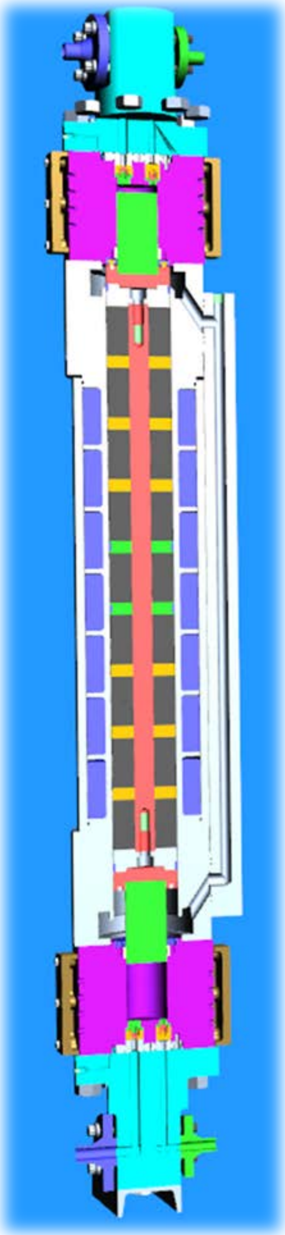
Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)



Buddy Broerman (PI)

Southwest Research Institute

Norm Shade

ACI Services

June 10, 2015

SwRI®

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ACI Services, Inc.

Project ID: PD108

Overview

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Timeline

Description	Date / Timeframe
Project Start Date	9/05/14
Project End Date	10/04/17
Project Duration	3.0 years
Project Progress	6 months

Budget

- Total Project Budget: $2,284,553
  - Total Cost Share: $459,160
  - Total Federal Share: $1,825,393
  - Total DOE Funds Spent*: $314,392

* As of 4/10/15, includes ACI's March 2015 charges

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 MYRD&D for 2020

Partners

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

Relevance

- Project Objectives:
  - Improve **isentropic efficiency above 95%** by minimizing aerodynamic losses
    - Low speed
    - High valve area ratio
  - **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
- This Budget Period (Fiscal Year 2015):
  - Design LMRC to be tested in BP2 and BP3
  - Analyze LMRC to predict efficiency and operability
  - Current isentropic efficiency predicted to be approximately 90%

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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.	65
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.	60
Valve Selection	Provide the valve type that will be used for the proposed system.	50
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.	25
Cooling System Design	Provide cooler sizes and cylinder cooling specifications	40
Materials and Coatings Selection	Deliver material specifications and manufacturer availability	80
Performance Predictions and Comparison	Deliver performance predications and final CFD calculations	60

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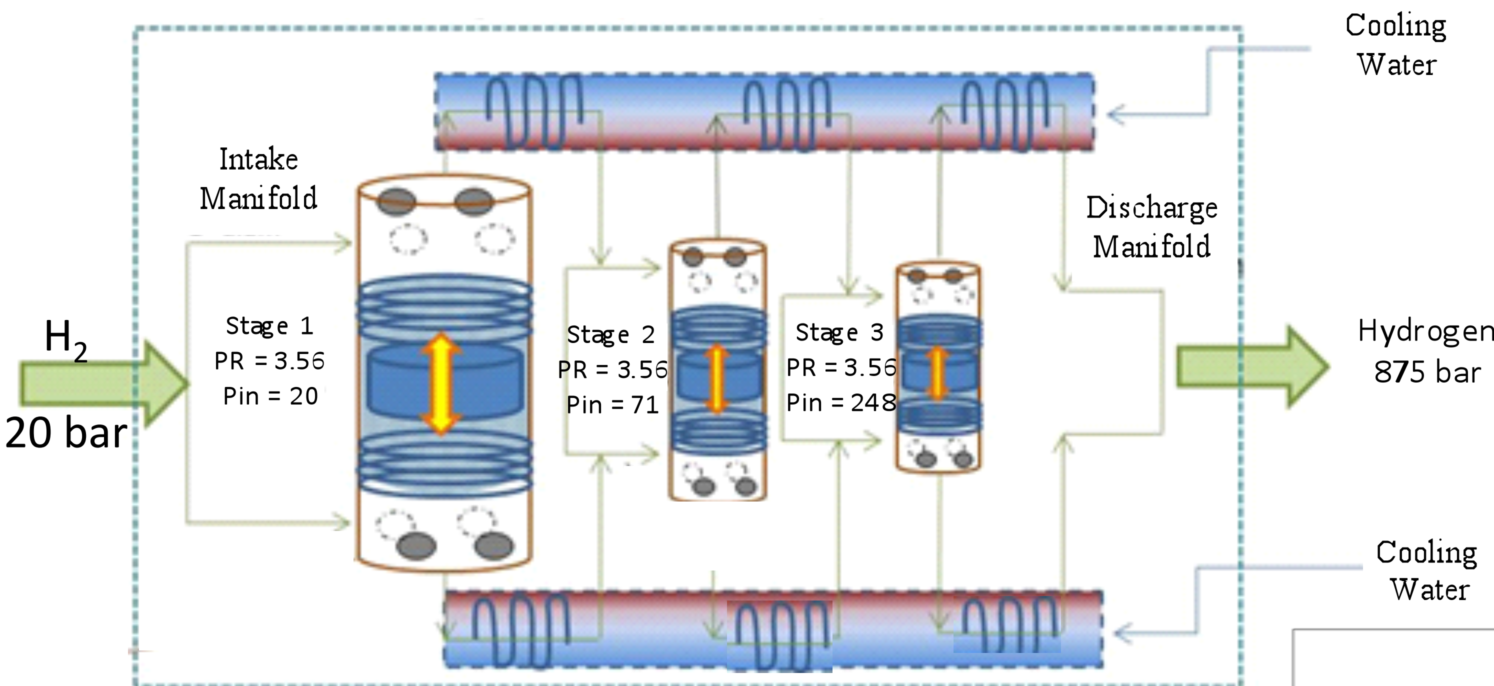
Approach / Milestones

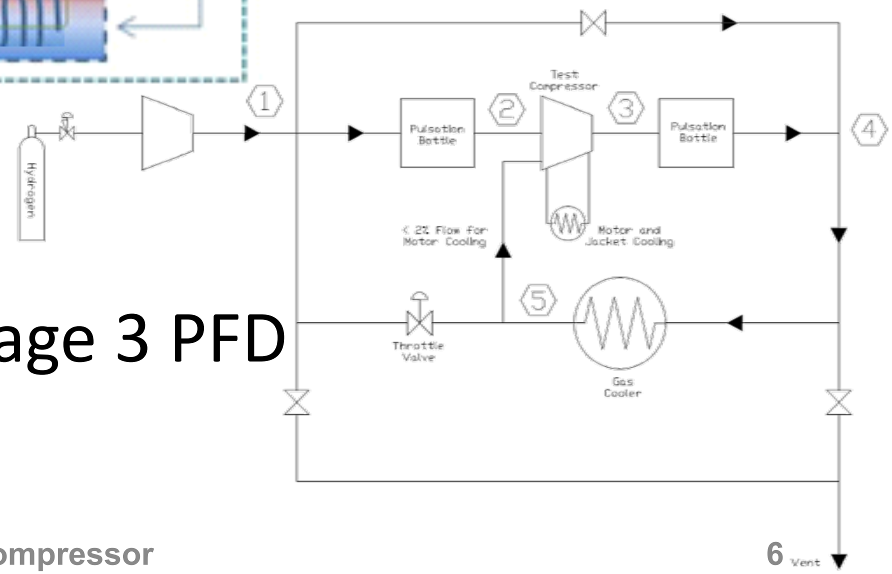
Fiscal Year 2016 – Fabricate and Test HP Stage

Task Title	Milestone Description (Go/No-Go Decision Criteria)	Planned Quarter
Detailed Mechanical Design	Provide final fabrication drawings of each compressor component and manufacturing/assembly drawings of the components	5
Estimate Cost Projection for full-scale version	Deliver cost estimate and calculations for a full-scale version	6
Design of Compressor Test Stand for HP Stage	Test Matrix for Bench Scale Testing. Plans for Commissioning, Safety, and Operation of Test Stand. Provide final compression system and test stand design.	6
High Pressure (HP) Stage Compressor Parts Fabrication	Order or fabricate the compressor parts in accordance with the detailed design.	7
High Pressure (HP) Stage Compressor Assembly	Complete assembly of the compressor based on the detailed design.	7
Test Stand Construction, Compressor Integration	Manufacture the test stand using the drawings and details created in the previous budget period.	7
Commissioning & Startup of Demonstration Model	Verify and report the operability of the compressor and test stand.	8
Bench Scale Testing	Report on the completion of the single-stage testing.	8

Accomplishments and Progress: Overall Concept



Compress H_2 in 3 stages with LMRCs

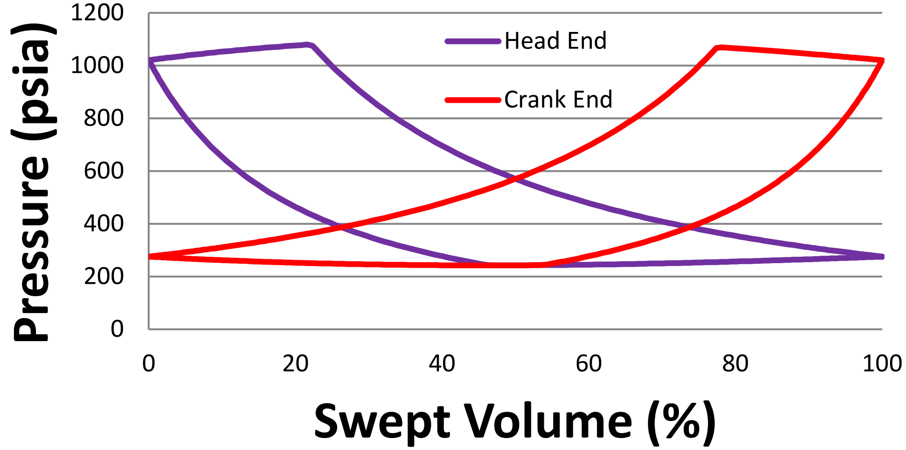


Stage 3 PFD

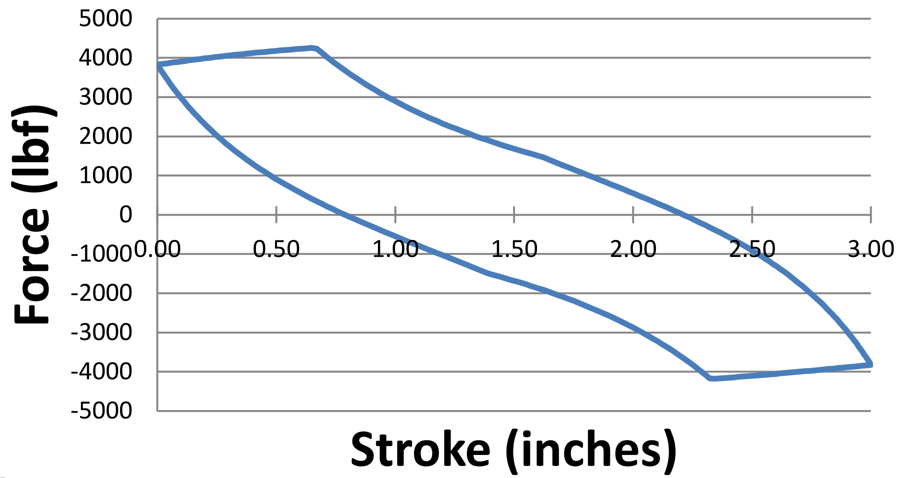
Accomplishments and Progress:
Stage Sizing

- Cylinders were sized to meet the required compression (20 to 875 bar) and flow (10 kg/hr) in 3 stages
- Sized for 95% isentropic efficiency per stage
- Inter-stage cooling planned for increased efficiency
- Supporting calculations based on reciprocating compressor performance equations

Stage 1 P-V Diagram



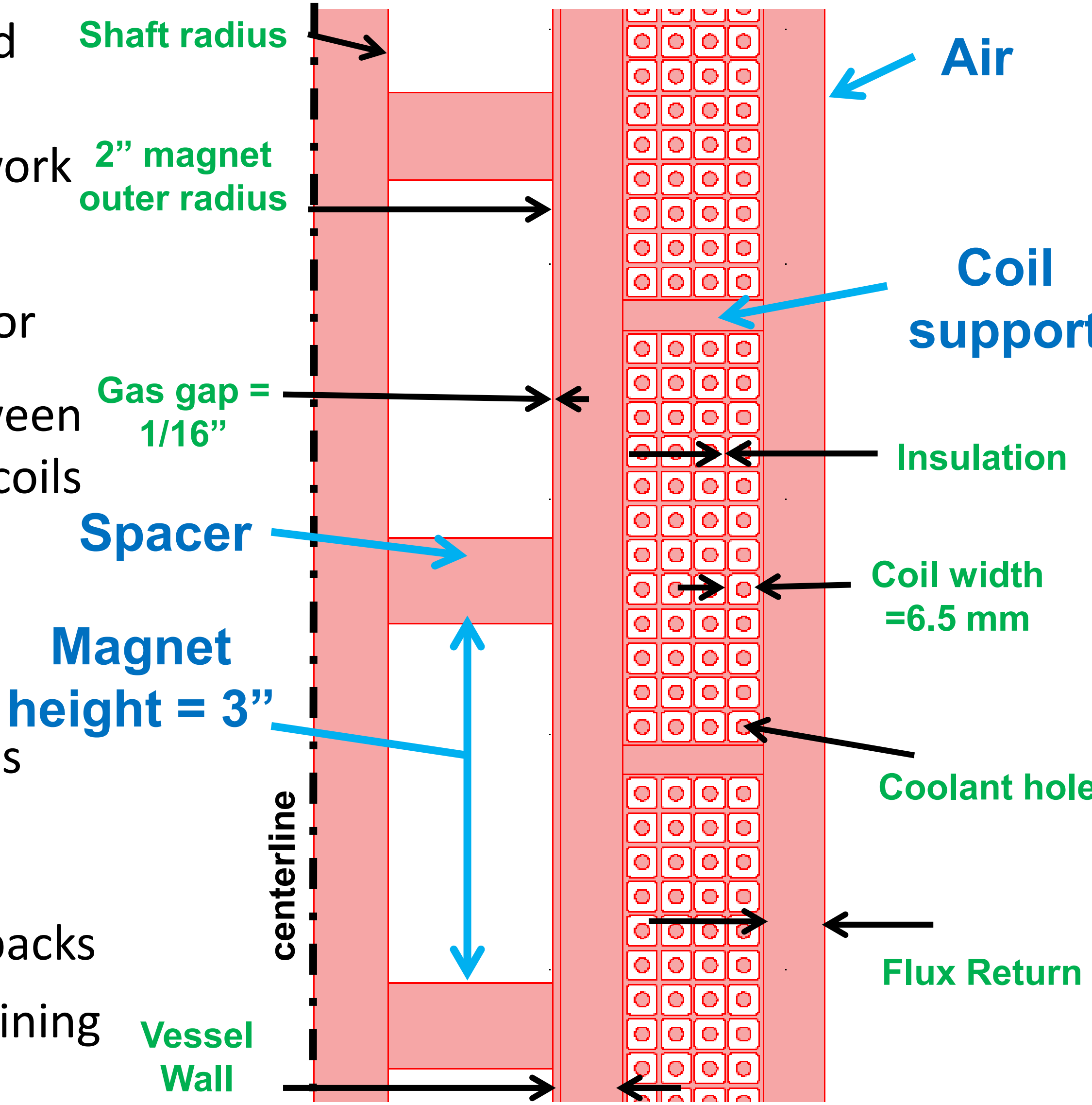
HE-CE Force Balance

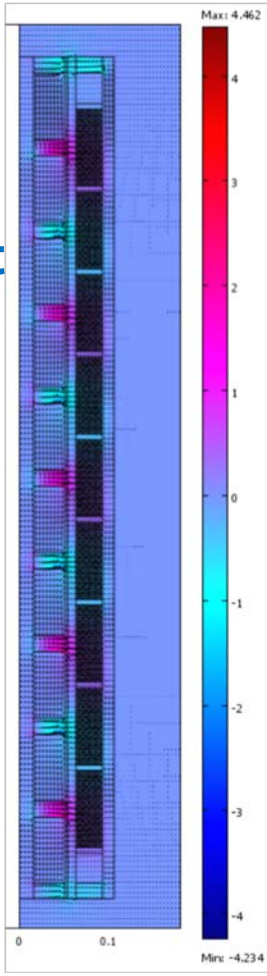


Accomplishments and Progress:

Linear Motor Design

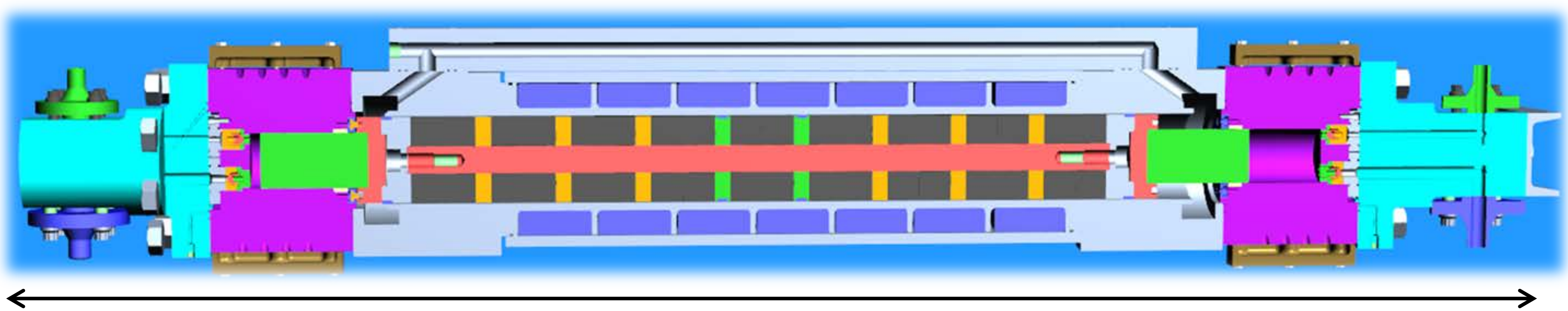
- Market search found that existing linear motors would not work
- Designed moving magnet type actuator
- Each stage has between 7 and 10 actuators/coils
- Each coil pack:
  - 12 rows
  - 4 columns
- Termination analysis determined there should be 2 more magnets than coil packs
- Focused on determining force of each coil





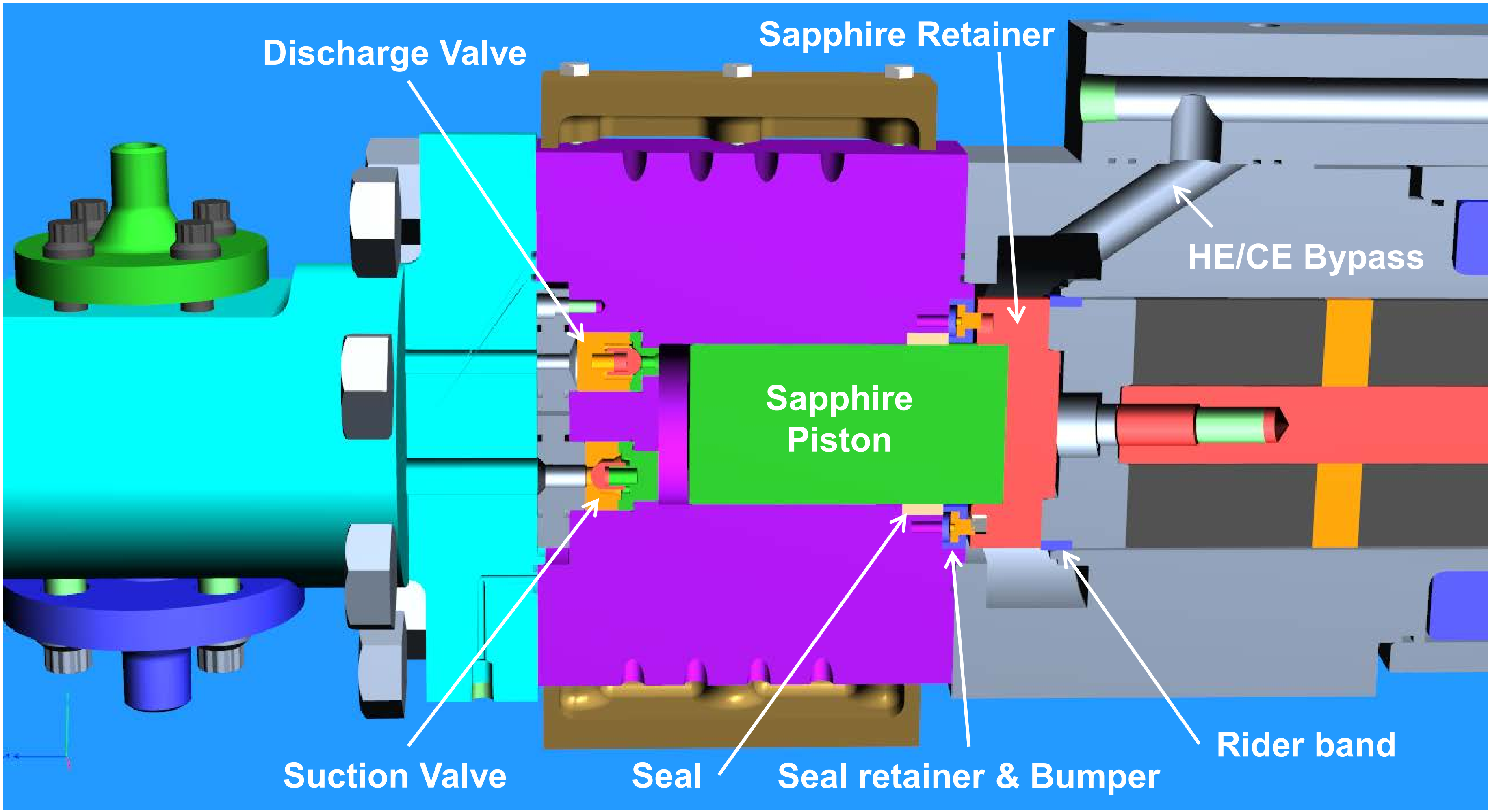
Accomplishments and Progress: LMRC Design Overview

- A preliminary structural design has been created and a preliminary FEA has been performed
- The configuration of Stage 1 is shown below with 7 Coils and 9 magnets

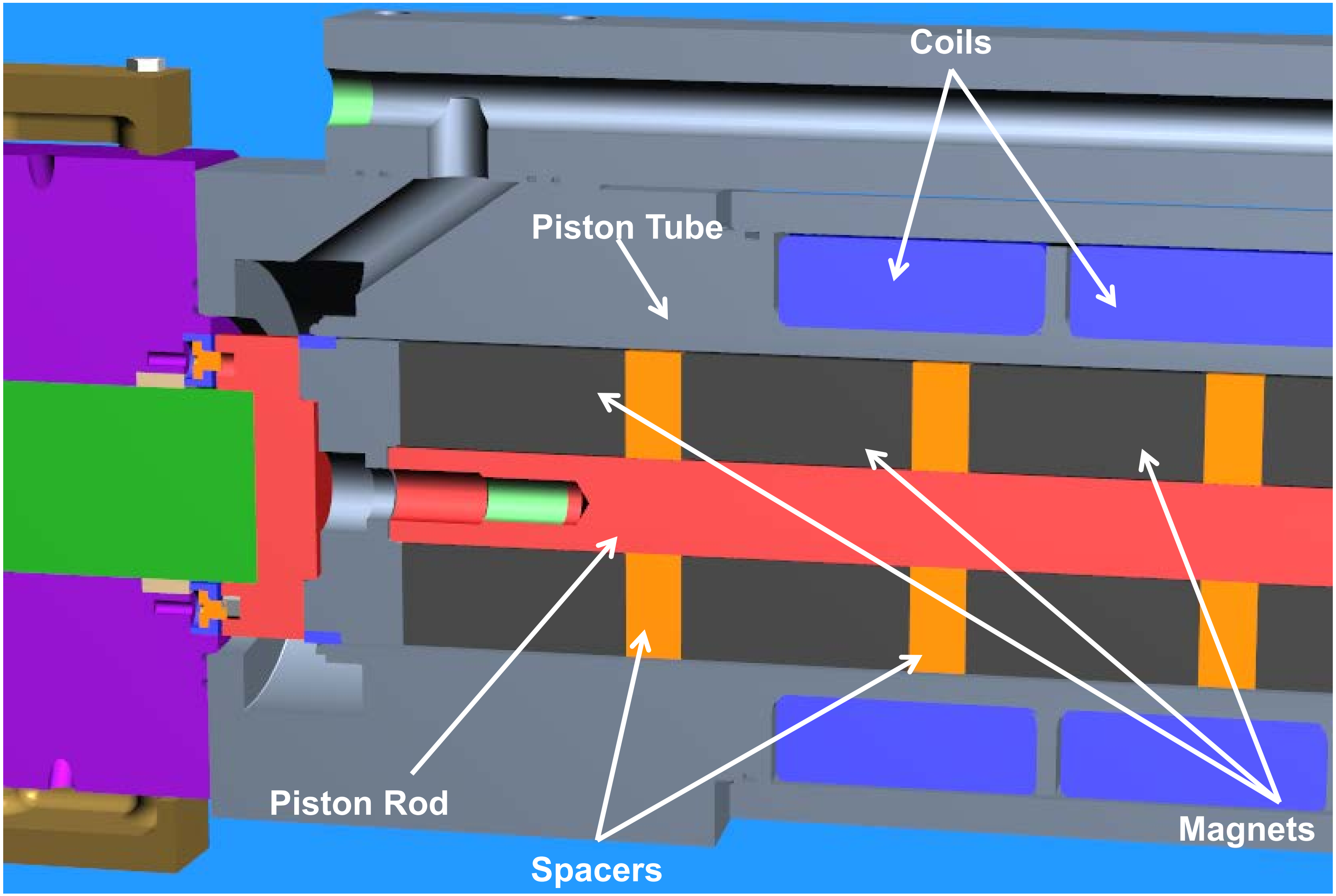


73”

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



Accomplishments and Progress:
3D Model: Magnet/Coil Close-up



Accomplishments and Progress: Material Selection

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- Detailed material selection was performed to ensure components are made with materials resistant to hydrogen embrittlement and with sufficient strength

- Primary structural components:
  - A286
    - For Structural Components
    - Good resistance to hydrogen embrittlement
    - High strength material
    - Low magnetic permeability
  - Carbon Steel 1010
    - For spacers between magnets
    - Good resistance to hydrogen embrittlement
    - Moderate Strength material
    - High magnetic permeability

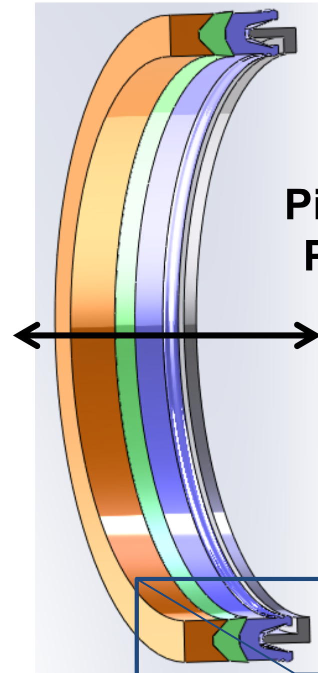
- Moving Seal:
  - PTFE (Poly Tetra Fluoro Ethylene) Teflon ®
  - PEEK (Poly Ether Ether Ketone)
  - Elgiloy
- Piston
  - Sapphire
    - Low coefficient of friction
    - Allows testing of high-life sapphire-on-sapphire seals after testing with poly seals
- Magnets
  - Neodymium Iron – nickel coating
    - Ultra strong magnets
    - Nickel coating avoids H_2 embrittlement

Accomplishments and Progress:
Moving Seal Design

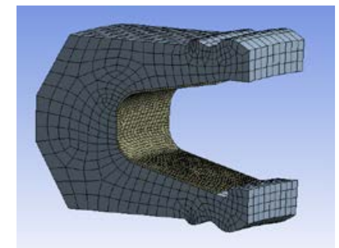
- The design of the bearing/seal is complete

A two step analysis is underway to determine seal acceptability:

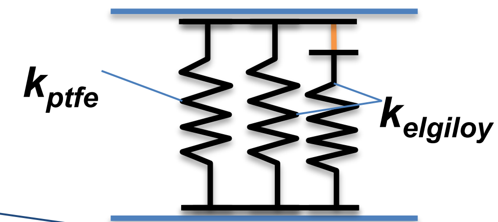
1. Finite element analysis of seal under the range of expected pressure conditions to determine how the gap size varies and seal deforms
2. Reynold's equation coupled with spring representation of seal to predict the leakage rate

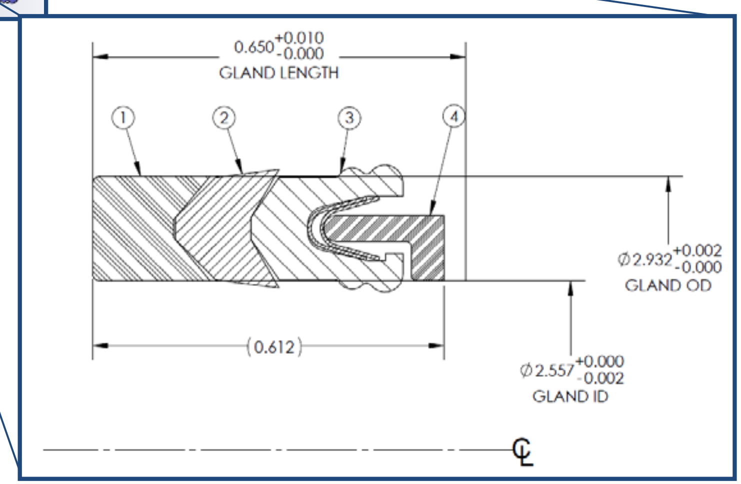


Finite-Element Model



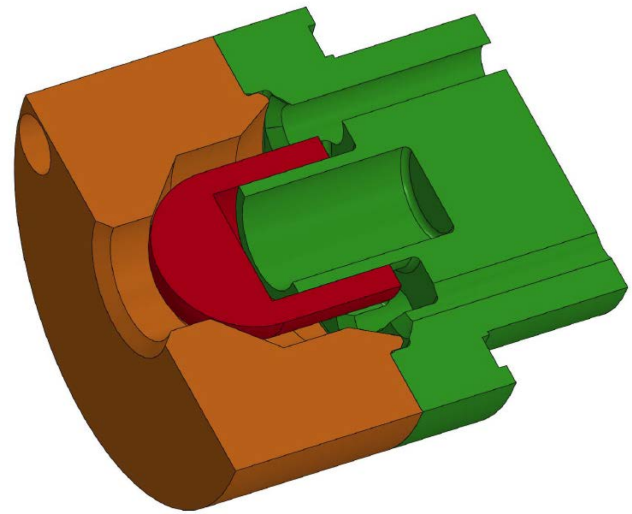
Reduced Spring Model

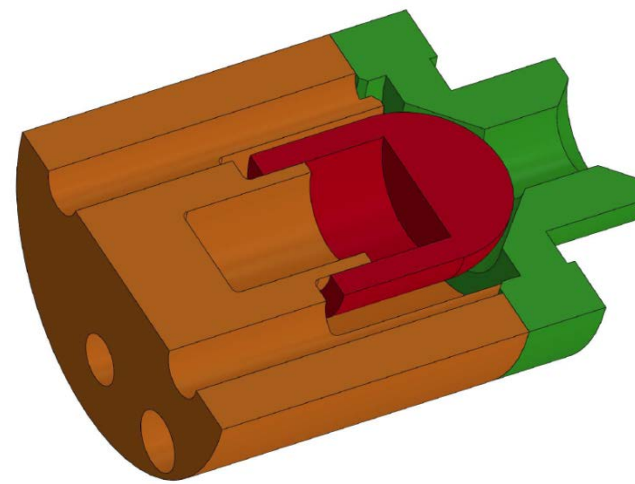




Accomplishments and Progress: Valve Selection/Design

- Market search determined that major manufacturers do not have any products that fit the desired operating conditions
- ACI has experience designing and building replacement and custom compressor valves
- The compressor design has a low throughput & tight space constraints therefore a single poppet valve has been identified as a solution
- Stage 1 valves are designed and being fine-tuned with performance analysis
- Stages 2 and 3 valves will be designed





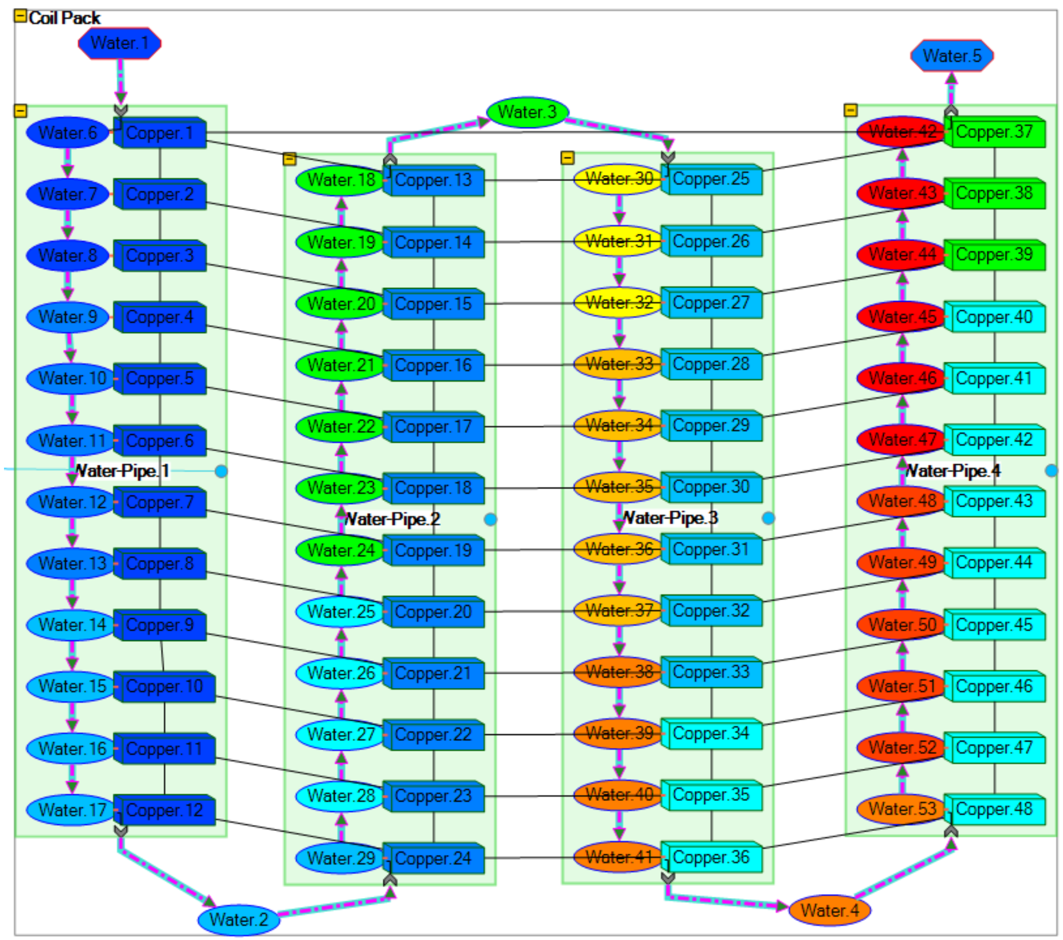
Accomplishments and Progress:
Cooling System Design

Inter-stage Cooling

- Several manufacturers will be able to operate in the desired environment and the next step is to down-select the exchangers that are best for this application

Coil cooling

- Peak current of 600 A will be traveling through the coils
- Therefore a conjugate heat transfer model (SINDA/FLUINT) was used to determine conditions required for adequate cooling



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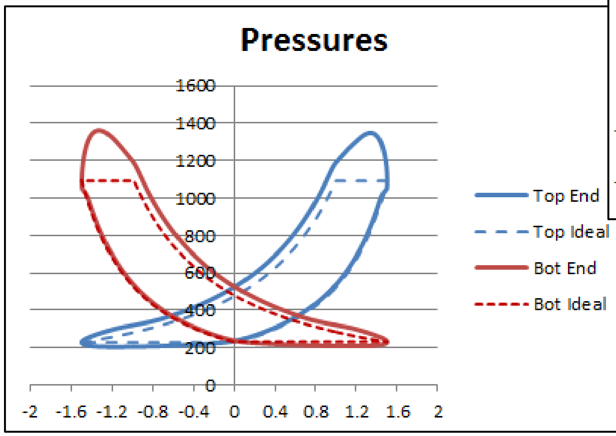
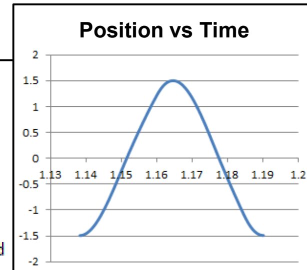
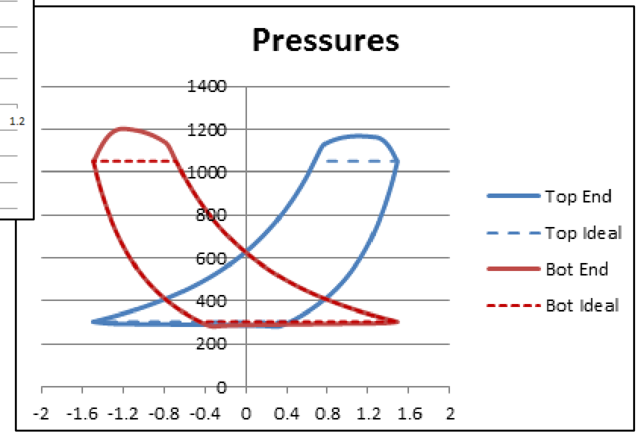
Accomplishments and Progress:
Performance Prediction/Control Scheme

Original Valve





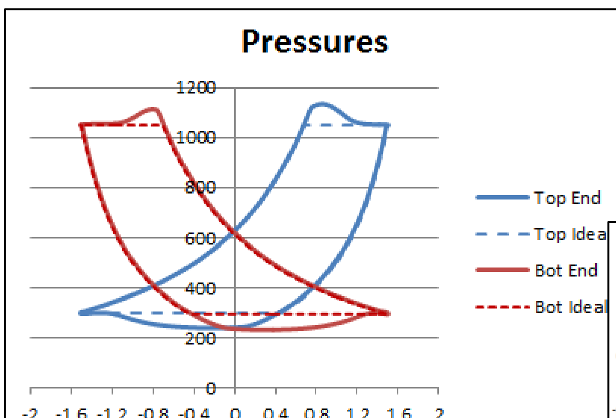
New Valve



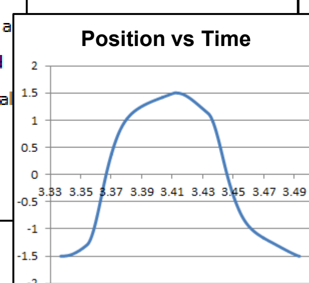
Isen. Eff 73%

Max Force Scheme (22 cps)

Isen. Eff 89%



Custom Scheme (6 cps)



?

Isen. Eff 88%

Isen. Eff ?%

Target is > 95%

Accomplishments and Progress:
Responses to Previous Year Reviewers' Comments

- This project started 6 months ago and was not reviewed last year.

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Collaborations

- DOE – Sponsor, Steering
- SwRI – Project lead, design, location for testing
- ACI Services – Overall project partner, lead for mechanical design, fabricator of some parts
- Thar Energy – Project partner, seal and sapphire piston design
- American Applied Materials Corporation (AAMC) – Neodymium Iron Magnets
- Carotron, Inc. – Power Supply

Remaining Challenges and Barriers

1. Mechanical design of compression stages 2 and 3
2. Piston Seal verification/design
3. Design efficient valves for given application
4. Coils cooling system for stages 2 and 3
5. Compressor generated pulsations
6. Evaluate overall system thermal growth

Proposed Future Work

1. FEA and design modifications/updates for compression stages 2 and 3 design
   a) Bumper/stop design
2. Piston seal analysis/evaluation
3. Valves
   a) Performance analysis (stage 1)
   b) Valve design & performance analysis (stages 2 & 3)
4. Coils cooling system design for stages 2 and 3
5. Pulsation Analysis
6. System thermal analysis

Summary

- Significant progress made for stage sizing, motor design, mechanical design, and performance/controls software
- Stage 1 overall design nearly complete
- Efficiency predictions near 95%
- Currently no technical/commercial off-ramp issues identified

Thank You

We will be happy to answer any questions

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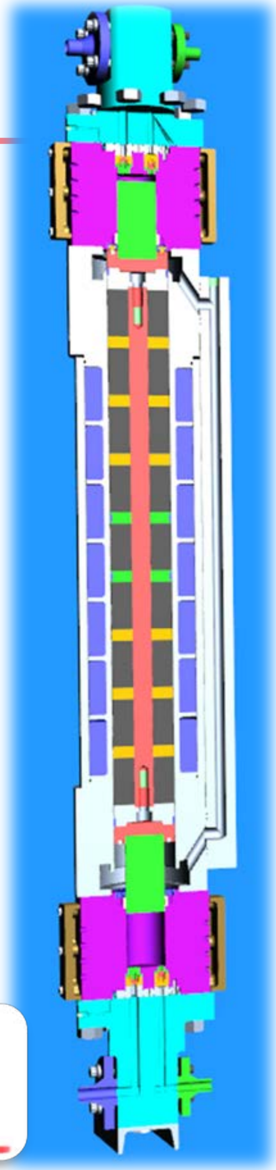

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Technical Backup Slide

Seal Selection Criteria:

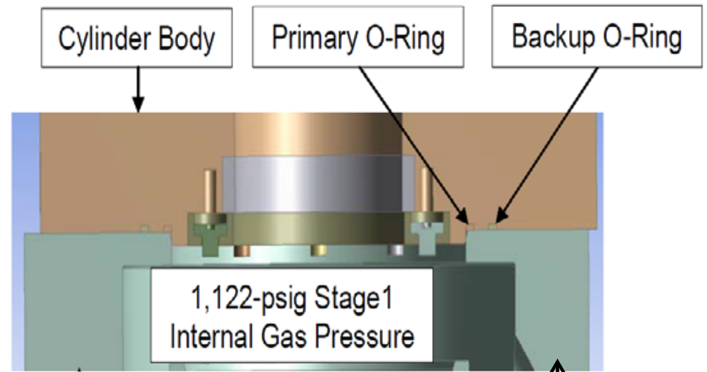
1. Face seals with zero gap for all primary & secondary (back-up) seal locations

2. Impermeable & resistant to 100% hydrogen gas

3. Explosive decompression resistant

Cylinder Body and Central Casing

1st stage (typical)



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

** approved with stipulation of 300 psig/min depressurization rate at pressures above 10,000 psig; Investigating alternative seals for 3rd stage.

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	-15 to 400	3/32	V1238-95** Fluorocarbon	Parker Hannifin	95

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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 °F) (IN / IN / °F)	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 x 10^{-6}	28.8 x 10^{6} psi	1,2,7
Magnet Spacers	AISI M1010 hot rolled bar or	47 ksi	26 ksi	21 ksi	Magnetic (3290Mu)	6.78 X 10^{-6}	29 X 10^{6} psi	3,4,5,15
	AISI 1018 hot rolled bar	69 ksi	47 ksi	31 ksi	Magnetic (2540Mu)	6.50 X10^{-6}	29 X 10^{6} psi	
Piston Rod	A-286 Sol & Age(AMS 5737P)	145 ksi	95 ksi	61 ksi	Non-Magnetic (1.007Mu)	9.17 x 10^{-6}	28.8 x 10^{6} psi	1,2,7
Magnet Retainer	AISI M1010 hot rolled bar or	47 ksi	26 ksi	21 ksi	Magnetic (3290Mu)	6.78 X 10^{-6}	29 X 10^{6} psi	3,4,5,15
	AISI 1018 hot rolled bar	69 ksi	47 ksi	31 ksi	Magnetic (2540Mu)	6.50 X 10^{-6}	29 X 10^{6} psi	
Magnet Holder	Incoloy 903 Sol & Age	190 ksi	160 ksi	68 ksi	Magnetic	4.0 x 10^{-6}	21.35 x 10^{6} psi	6,14
	AISI 1018 or M1010	69 / 47 ksi	47 / 26 ksi	31 / 21 ksi	Magnetic (2540 / 3290Mu)	6.5 / 6.78 x 10^{-6}	29 x 10^{6} psi	3,4,5,15
Piston	Sapphire	58 ksi	NA	NA	NA	3.4 x 10^{-6}	50 x 10^{6} psi	16
Cylinder	A-286 Sol & Age(AMS 5737P)	145 ksi	95 ksi	61 ksi	Non-Magnetic (1.007Mu)	9.17 x 10^{-6}	28.8 x 10^{6} psi	1,2,7
Head	AISI 316 Annealed	85 ksi	36 ksi	29 ksi	Non-Magnetic (1.008Mu)	8.89 x 10^{-6}	28 x 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 x 10^{-6}	28.8 x 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 x 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 x 10^{-6}	28 x 10^{6}	22
Valve Springs or	Elgiloy (Cold Drawn & aged) or	350/220 ksi	NA	NA	Non-Magnetic	NA	29.5 x 10^{6} psi	8
Piston Travel Stop Springs	MP35N (Cold Drawn & aged) or	330/230 ksi	NA	NA	Non-Magnetic	NA	34 x 10^{6} psi	8
	AISI 316 (Cold Drawn)	245/110 ksi	NA	NA	Non-Magnetic (1.008Mu)	NA	28 x 10^{6} psi	8,3
Valve Poppets	PEEK (Unfilled)	13-15 ksi	NA	NA	NA	26.7 x 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 x 10^{-6}	28.8 x 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 x 10^{-6}	10.0 x 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 x 10^{-6}	24.5 x 10^{6} psi	11,12
External Bolting	Alloy Steel A193-B7	125 ksi	105 ksi	61.2 ksi	Magnetic	6.78 X 10^{-6}	29.7 x 10^{6} psi	14,3
Bolting for Piston	17-4PH H1150-D or	125 ksi	105 ksi	62.5 ksi	Magnetic	6.6 X 10^{-6}	28.5 X 10^{6} psi	1,3
Holder & Magnet Retainer	17-4PH H1150-M	115 ksi	75 ksi	57.5 ksi	Magnetic	6.6 X 10^{-6}	28.5 X 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

9 - AMS 4027N Standard (Aluminum Alloy Sheet and Plate)

10 - Alcoa Aluminum Handbook

11 - Iron Castings Handbook (Iron Castings Society)

12 - ASTM A536 Standard (Specifications for Ductile Iron Castings)

13 - ASTM B152 Standard (Copper Sheet, Strip, and Plate)

14 - ASTM A193 B7 Standard (Alloy Steel & Stainless Steel Bolting)

15 - Yeadon Handbook of Small Electrical Motors (Soft Magnetic Materials Properties)

16 - Roditi Data Sheet

17 - Clark, R. "Magnetic Properties of Materials"

18 - AZO Materials Web Site

19 - "A Silicon - Containing, Low-Expansion Alloy with Improved Properties" , DF Smith ar 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)

Technical Backup Slide

Control panel for developing control schemes while simulating LMRC motion and predicting performance (+ many other system characteristics)