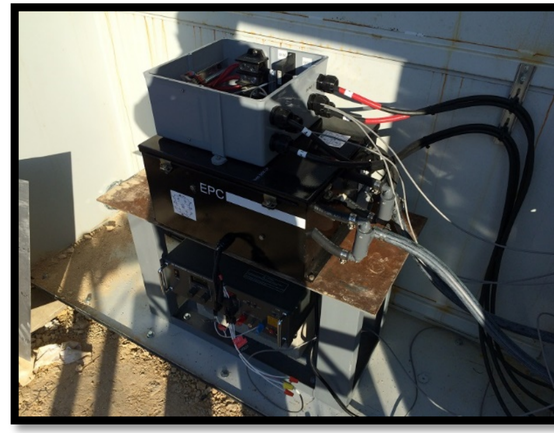


Accomplishments and Progress: Electrical Controller Replaced

- Failure of original controller was likely a result of voltage spike in circuit that exceeded IGBT breakdown voltage
  - Original IGBTs
    - 1200V rating
    - Max switching frequency ~15kHz
  - New IGBTs
    - 3300V rating
    - Max switching frequency ~4kHz

- Undersized bus capacitors also failed from voltage spike
  - Original Capacitors (four total)
    - 400V rating
    - Total current capacity ~300A
  - New Capacitors (three total)
    - 1000V rating
    - Total current capacity ~900A

Failed Original Controller



New Controller

Accomplishments and Progress:
Leaks in Piping Sealed

Snoop bubbles indicate leak

Leaks were tracked down to get ready for testing

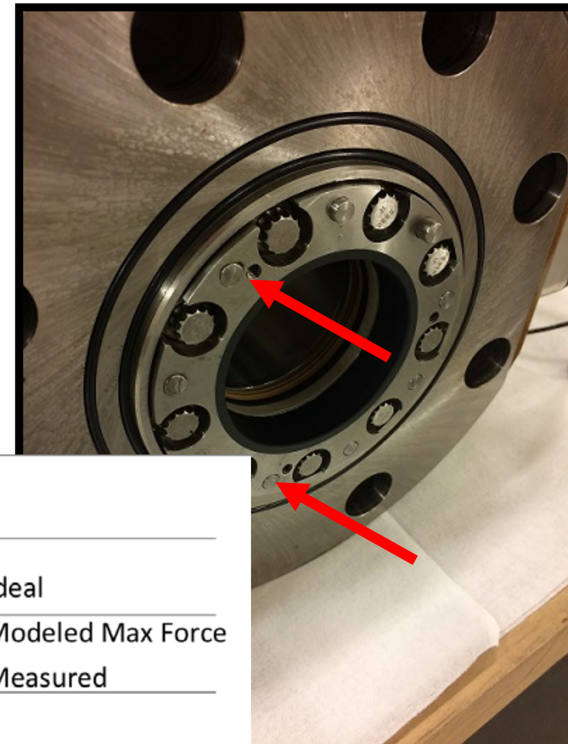
Accomplishments and Progress: LVDT Seal Replaced then LVDT Removed

- LVDT Seal was modified to be able to seal sufficiently
- Testing indicated insufficient readings from the LVDT primarily due to underestimated effects of electromagnetic interference and inability of LVDT to maintain contact with piston face
- LVDT removed, and electromagnetic sensors used for position measurement
- Still insufficient position sensors have resulted in inaccurate motor control

Accomplishments and Progress:
Bumpers Damaged due to Lack of Control

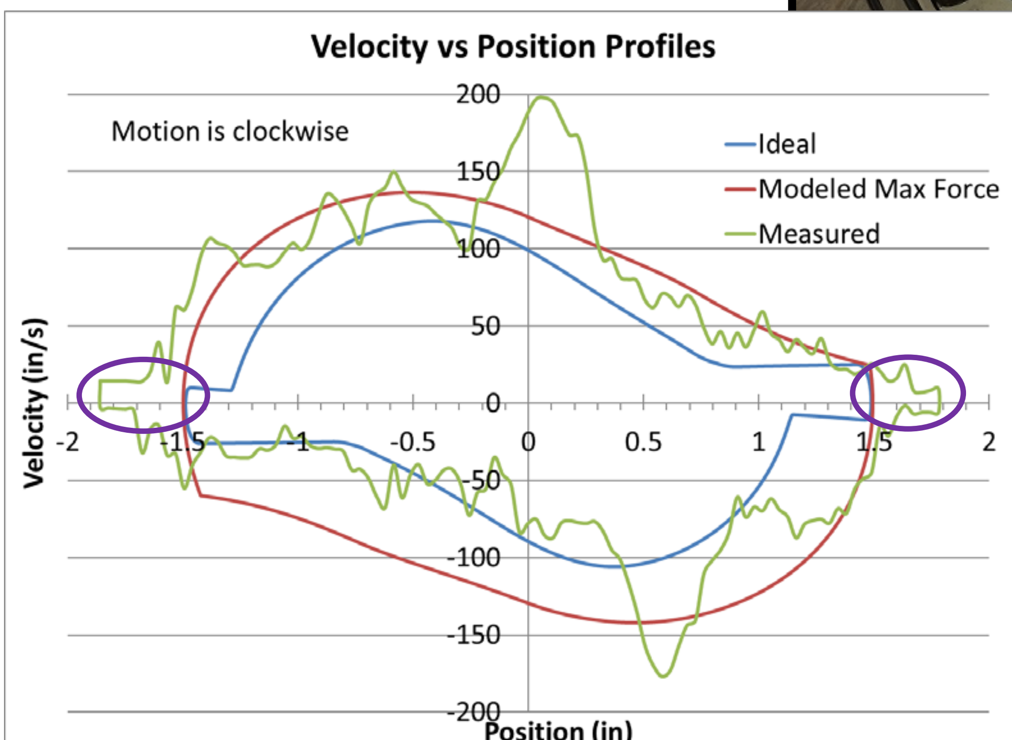
- Inconsistent currents, ‘slow’ switching speeds (due to performance issues with the electronics controller) and inaccurate position measurements led to inaccurate motor control

- Inaccurate motor control led to damage of the piston bumpers



A) Jaggedness due to measurement errors

B) High peaks on either side of 0.25” = likely a result of mag position sensor errors due to changing currents that happen during those periods



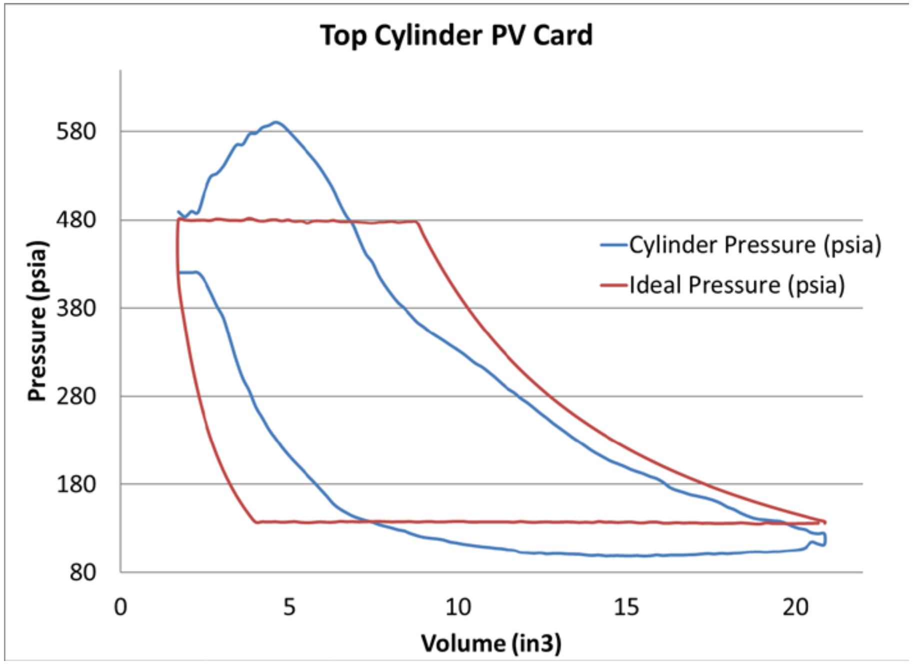
Over-travel of piston due to inaccurate motor control

Accomplishments and Progress: LMRC Operational

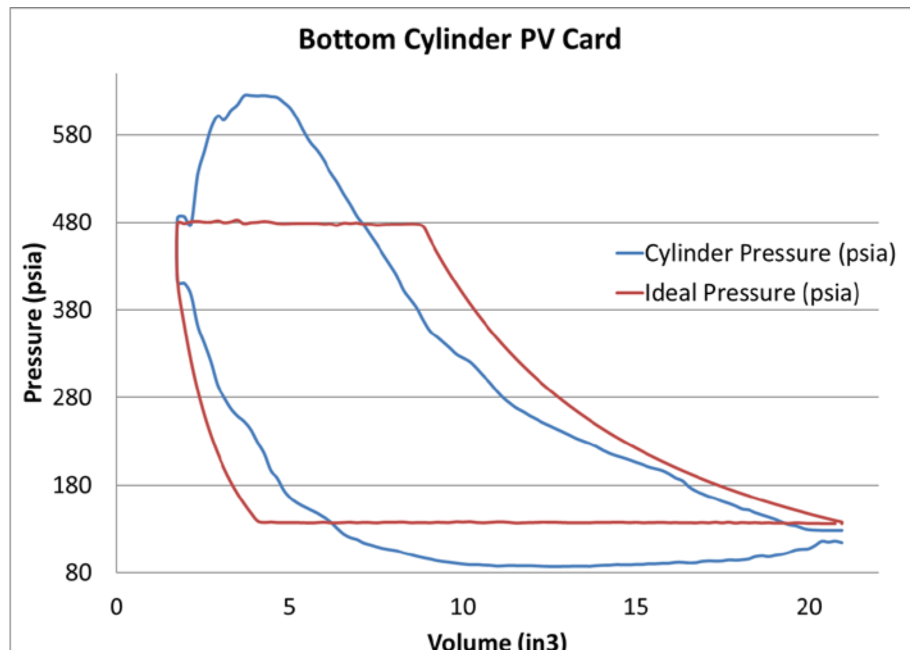
- Commissioning issues sufficiently resolved – prepared for H_2 testing
- Internal discussions for final check regarding Hydrogen Safety

- Test layout designed for accessibility and part re-use.
- Final package layout will be much tighter

Accomplishments and Progress: LMRC Prototype Performance



- Suction Pressure – 137 psia
- Discharge Pressure – 478 psia
- Pressure Ratio – 3.5
- 456 cpm



- 8.2 kg/hr H_2 gas flow
- Isentropic Efficiency ~80-90% - - Still being evaluated

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- *Show speeds the current design is able to achieve the high isentropic efficiency* – 330 for first stage and 300 rpm for 2nd and 3rd stages
- *Concerns about the overall efficiency of the compressor + driver* – – Plans to work with Libertine in Budget Period 3 will significantly advance and increase the overall system efficiency. At the end of BP3 the LMRC should be near the commercialization stage.
- *Concerns that compressor footprint is too large* –– The test loop layout is not ideal. It is laid out in a way that equipment is accessible for alterations during testing and to allow reuse of existing equipment. Previously shown layouts configure the equipment on space-efficient vertical panels that greatly reduce the footprint.

Collaborations

- DOE – Sponsor, Steering
- SwRI – Project lead, design, location for testing
- ACI Services – Overall project partner and cost-share provider, lead for mechanical design, fabricator of many parts
  - SwRI & ACI Services worked together to design the LMRC and test loop.
- Thar Energy – Project partner, seal and ceramic piston design and fabricator
- Dexter Magnetic Technologies – Neodymium Iron Magnets
- TechniCoil – Coils and winding
- Enterprise Power Corp. – Power Controller

Discussed with each collaborator how their individual components fit into the overall project

Remaining Challenges and Barriers

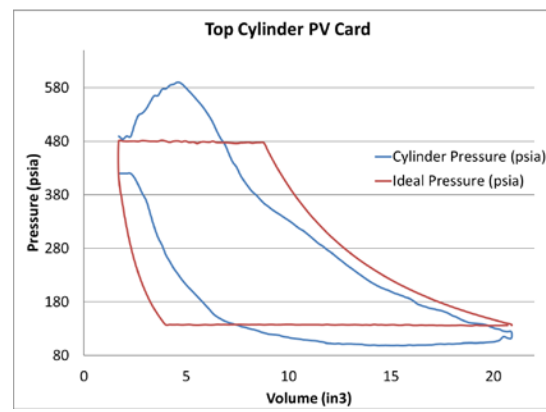
- **Challenge**: Electric power controller inconsistencies
- **Resolution**: Found company (Libertine) that has overcome these challenges and has a commercialized free-piston motor and controller
- **Challenge**: Compressor Valve leakage due to erratic motion during commissioning
- **Resolution**: Rebuild/replace the valves and work with Libertine to be able to test with a more efficient and proven motor, controller, and position sensor to avoid erratic motion
- **Challenge**: Seal life
- **Resolution**: Ceramic seal is an alternative
- **Challenge**: Maintaining budget
- **Resolution**: Weekly budget re-evaluations and borrow test equipment to leverage benefit of large SwRI testing community
- **Challenge**: Full scale production cost target
- **Resolution**: Investigate further the possibilities of increasing the LMRC size instead of speed & numbers

Proposed Future Work

Confirm the Go/no-go criteria are sufficiently met from completed testing and can be met with or exceeded with the partnership of Libertine:

- ❑ flow rate of 10 kg/hr of Hydrogen ±10%,
- ❑ a discharge pressure of ~71 bara (1030 psi) ±10%, and
- ❑ an isentropic efficiency of > 73% is achieved

Proceed to BP3 – Mate a more efficient motor with the existing stage 1 compression chamber and test loop to develop and test a system that is more efficient overall (FCTO's specific energy target of 1.6 kWh/kg) and is near commercialization



Any proposed future work is subject to change based on funding levels.

Summary

- BP1 & BP2 complete
- Compression Ratio and Flow near the goals
- Found a new partner (Libertine) to help reach the original & new goals

Questions?

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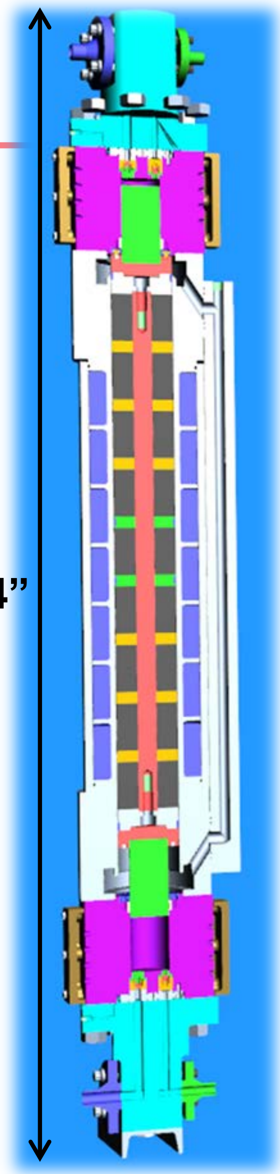

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Technical Back-Up Slides

(Note: please include this “divider” slide if you are including back-up technical slides [maximum of five]. These back-up technical slides will be available for your presentation and will be included in the USB drive and Web PDF files released to the public.)

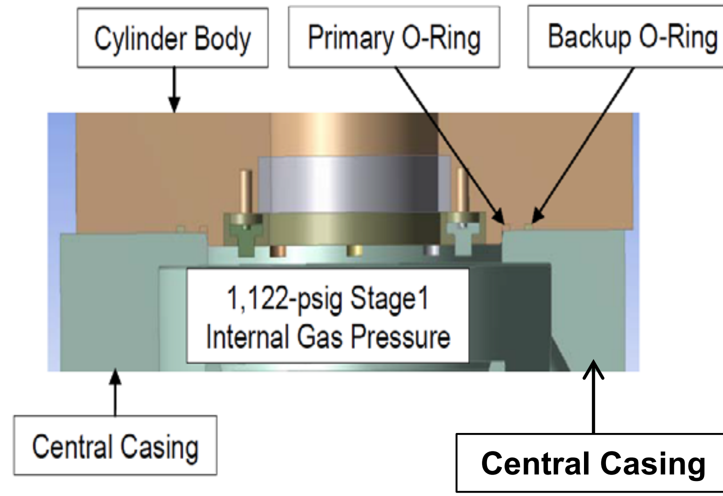
Technical Backup Slide

Seal Selection Criteria:
1. Face seals with zero gap for all primary & secondary (back-up) seal locations
2. Impermeable & resistant to 100% hydrogen gas
3. Explosive decompression resistant

Approved by T. Anderson; Application Engineering Parker Hannifin O-Ring Division

**** outer seal will be V1238-95 Fluorocarbon due to lower pressures**

Cylinder Body and Central Casing
1st stage (typical)



Stage	Max. Internal Operating Press. (psig)	Temp. Range (˚F)				
			Size (in.)	Material	Manufacturer	Durometer (Shore A)
1	1,125	-15 to 400	3/32	V1238-95 Fluorocarbon	Parker Hannifin	95
2	4,101	-15 to 400	3/32	V1238-95 Fluorocarbon	Parker Hannifin	95
3	14,069 (inner seal**)	-15 to 400	1/8	Inconel 718 w/gold plate	Parker Hannifin	NA

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Technical Backup Slide

Materials selected for each of the compressor components, and the significant mechanical and physical properties for each

COMPONENT	MATERIAL	TENSILE STRENGTH	YIELD STRENGTH	ENDURANCE STRENGTH	MAGNETIC PROPERTIES	COEFFICIENT OF EXPANSION (77-212 ºF) (IN / IN / ºF)	YOUNG'S MODULUS	INFORMATION SOURCE
Central Casing	A-286 Sol & Age(AMS 5737P)	145 ksi	95 ksi	61 ksi	Non-Magnetic (1.007Mu)	9.17×10^{-6}	28.8×10^{6} psi	1,2,7
Magnet Spacers	AISI M1010, 1010 hot rolled bar	47 ksi	26 ksi	21 ksi	Magnetic (3290Mu)	6.78×10^{-6}	29×10^{6} psi	3,4,5,15
	or AISI 1018 hot rolled bar	69 ksi	47 ksi	31 ksi	Magnetic (2540Mu)	6.50×10^{-6}	29×10^{6} psi	
Piston Rod	A-286 Sol & Age(AMS 5737P)	145 ksi	95 ksi	61 ksi	Non-Magnetic (1.007Mu)	9.17×10^{-6}	28.8×10^{6} psi	1,2,7
Magnet Retainer	AISI M1010, 1010 hot rolled bar	47 ksi	26 ksi	21 ksi	Magnetic (3290Mu)	6.78×10^{-6}	29×10^{6} psi	3,4,5,15
	or AISI 1018 hot rolled bar	69 ksi	47 ksi	31 ksi	Magnetic (2540Mu)	6.50×10^{-6}	29×10^{6} psi	
Piston Holder	Incoloy 903 Sol & Age	190 ksi	160 ksi	68 ksi	Magnetic	4.0×10^{-6}	21.35×10^{6} psi	6,14
	or Carpenter CTX-1				Magnetic	4.19×10^{-6}		1
Piston	Sapphire	58 ksi	NA	NA	NA	3.4×10^{-6}	50×10^{6} psi	16
Cylinder	A-286 Sol & Age(AMS 5737P)	145 ksi	95 ksi	61 ksi	Non-Magnetic (1.007Mu)	9.17×10^{-6}	28.8×10^{6} psi	1,2,7
Head	AISI 316 Annealed	85 ksi	36 ksi	29 ksi	Non-Magnetic (1.008Mu)	8.89×10^{-6}	28×10^{6} psi	3,18
Suction/Discharge Valves	A-286 Sol & Age(AMS 5737P)	145 ksi	95 ksi	61 ksi	Non-Magnetic (1.007Mu)	9.17×10^{-6}	28.8×10^{6} psi	1,2,7
Rider Bands	PEEK (PTFE filled)							
Thar Seal Rings	Filled PTFE							
Thar Seal Springs	Elgiloy (Cold Drawn & aged)	350/220 ksi	NA	NA	Non-Magnetic	NA	29.5×10^{6} psi	8
Seal Retainer Bolting	AISI 316 ASTM F593 Gr 2 Cond.CW	100 ksi	65 ksi	34 ksi	Non-Magnetic (1.008Mu)	8.89×10^{-6}	28×10^{6}	22
Valve Springs or	Elgiloy (Cold Drawn & aged) or	350/220 ksi	NA	NA	Non-Magnetic	NA	29.5×10^{6} psi	8
Piston Travel Stop Springs	MP35N (Cold Drawn & aged) or	330/230 ksi	NA	NA	Non-Magnetic	NA	34×10^{6} psi	8
	AISI 316 (Cold Drawn)	245/110 ksi	NA	NA	Non-Magnetic (1.008Mu)	NA	28×10^{6} psi	8,3
Valve Poppets	PEEK (Unfilled)	13-15 ksi	NA	NA	NA	26.7×10^{-6}	NA	20,21
Valve Nose Gasket	Cooper (OFHC)C10200/C10100	31.9 ksi	10 ksi	NA	Non-Magnetic (0.999Mu)	NA	NA	3,17
Valve Retainer	A-286 Sol & Age(AMS 5737P)	145 ksi	95 ksi	61 ksi	Non-Magnetic (1.007Mu)	9.17×10^{-6}	28.8×10^{6} psi	1,2,7
Cylinder Cooling Jacket	Aluminum 6061-T6	40 ksi	35 ksi	12.4 ksi	Non-Magnetic (1.000 Mu)	13.1×10^{-6}	10.0×10^{6} psi	9,10,17
Coil Housing	Ferritic Ductile Iron Casting ASTM A536 Gr. 60-40-18	60 ksi	40 ksi	27 ksi	Magnetic (1500Mu)	6.5×10^{-6}	24.5×10^{6} psi	11,12
External Bolting	Alloy Steel A193-B7	125 ksi	105 ksi	61.2 ksi	Magnetic	6.78×10^{-6}	29.7×10^{6} psi	14,3
Bolting for Piston	17-4PH H1150-D or	125 ksi	105 ksi	62.5 ksi	Magnetic	6.6×10^{-6}	28.5×10^{6} psi	1,3
Holder & Magnet Retainer	17-4PH H1150-M	115 ksi	75 ksi	57.5 ksi	Magnetic	6.6×10^{-6}	28.5×10^{6} psi	1,3

1 - Carpenter Steel Corp. Data Sheet
2 - AMS 5737P Standard for A-286
3 - MatWeb
4 - Ryerson Data Book
5 - ASM Metals Handbook
6 - Special Metals Co. Data Sheet
7 - "Physical Properties Data Compilations Relevant to Energy Storage - V Mechanical Properties Data", HM Ledbetter, NSRDS, Jan. 1982
8 - Suhm Spring Works Data Book

18 - AZO Materials Web Site
19 - "A Silicon - Containing, Low-Expansion Alloy with Improved Properties", DF Smith and JS Smith, Huntington Alloys
20 - MakeItFrom.com, Materials Properties
21 - Victrex - PEEK Data Sheet
22 - ASTM F593 Standard Gr.2 Cond. CW (Specification for Stainless Steel Bolts)