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

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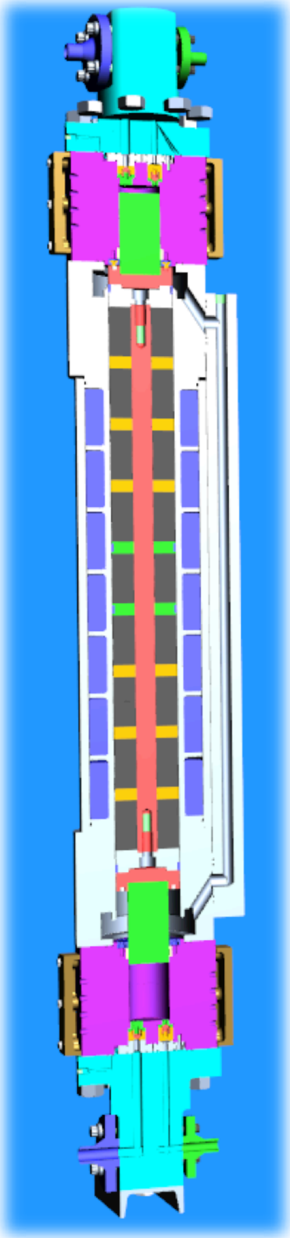
June 7, 2016



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ACI Services, Inc.

Project ID: PD108

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Overview

Timeline

Description	Date / Timeframe
Project Start Date	9/05/14
Project End Date	10/04/17
Project Duration	3.0 years
Project Progress	1.5 years

Budget

- Total Project Budget: $2,284,553
  - Total Cost Share: $459,160
  - Total Federal Share: $1,825,393
  - Total DOE Funds Spent*: $624,690

* As of 4/6/15, includes ACI's March 2016 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 2012 MYRD&D for 2020

Partners

- **ACI Services**

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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
- BP1: Analyzed and Designed LMRC to be tested in BP2 & BP3
- This Budget Period (Fiscal Year 2016, BP2):
  - Detailed Mechanical Design
  - Estimated Cost Projection for full-scale version
  - Designed Compressor Test Stand for LP Stage

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Approach / Milestones

Fiscal Year 2015 – Design All 3 Stages

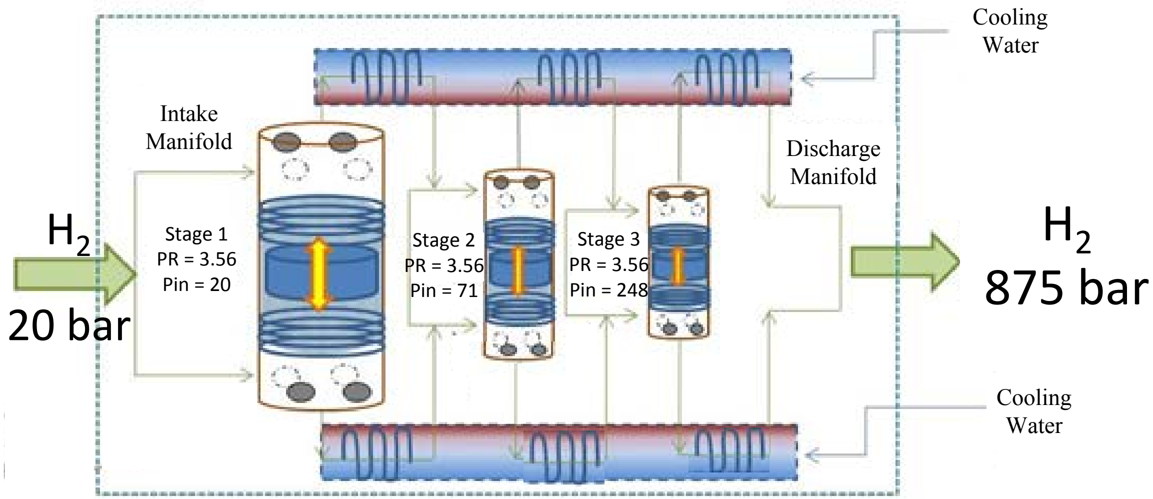
Task Title	Milestone Description (Go/No-Go Decision Criteria)	% Complete
Stage Sizing	Provide cylinder size for each stage and accompanying calculations.	100
Basic Mechanical Design	Provide FEA results and analysis, basic structural design, and material selection.	100
Linear Motor Design	Provide linear 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

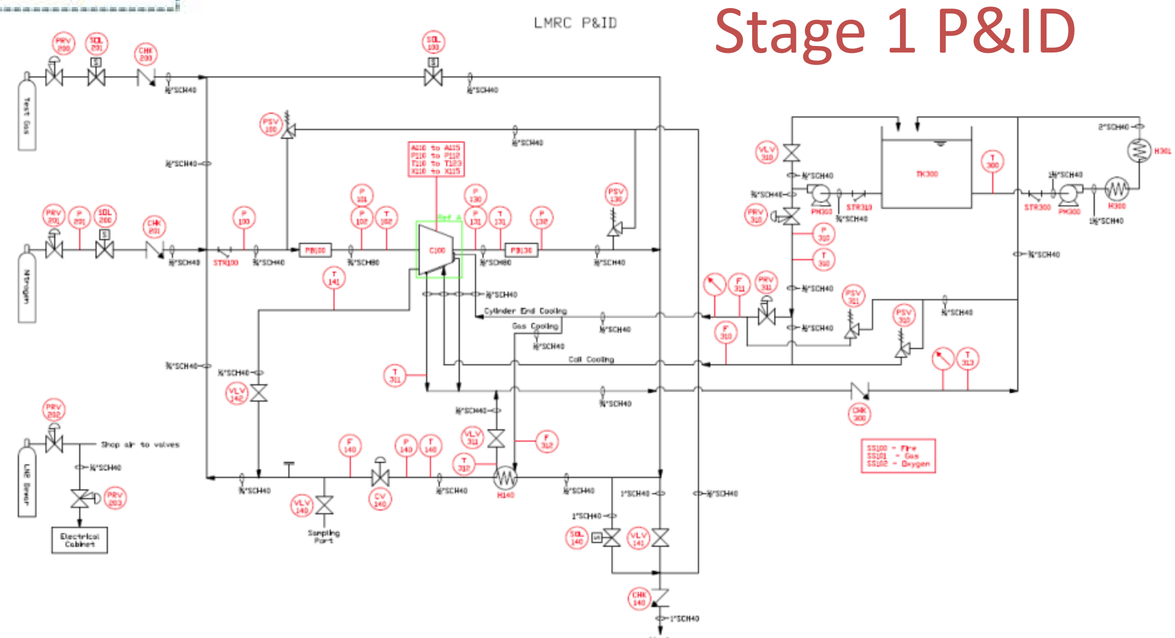
Fiscal Year 2016 – Fabricate and Test LP Stage

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.	90	6
Low Pressure (LP) Stage Compressor Parts Fabrication	Order or fabricate the compressor parts in accordance with the detailed design.	30	7
Low Pressure (LP) Stage Compressor Assembly	Complete assembly of the compressor based on the detailed design.	0	7
Test Stand Construction, Compressor Integration	Manufacture the test stand using the drawings and details created in the previous budget period.	0	7
Commissioning & Startup of Demonstration Model	Verify and report the operability of the compressor and test stand.	0	8
Bench Scale Testing	Report on the completion of the single-stage testing.	0	8

Accomplishments and Progress: Overall Concept & Test Loop



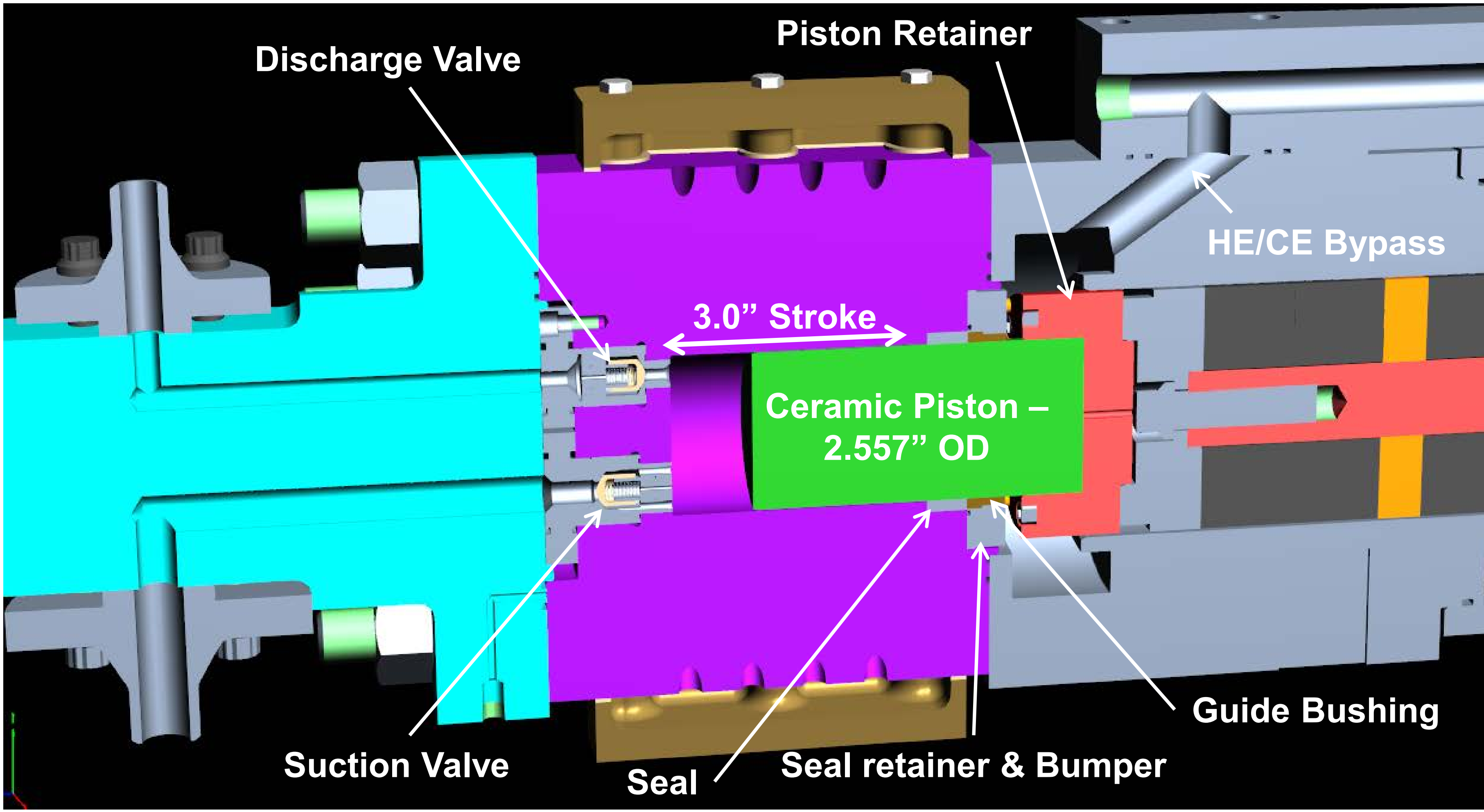
Stage 1 P&ID



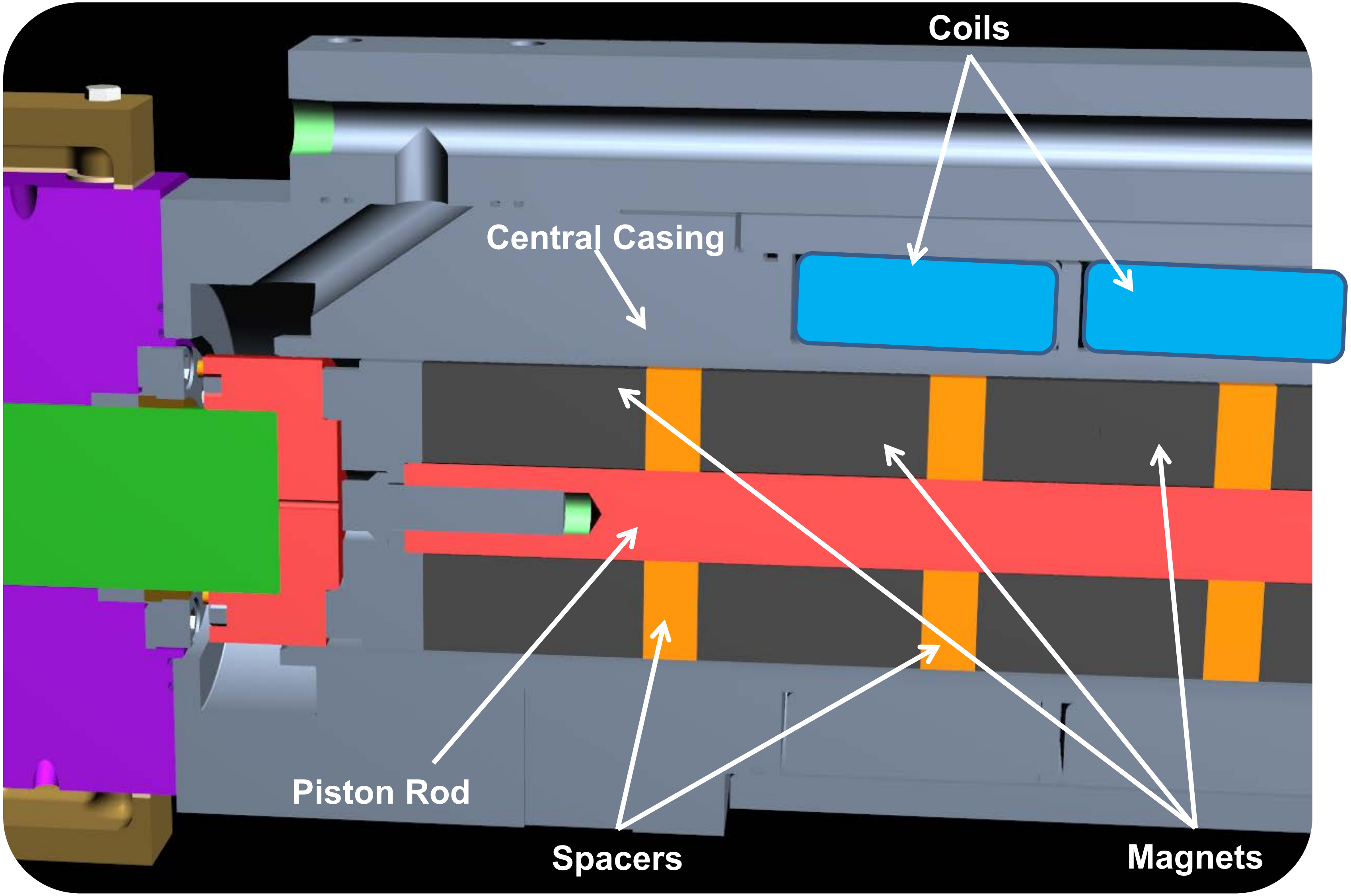
Compress H_2 in 3 stages with LMRCs

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

- Structural design created & FEA performed for each of the 3 stages
- Materials selection is complete



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



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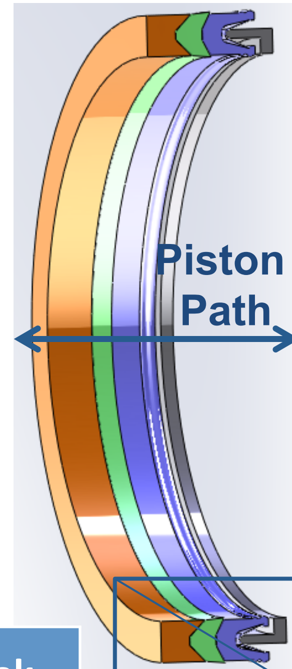
Accomplishments and Progress: Dynamic Seal Design/Analysis

A two step analysis was performed:

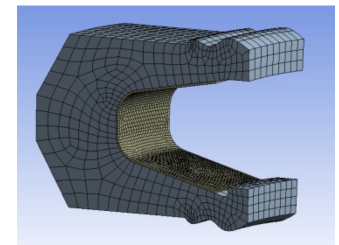
1. FE analysis of seal under range of expected pressure conditions to determine how gap size varies & seal deforms
2. Reynold's equation coupled with spring representation of seal to predict the leakage rate

Predicted seal leak rate is acceptable:

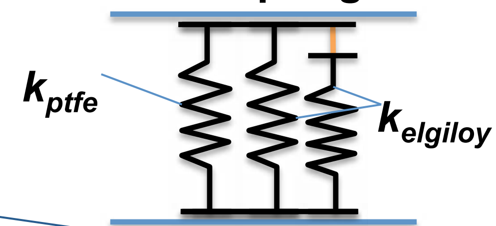
Stage	Individual Seal Leak Rate (g/hr)	Individual Seal Leak Rate (% of full flow)
1	1.1	0.01
2	8.0	0.08
3	35	0.35

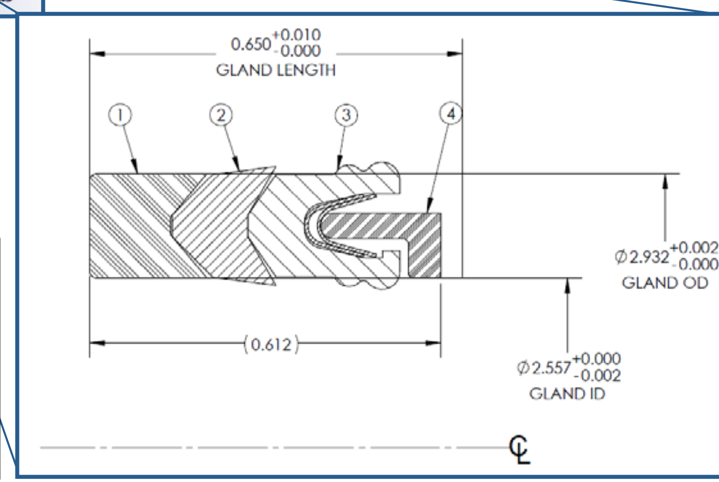


Finite-Element Model

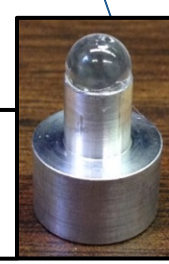


Reduced Spring Model



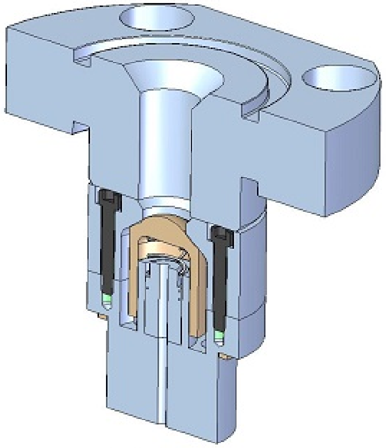


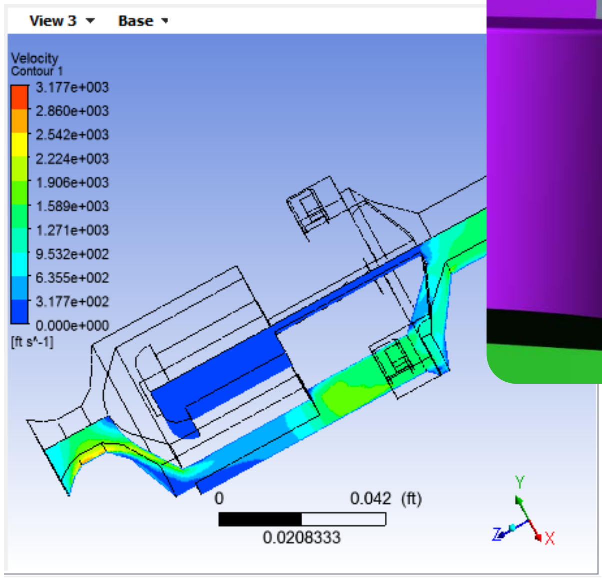
Ceramic seal and tentatively a DLC poly seal are alternatives



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
- Stages 1, 2, and 3 valves are designed and fine-tuned with performance analysis

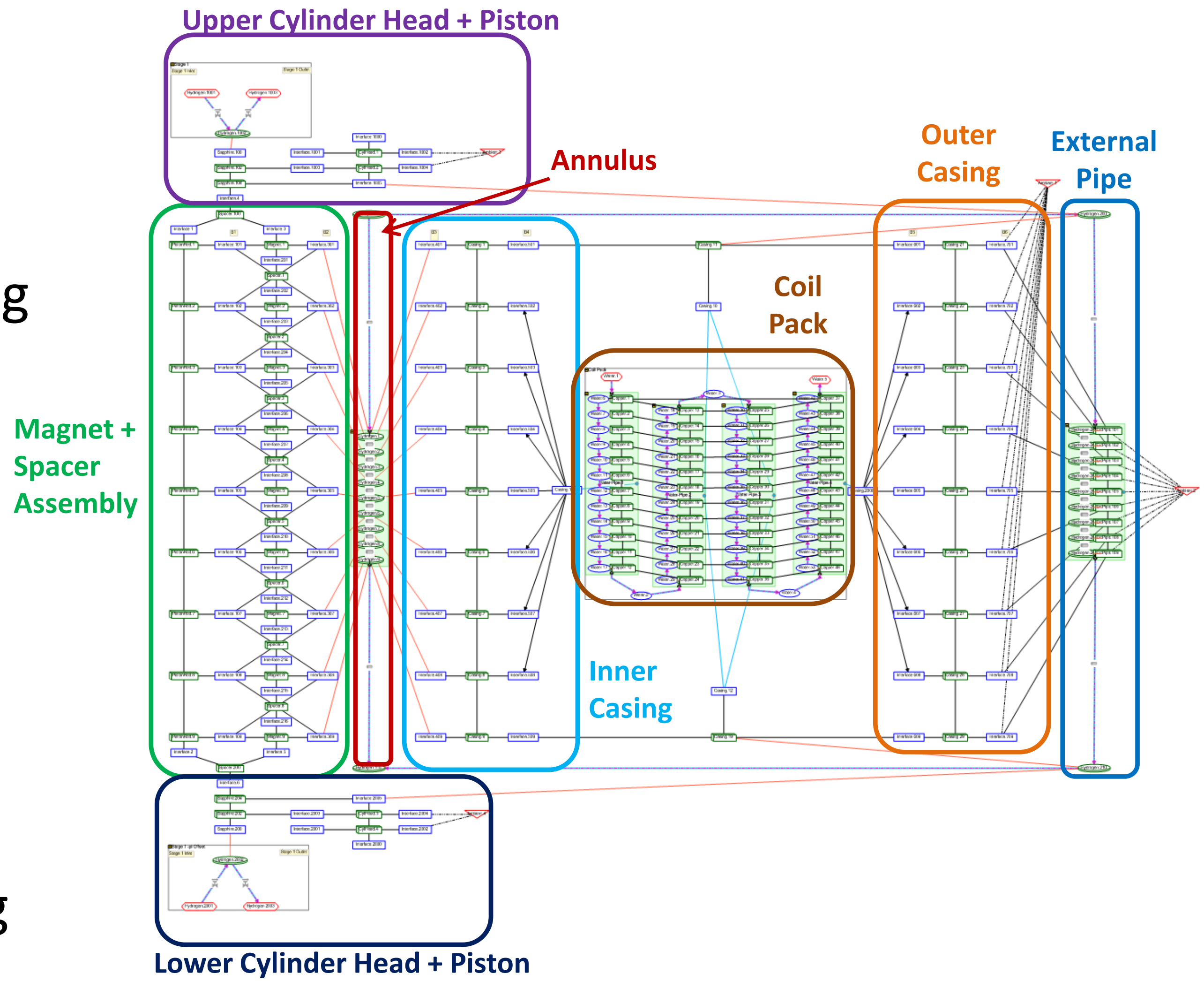




Accomplishments and Progress:
LMRC Cooling System Design

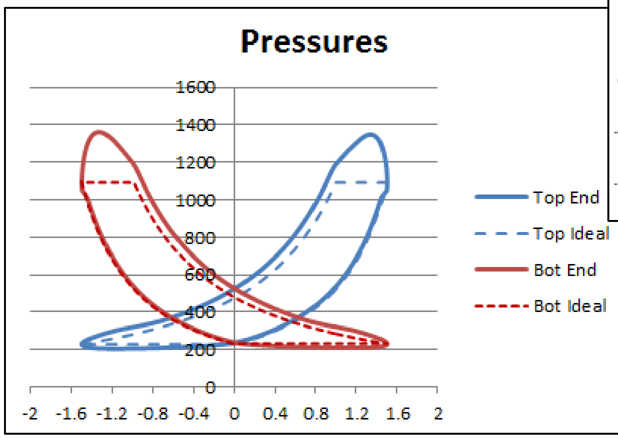
Coil cooling

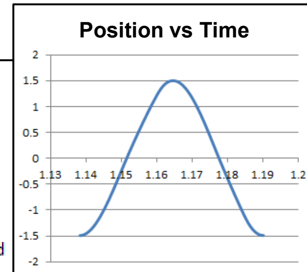
- Average value of 560A will be traveling through the coils
- Therefore a conjugate heat transfer model (SINDA/FLUINT) was used to determine conditions required for adequate cooling



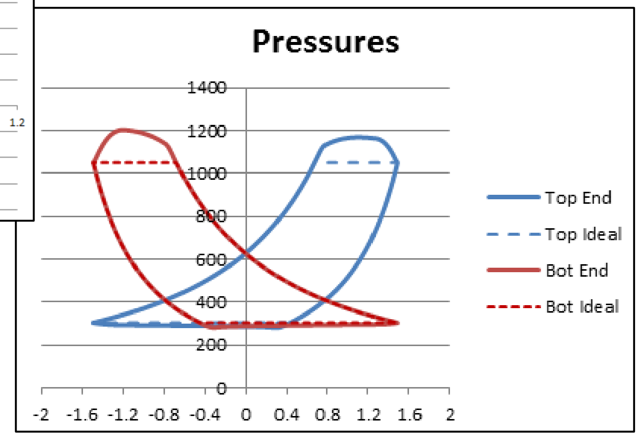
Accomplishments and Progress:
Performance Prediction/Control Scheme

Original Valve





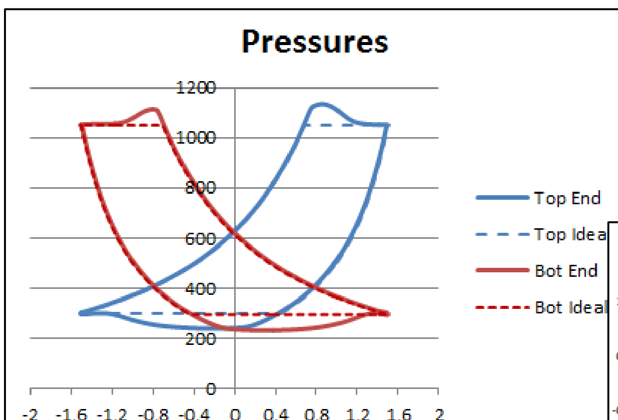
New Valve



Isen. Eff 73%

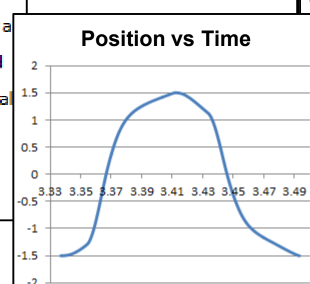
Max Force Scheme (22 cps)

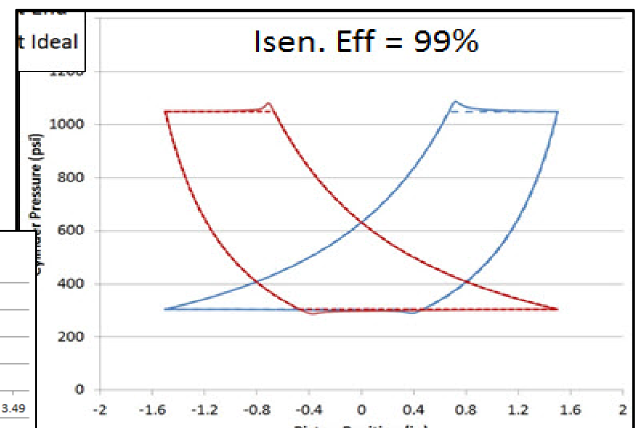
Isen. Eff 89%



Isen. Eff 88%

Custom Scheme (6 cps)





1st Stage Isen. Eff 99%

Target is > 95%

97% 2nd Stage, 97% 3rd Stage

Accomplishments and Progress: System Efficiency and Specific Energy

- LMRC predicted efficiency & specific energy:
  - 20% overall 3 stage (and 20% per stage)
  - 9.2 kWh/kg overall (2.8 to 3.5 kWh/kg per stage)
- Could be > 90% by implementing design improvements
  - Move coils to inside of casing.
  - Locate coils as close as possible to the magnets.
  - Increase # of rows of coils (predictions indicate this is only useful after moving coils closer to magnets)
  - Use superconducting coils. (This may require complex additional system to keep the coils super cold.)
  - Further optimization of control scheme.
- ~1.3 kWh/kg is expected with advanced LMRC actuator design & 100 bar inlet pressure (1.6 is 2015 MYRDD target)

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Accomplishments and Progress: Full Scale (100 kg/hr) Cost and Life Estimates

- 3 LMRCs in parallel per stage = 9 LMRCs total
- operating at ~930 cpm with ceramic seals

	Conventional Reciprocating Compressor Technologies	LMRC
Seal Life	12-18 months	48 months (ceramic)*
Packing Life	3 years	Infinite (NO PACKING)
Valve Life	1-3 years	4 years
Isentropic Efficiency	2015 goal > 73%, 2020 goal > 80%	80% for all 3 stages in series
O&M Cost	2015 goal < $10,000/year, 2020 goal < $4,800	$3,300 / year
Mnfactr Cost	2015 goal < $400,000, 2020 goal < $240,000	$284,000**

2015 and 2020 goals are from the 2012 MYRD&D plan per the goals of the project contract

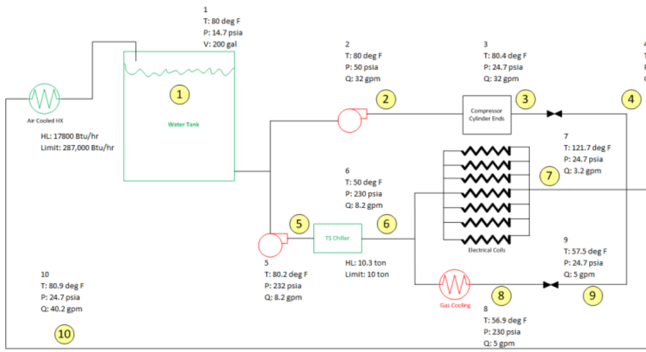
* Assumes operation time is ~1/4 of a 24 hour day

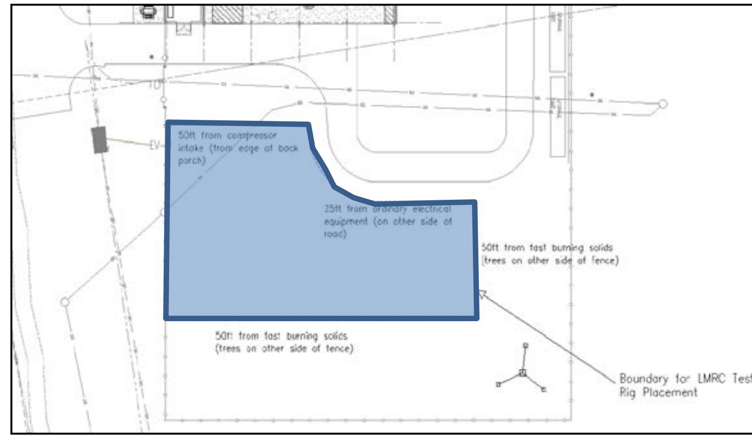
** Includes inter-stage piping and coolers. Assumes ~100 units built per year. 2007$ like targets

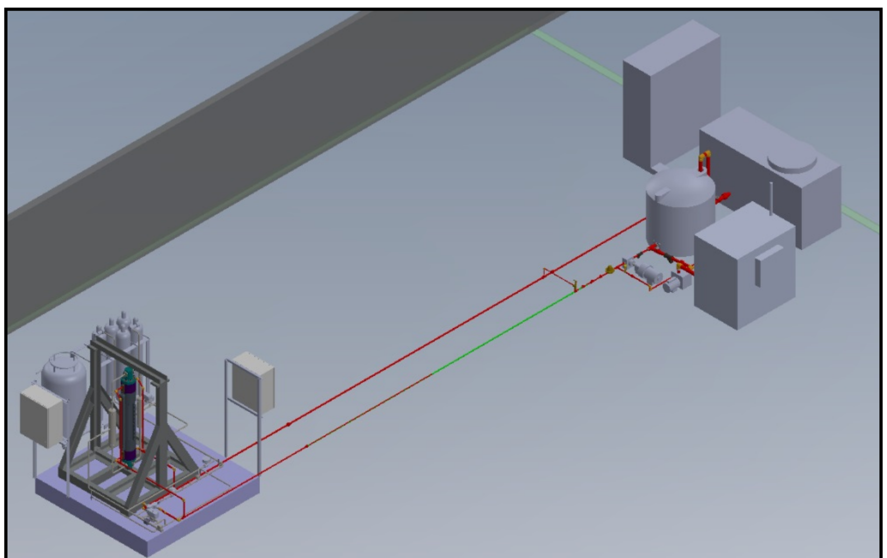
The most understood path to 100 kg/hr was used. Larger may be better, but harder to quantify. Also, overall system efficiency gains (design change) should significantly reduce the cost per LMRC.

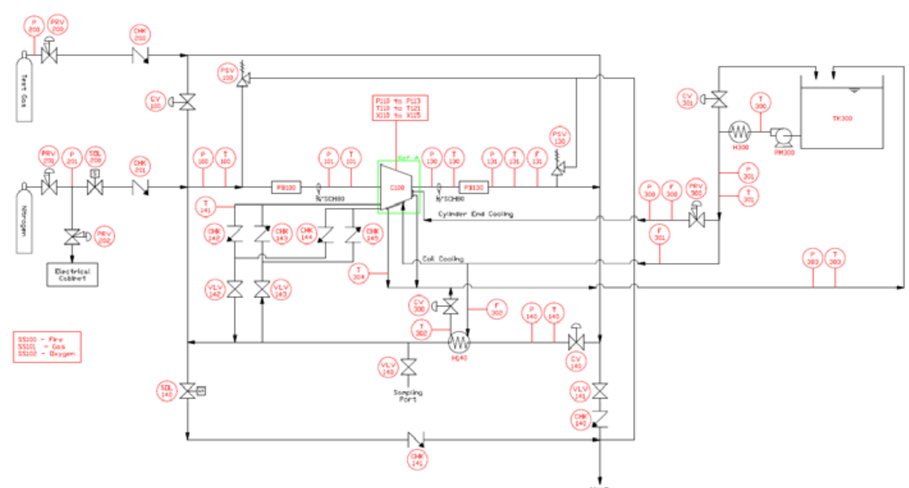
Accomplishments and Progress: Test Loop Design

- After review of OSHA, Occupancy classification letter filed with City of San Antonio, and SwRI requirements, test stand will be located outside building with required electrical supply
- P&ID
- 3D model









Accomplishments and Progress:
Responses to Previous Year Reviewers' Comments

- Cost analysis requested – Described in a previous slide
- Flow rate questioned – Calculations described in quarterly reports
- Thermal management questioned– Described in a previous slide
- H_2 inside of magnets chamber? – Yes, intentionally
- Dynamic seal leak rate questioned – predictions acceptable per detailed analysis
- Control system required to manage power delivery questioned – power controller from electric automotive industry

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 ceramic piston design
- Dexter Magnetic Technologies – Neodymium Iron Magnets
- TechniCoil – Coils and winding
- Enterprise Power Corp. – Power Supply/Controller

All major suppliers/manufacturers are in the USA

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Remaining Challenges and Barriers

- **Challenge**: Seal life
- **Resolution**: Ceramic seal and tentatively a DLC poly seal are alternatives
- **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

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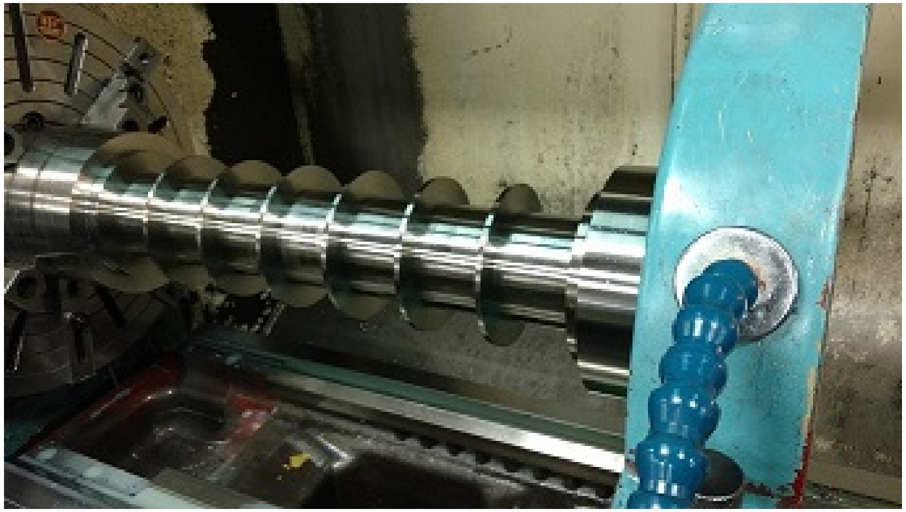
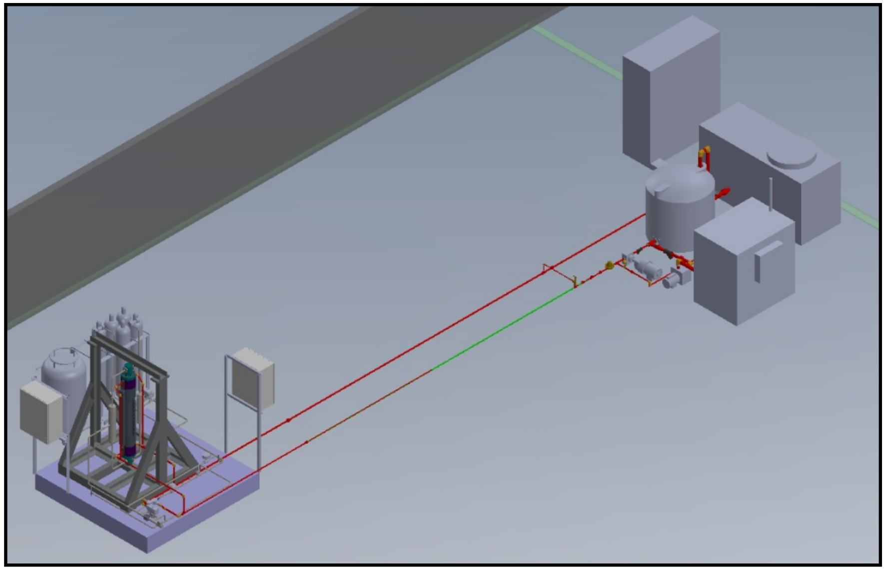
Proposed Future Work

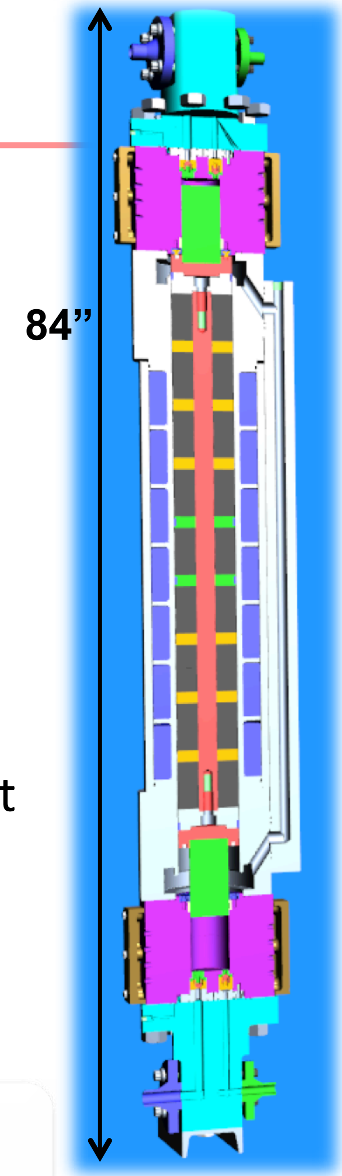
1. Parts Fabrication
2. Test Loop Construction
3. Commissioning
4. Testing
5. Data Analysis
6. BP3 – Fabricate stages 2 and 3 then test stages 2 and 3 in series with stage 1





Summary

- BP1 complete = Stage 1 overall design complete
- Efficiency predictions greater than 95%
- Fabricating and purchasing parts/components
- Currently no technical/commercial off-ramp issues identified



Questions?

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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

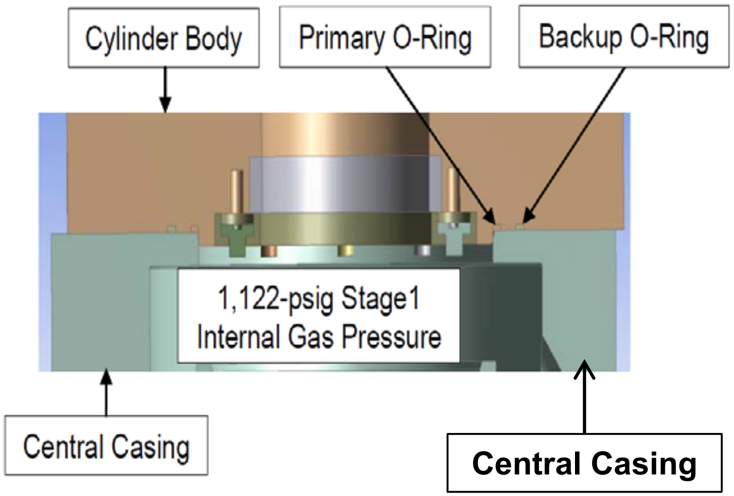
3. Explosive decompression resistant

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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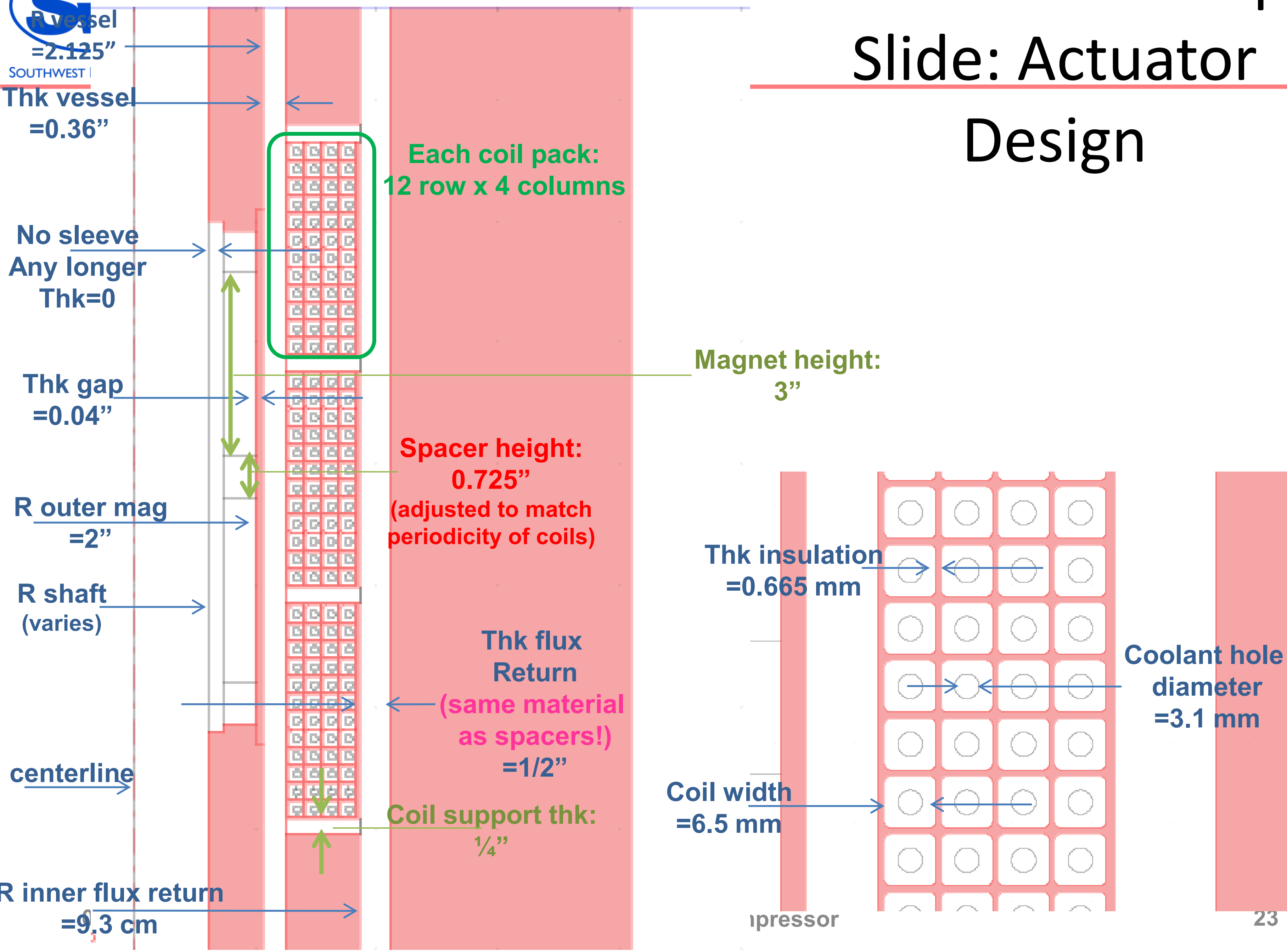
Technical Backup Slide

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					4.19×10^{-6}		1
Piston Holder Alternate Mat'l	Kovar K-Alloy K94610	75 ksi	40 ksi	NA	Magnetic	3.3×10^{-6}	20.0×10^{6} psi	1,6
	ASTM F-15 Temper A							
Piston	Ceramic (95% Zirconia, 5%Yttria)	36 ksi	NA	NA	NA	5.8×10^{-6}	30×10^{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
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 - Thar and https://www.ceramicindustry.com/ext/resources/pdfs/
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)

Technical Backup Slide: Actuator Design



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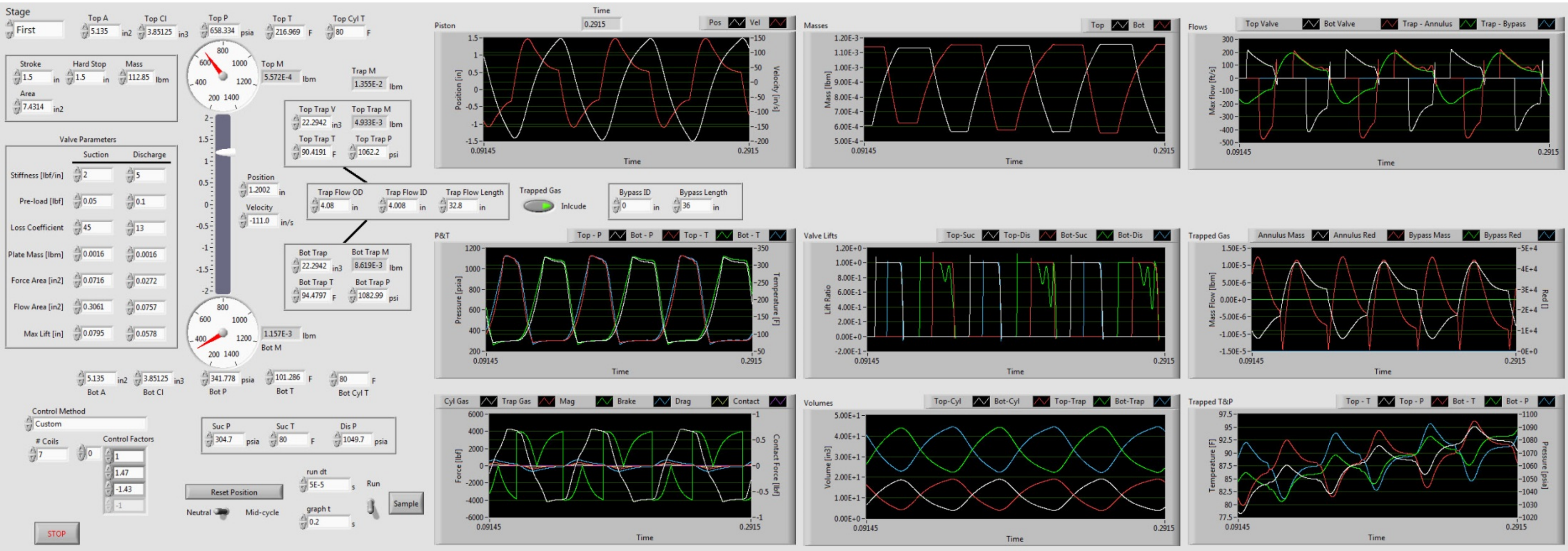
Technical Backup Slide

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



Seal-Sapphire COF Determination

- It was determined through pin-on-disk testing that the coefficient of friction (COF) for sapphire on PEEK is 0.15
- Due to the higher than expected COF, two other seal options are planned for testing
  - Poly seal with DLC
  - Sapphire or ceramic seal (~0.0001”-0.0005” clearance)