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

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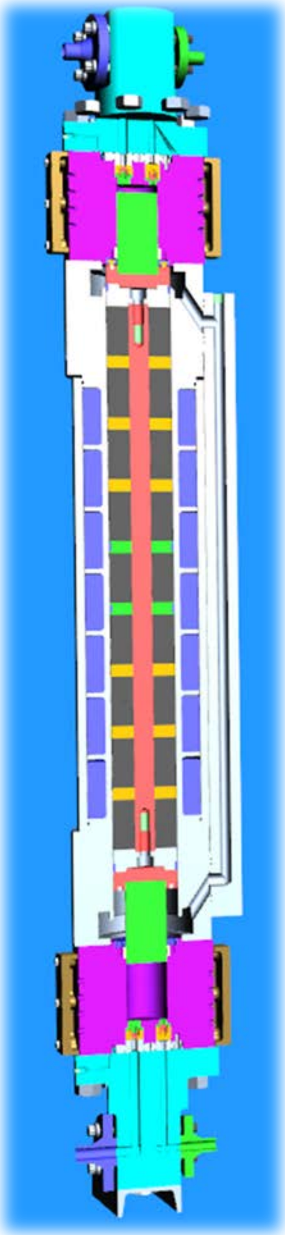

Project ID: PD108

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Overview

Timeline

Description	Date / Timeframe
Project Start Date	9/05/14
Project End Date	10/04/18
Project Duration	4.0 years
Project Progress	2.5 years

Budget

- Total Project Budget: $2,284,553
  - Total Cost Share: $459,160
  - Total Federal Share: $1,825,393
  - Total DOE Funds Spent*: $1,091,641

* As of 3/31/17 (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

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

Approach / Milestones

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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

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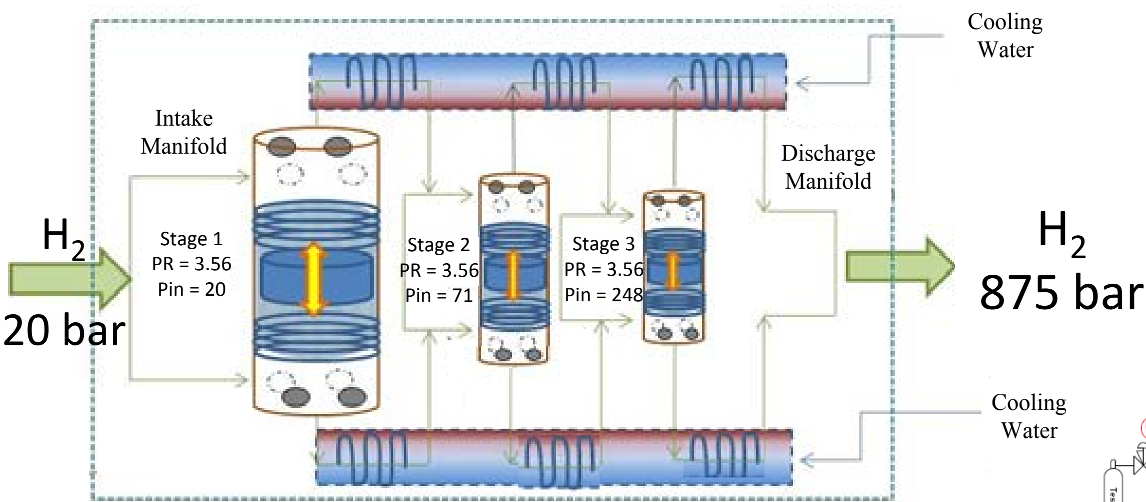
Approach / Milestones

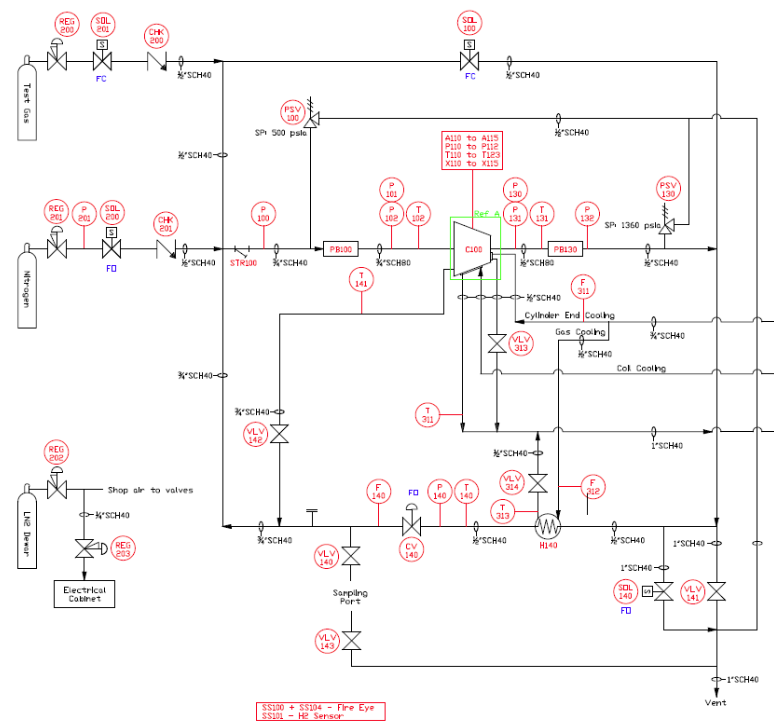
Fiscal Year 2016 – Fabricate and Test LP Stage

Task Title	Milestone Description (Go/No-Go Decision Criteria)	% Complete	Planned Quarter
Detailed Mechanical Design	Provide final fabrication drawings of each compressor component and manufacturing/assembly drawings of the components *(order long-lead items late Q5 or early Q6)*	100	5
Estimate Cost Projection for full-scale version	Deliver cost estimate and calculations for a full-scale version	100	6
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	6
Low Pressure (LP) Stage Compressor Parts Fabrication	Order or fabricate the compressor parts in accordance with the detailed design.	100	7
Low Pressure (LP) Stage Compressor Assembly	Complete assembly of the compressor based on the detailed design.	100	7
Test Stand Construction, Compressor Integration	Manufacture the test stand using the drawings and details created in the previous budget period.	95	7
Commissioning & Startup of Demonstration Model	Verify and report the operability of the compressor and test stand.	15	8
Bench Scale Testing	Report on the completion of the single-stage testing.	0	8

Accomplishments and Progress:
Overall Concept & Test Loop

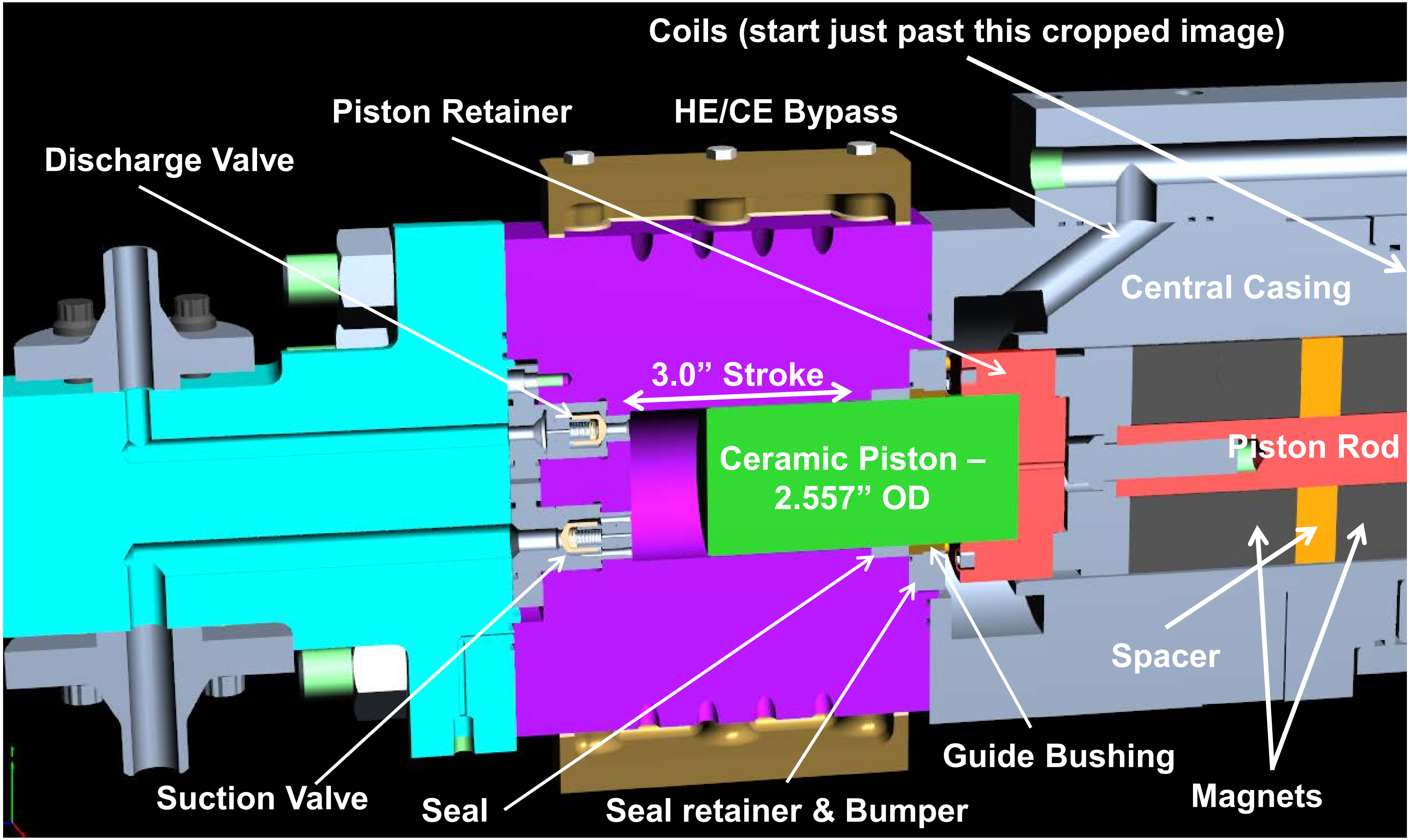


Stage 1 Test Loop P&ID

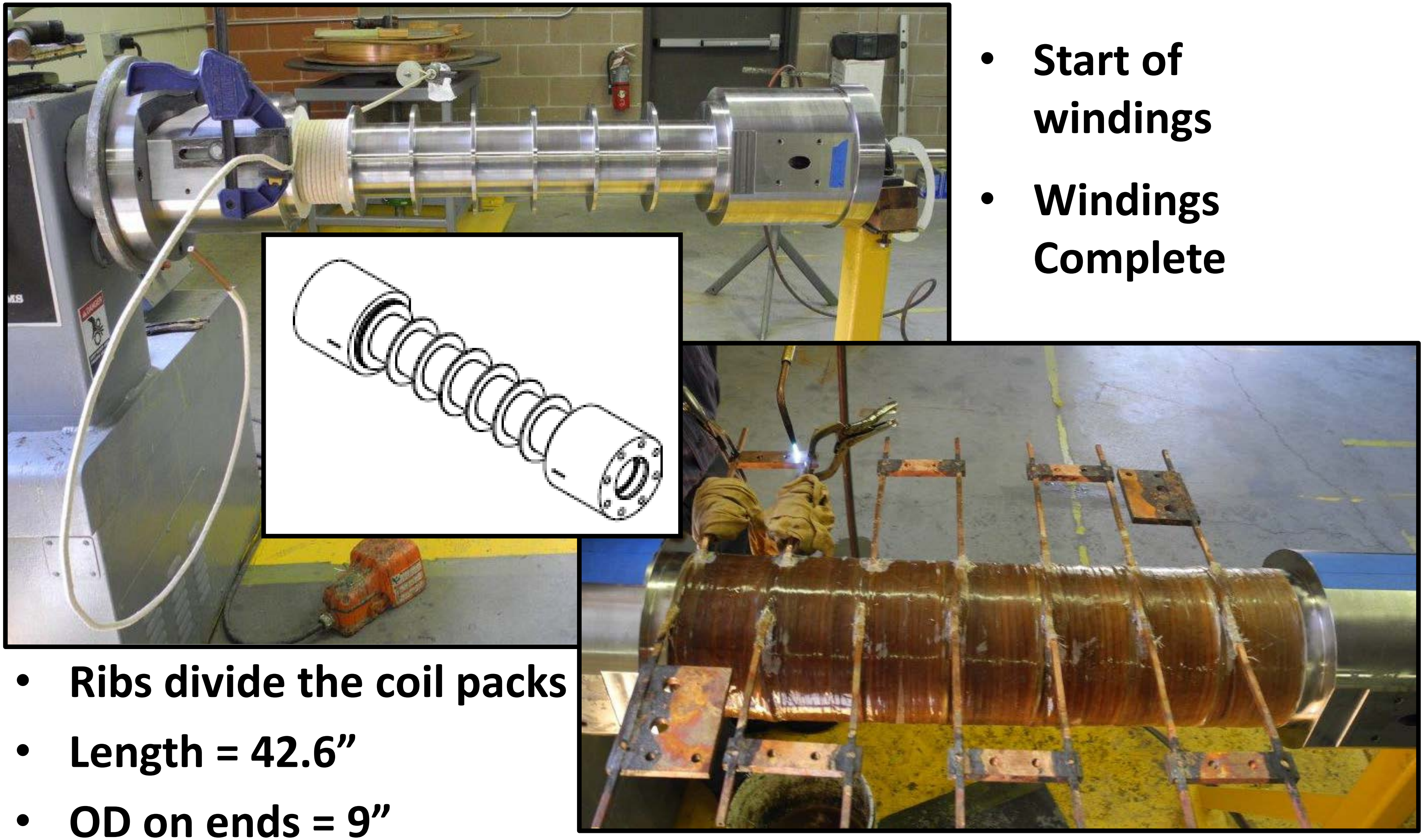


Compress H_2
in 3 stages
with 3 LMRCs

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



Accomplishments and Progress: Winding Coils Onto Casing



- Start of windings
- Windings Complete

- Ribs divide the coil packs
- Length = 42.6”
- OD on ends = 9”

Accomplishments and Progress:
Central Casing at ACI with Windings

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Accomplishments and Progress:
Special Tooling Made for Assembling Magnets on Shaft

Aluminum assembly fixture used on assembly press to place one magnet and one spacer together to form an assembled pair

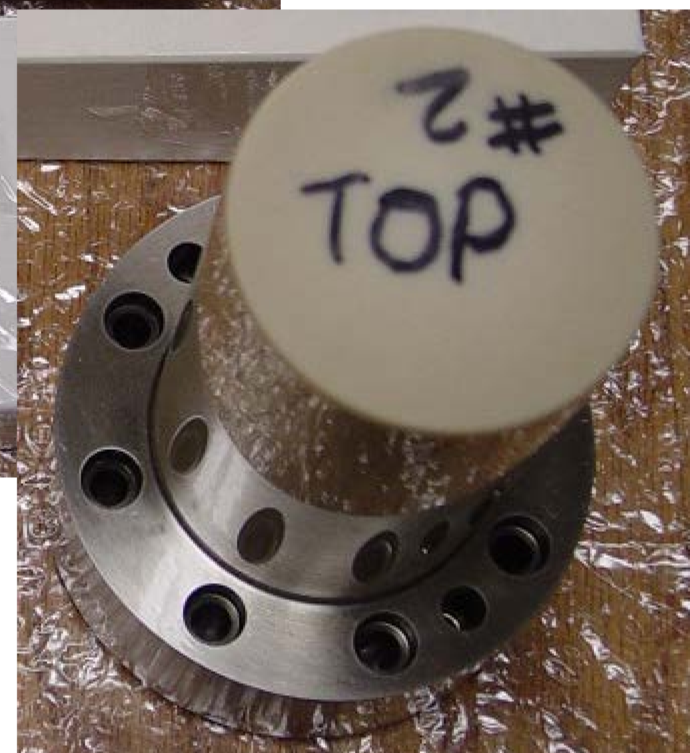
Aluminum pushing fixture with magnet/spacer pair being pushed by the hydraulic press into lower assembly tube

Stainless steel retainer pins inserted to hold upper magnet/spacer pair in place (against the repelling force of the lower magnet) so hydraulic press force can be relieved and the pushing fixture can be removed.

Accomplishments and Progress:
Fabrication and Assembly of Parts

Head with Cylinder

Accomplishments and Progress:
Assembly of Parts – Piston into Holder



Diametral clearances of backup seal

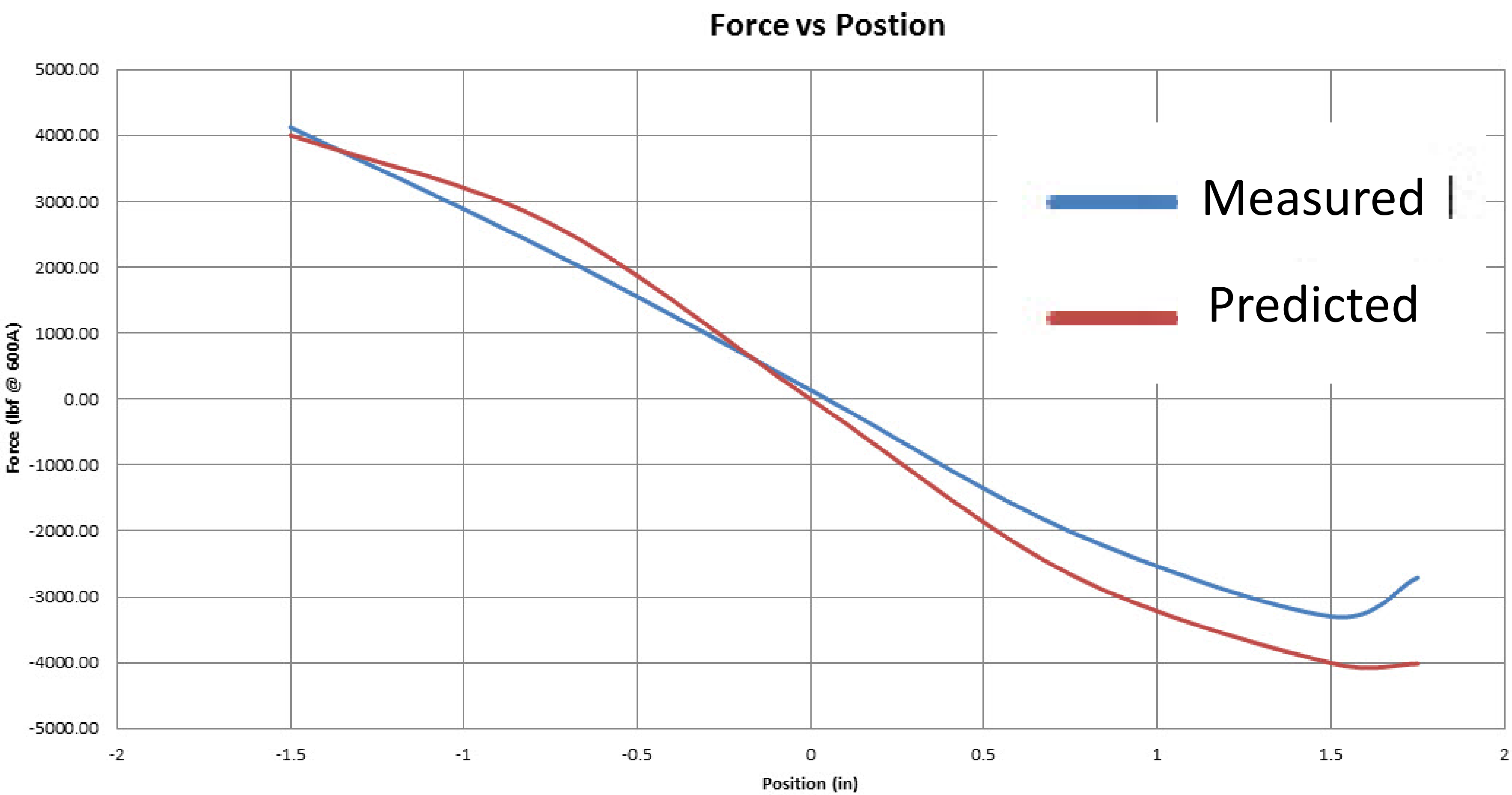
- **0.00012" on #1**
- **0.00010" on #2**

Accomplishments and Progress:
LMRC Installed in Frame at Test Loop

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

Discussions with the Hydrogen Safety Board resulted in a few test loop modifications to increase the overall safety

Accomplishments and Progress: Initial Testing



Initial testing with piston and magnets assembly locked indicates forces reasonably consistent with predictions

Accomplishments and Progress:
Planned Test Matrix

Test No.	Variable Parameters						Decision Point/Other Testing Aspect
	Speed (cpm)	Suction Pressure (psia)	Suction temperature (deg F)	Pressure Ratio	Piston Seal	Test Gas	
Design Point/Commissioning							
1	330	290	80	3.57	Polymeric	Helium	May test at lower pressure to reduce temperatures in system
2	330	290	80	3.57	Polymeric	Hydrogen	Capture hydrogen sample before and after to evaluate contamination
Polymer Seal Performance Check **- If polymer seal performance OK, go to test 3** **- If polymer seal performance not OK, go to test 8**							Seal not performing = mass flow rate is less than 98% of design flow (< 9.8 kg/hr)
Vary Compressor Conditions							
3	300	290	80	3.57	Polymeric	Hydrogen	
4	360	290	80	3.57	Polymeric	Hydrogen	
5	330	260	80	3.4	Polymeric	Hydrogen	
6	330	320	80	3.8	Polymeric	Hydrogen	
7	Max	290	80	3.57	Polymeric	Hydrogen	Test at max speed system can handle
Compressor Internal Inspection & Switch Piston Seals							
8	330	290	80	3.57	Ceramic	Hydrogen	Verify condition of polymeric seals Install ceramic seals Inspect alignment bushing and evaluate wear
Vary Compressor Conditions							
9	300	290	80	3.57	Ceramic	Hydrogen	
10	360	290	80	3.57	Ceramic	Hydrogen	
11	330	290	80	3.4	Ceramic	Hydrogen	
12	330	290	80	3.8	Ceramic	Hydrogen	
13	Max	290	80	3.57	Ceramic	Hydrogen	Test at max speed system can handle
Compressor Internal Inspection							Verify condition of compressor components

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- *Concern that a 100 bar inlet restricts the usefulness of the LMRC in H_2 applications* – The LMRC is designed for a 20 bar inlet pressure. There was a reference to a 100 bar inlet pressure that was only used for a direct comparison of the LMRC design with the newer DOE target.
- *Concerns about the overall efficiency of the compressor + driver* –– The originally specified DOE goal for the project was isentropic efficiency, which is the efficiency of only the compression process. There was no mention of an overall system efficiency goal or requirement. Project focus has been on compression efficiency. The decision to mount coils externally reduced initial development risk, which reduces the efficiency of the driver in this initial prototype. Possible means to improve overall efficiency once proof of concept has been accomplished have been evaluated.
- *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.
- *The project needs input from a compressor manufacturer.* –– For clarification, partner and co-funder, ACI Services designs custom compressors and compressor components, and supplies major components and systems to the industry as well as to the major compressor OEMs, and is highly-regarded in the gas compression industry.

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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

All major suppliers/ manufacturers are in the USA

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Remaining Challenges and Barriers

- **Challenge**: Electric power controller failure
- **Resolution**: Found internal (SwRI) resource with extensive experience designing these devices. Expediting delivery of new device.
- **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

1. Finish Commissioning
2. Testing
3. Data Analysis

Confirm the Go/no-go criteria are met:

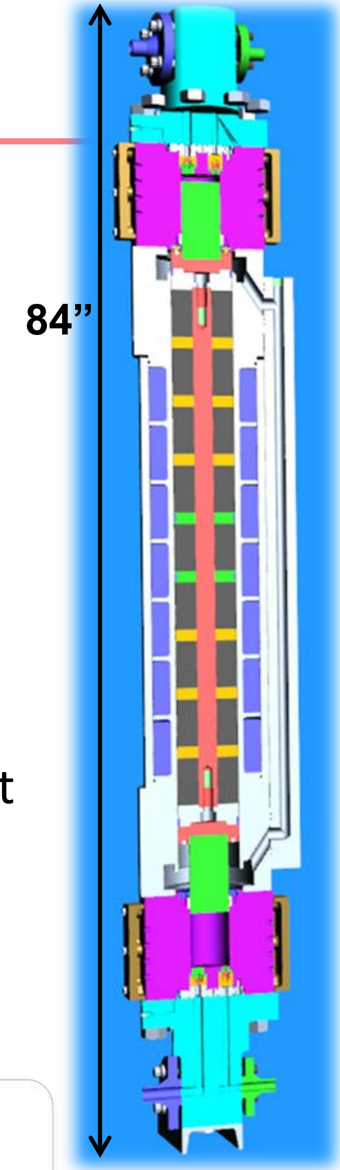
- ❑ flow rate of 10 kg/hr of Hydrogen ±10%,
- ❑ a discharge pressure of ~71 bara (1030 psi) ±10%, and
- ❑ an isentropic efficiency of > 73% is achieved

4. Proceed to BP3 – Fabricate stages 2 and 3 then test stages 2 and 3 in series with stage 1

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

Summary

- BP1 complete, BP2 is nearly complete
- Efficiency predictions greater than 95%
- LMRC & Test Loop are fabricated & assembled
- Currently no technical/commercial off-ramp issues identified



Questions?

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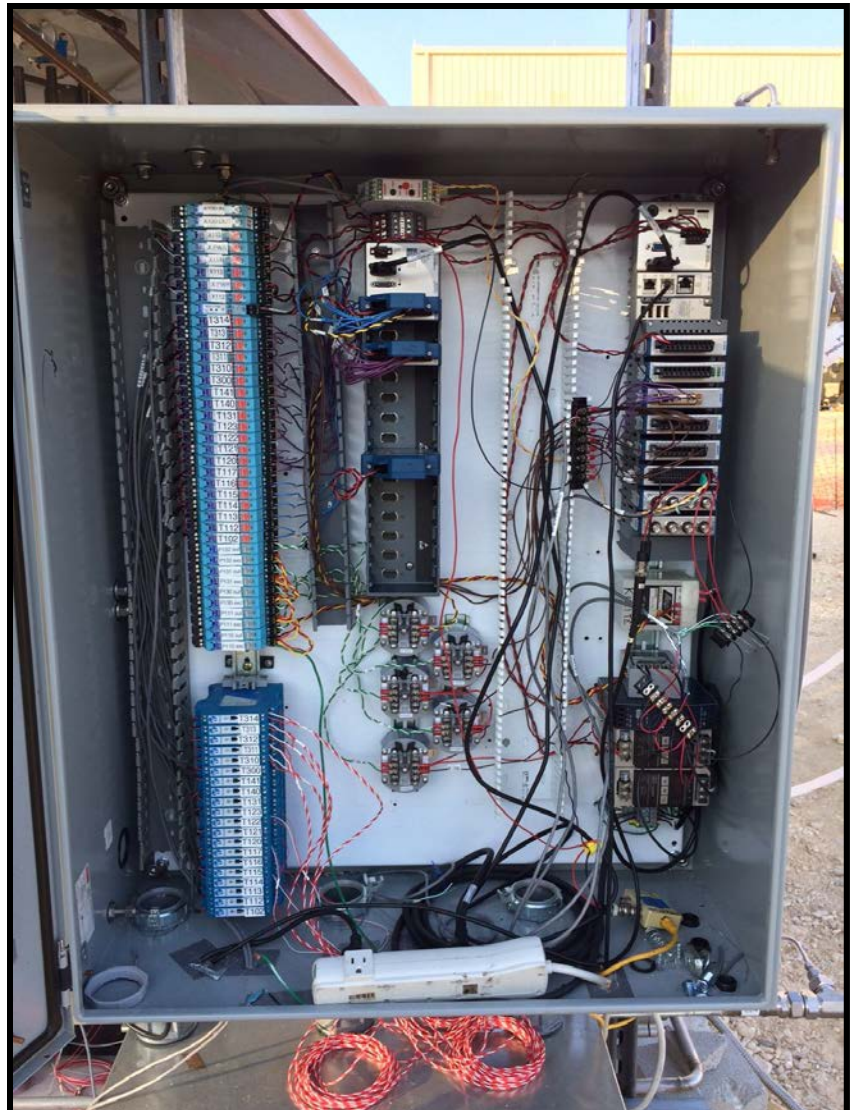
Technical Back-Up Slides

Technical Backup Slide

DAQ wiring is complete



Technical Backup Slide

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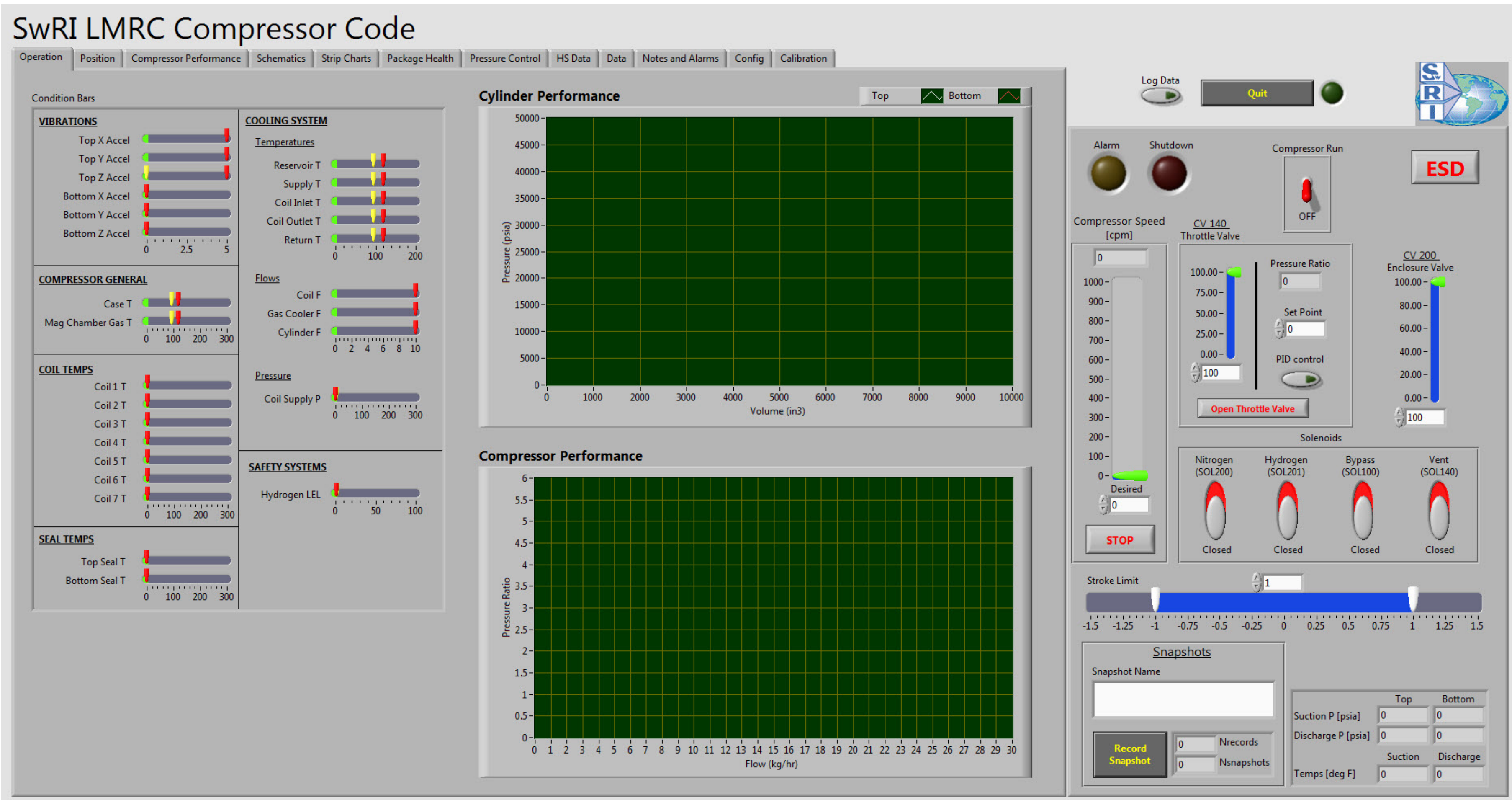
Control panel for controlling LMRC motion and providing real-time feedback during operation



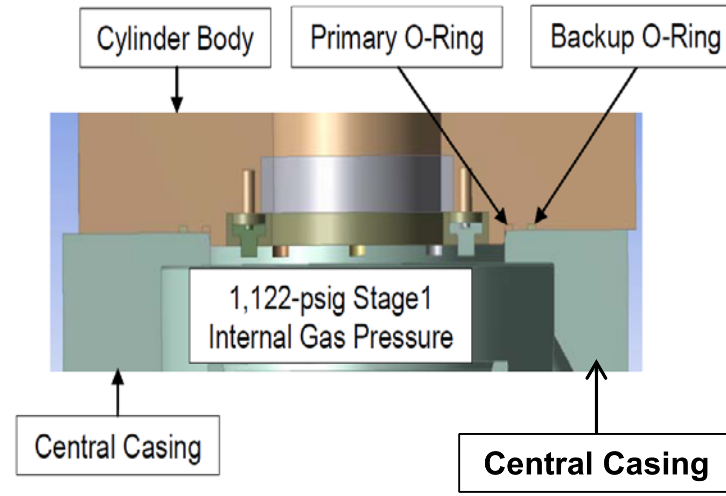
Technical Backup Slide

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 °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)	9.17×10^{-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.CV	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
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 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)