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

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Norm Shade (project partner and cost share provider point of contact)

Southwest Research Institute
ACI Services

April 30, 2019

Project ID # in003

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**Timeline**

<table>
<thead>
<tr>
<th>Description</th>
<th>Date / Timeframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Start Date</td>
<td>9/5/14</td>
</tr>
<tr>
<td>Project End Date</td>
<td>9/4/19</td>
</tr>
<tr>
<td>Project Duration</td>
<td>5 years</td>
</tr>
<tr>
<td>Project Progress</td>
<td>4.5 years</td>
</tr>
</tbody>
</table>

**Budget**

- Total Project Budget: $2,294,553
- Total Cost Share: $469,160
- Total Federal Share: $1,825,393
- Total DOE Funds Spent*: $1,304,412

* As of 2/12/19

**Barriers**

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Compressor Efficiency</td>
<td>&gt;73% Isentropic Efficiency*</td>
</tr>
<tr>
<td>Capital Cost</td>
<td>&lt;$240,000 per compressor**</td>
</tr>
<tr>
<td>O&amp;M Costs</td>
<td>&lt;$4,800 per year**</td>
</tr>
</tbody>
</table>

* 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
- **Libertine**: Project Partner, motor
**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 item

**DOE Technical Targets:**
- Flow rate of 10 kg/hr of Hydrogen ±10%,
- Discharge pressure of ~71 bara (1030 psi) ±10%, and
- Isentropic efficiency of > 73% is achieved

- **BP1:** Analyzed and Designed LMRC to be tested in BP2 & BP3
- **BP2:** Built and tested prototype LMRC, stage 1
  - 8.2 kg/hr H₂ gas flow
  - Discharge Pressure = 478 psia
  - Isentropic Efficiency ~80-90%
- **BP3** – Current Budget Period:
  - Incorporated Libertine motor design with existing LMRC compression chamber
  - Fabricate and assemble the more efficiently designed LP-stage LMRC
  - Modify compressor test stand for new LMRC design
  - Test the more efficient stage 1 compressor
# APPROACH / MILESTONES: BP1

## Fiscal Year 2015 – Design All 3 Stages

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

## Budget Period 1: Complete

04/30/2019

SwRI H2 Linear Compressor
## APPROACH / MILESTONES: BP2

### Fiscal Year 2016-mid2018 – Fabricate and Test LP Stage

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

### Budget Period 2: Complete
## APPROACH / MILESTONES: BP3

### Fiscal Year 2019 – Fabricate and Test More Efficient LP Stage

<table>
<thead>
<tr>
<th>Task Title</th>
<th>Milestone Description</th>
<th>% Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Update Basic Mechanical Design of Central Casing to Improve Motor Efficiency</td>
<td>To implement the improved design, the basic mechanical design, linear motor design, cooling system design, materials and coatings selection, and performance predictions will need to be updated.</td>
<td>100</td>
</tr>
<tr>
<td>Update Detailed Mechanical Design</td>
<td>Produce final manufacturing drawings for the redesigned LP stage</td>
<td>90</td>
</tr>
<tr>
<td>Compressor Parts Fabrication</td>
<td>Fabricate and order parts for the LP stage.</td>
<td>25</td>
</tr>
<tr>
<td>Compressor Assembly</td>
<td>Assemble the LP stage</td>
<td>0</td>
</tr>
<tr>
<td>Compressor Integration into</td>
<td>Completely install the redesigned LMRC stage 1 in the test</td>
<td>0</td>
</tr>
<tr>
<td>Commissioning and Startup of Demonstration Model</td>
<td>Demonstrate and report the operability of the complete compressor and test stand.</td>
<td>0</td>
</tr>
<tr>
<td>Bench Scale Test Measurements</td>
<td>Demonstrate to DOE that the system is operational at the specified criteria. Specific energy goal = 1.6 kWh/kg or lower.</td>
<td>0</td>
</tr>
<tr>
<td>Data Analysis for Redesigned LP Compressor Testing</td>
<td>Deliver the final report documenting performance measurements and capability of the compressor to meet the specified criteria. The specific energy goal is 1.6 or less.</td>
<td>0</td>
</tr>
</tbody>
</table>

Budget Period 3: In Progress

04/30/2019

SwRI H2 Linear Compressor
Overall Concept = Compress $\text{H}_2$ in 3 stages with 3 LMRCs

The BP3-LMRC will be a single acting (one end of compression instead of 2) compressor for the first stage of compression. It will initially be tested at half the target flow, and then it will be tested at the target flow by doubling the speed/frequency.
ACCOMPLISHMENTS AND PROGRESS:
3D MODEL: MOTOR DESIGN CHANGED

- Motor Design Changed
- Required adapter to connect new motor to existing compression chamber

Compression chamber will not be modified
No Changes

Existing LMRC

04/30/2019
SwRI H2 Linear Compressor
ACCOMPLISHMENTS AND PROGRESS:
3D MODEL: PISTON CLOSE-UP

- Ceramic Piston – 2.557” OD
- Suction & Discharge Valves
- Bypass
- Seal retainer & Bumper
- Seal
- Coils
- Piston Retainer
- Magnets
- Piston Rod

3.0” Stroke

04/30/2019

SwRI H2 Linear Compressor
ACCOMPLISHMENTS AND PROGRESS:
Electrical Controller Will Be Replaced

Old Controller

- Old controller: Capable of moving the translator, but insufficient for the overall control of the LMRC motor

New Controller

- New controller: Libertine has tested the new controller on previous project, and it has been found to be a reliable controller
ACCOMPLISHMENTS AND PROGRESS:
Libertine Motor Design Modified

Existing successful Libertine linear machine design → modified for hydrogen application and for pressure containment
- Previous materials maintained except where modifications required for resistance to hydrogen embrittlement and/or increased strength.
  - Translator shafts changed to AISI 410 SST with special heat treatment to limit the hardness.
  - Inner and outer housing material upgraded to higher strength 6061-T6 material.
- Thickness of inner housing increased to accommodate required internal pressure.
- O-ring materials upgraded to V1238-95 fluorocarbon.
- Redundant seals added at all joints for safe containment of hydrogen gas.
- Center shaft upgraded to A286 alloy to increase strength.
- Will disassemble, inspect and rebuild one compressor end with new seals, bushing and shock absorbers.

Libertine motor design modified for H₂ & pressure containment
ACCOMPLISHMENTS AND PROGRESS: Libertine Motor Design Modified continued

Existing successful Libertine linear machine design → modified for H₂ application & pressure containment

- Adapter housing added between existing compressor end and Libertine motor
- End housing added to accommodate dual encoders and provide pressure balance chamber
- High-pressure wire feed-through connectors sourced and integrated into the design
- Redesigned bumpers/shock absorbers – increases force absorption & fits on both sides of single piston
- Designed anti-rotation features to maintain encoder shaft alignment.
- Developed special potting tooling

Libertine motor design modified for H₂ & pressure containment
ACCOMPLISHMENTS AND PROGRESS:
Tested Encoder in Hydrogen Environment

- Planned encoder had never been tested in a hydrogen environment
- Encoder and track pair operation was tested prior to hydrogen exposure
- Encoder and track exposed to greater than 1000 psig (stage 1 discharge pressure) for at least 8 hours
- Follow-up testing of the encoder and track pair confirmed successful operation even after the hydrogen exposure

Tested encoder in pressurized hydrogen environment
ACCOMPLISHMENTS AND PROGRESS:
Pumping-losses results

• A simplified gas flow model was developed to evaluate pumping losses in the motor chamber
  • An assumed motion profile applied to model to evaluate gas pressures and flows

Flow restrictions in motor chamber found to be insignificant
  • Resulting pumping losses therefore negligible
  • Still need to evaluate influence of pressure change on performance
ACCOMPLISHMENTS AND PROGRESS: 
Responses to Previous Year Reviewers’ Comments

• It also is not clear why building the first low-pressure stage of the hydrogen compressor is the appropriate approach to building this three-stage compressor. – Building the 1st stage, while keeping in mind the requirements of stages 2 and 3, allows a significant advancement of the LMRC prototype closer to commercialization.

• Solving this problem (position sensing for motor control) is essential to future success. – Libertine has overcome this issue with their proven motor design, and Libertine is now part of the project team.

• The safety and safe operation of the test rig is a concern...Slide 9 [from 2018 AMR] shows...the label PSV100 (product specification to 500 psi) does not match the ink-pen-written setpoint of 1360 psi on the side of the valve body...attention to detail is critical...[as it] helps reduce the chance of accidents – Great attention to detail! The reviewer is correct that the PSV with the ink-pen-written value of ‘1360’ was in the wrong location. Prior to performing any testing, there were many system checks performed, and it was noticed that the suction and discharge PSV’s were installed in the wrong locations. Therefore, the PSV’s were swapped before any damage and/or safety issues could occur.
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
• **Thar Energy** – Project partner, seal and ceramic piston design and fabricator
• **Libertine** – Project partner, New (more efficient) Motor & Power Controller

SwRI, ACI Services, and Libertine worked closely to re-design and integrate the Libertine motor into the new LMRC.
REMAINING CHALLENGES AND BARRIERS

• **Challenge**: Maintaining Schedule
  • **Resolution**: Weekly conference calls between the US and UK to keep everyone up-to-date on progress and deadlines

• **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
Fabricate and assemble the new, more-efficient LMRC, and then test it to confirm the project criteria and goals are sufficiently 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
- Closer to commercialization
- Goal – Overall efficiency at or below 1.6 kWh/kg (FCTO’s specific energy target of 1.6 kWh/kg)

Libertine: Slotted stator machine *conceptual design & performance simulation* after testing results are analyzed

*Any proposed future work is subject to change based on funding levels.*
Next phase(s) & path to commercialization of the 3-stage system (*not in BP3 scope*):

- Encoder relocation to middle of machine for double-ended operation
- Bearing durability/development for slotted stator
- Pressure containment for stages 2-3 i.e. sizing axial seals & fixings for higher pressures
- Design a slotted stator machine for economic manufacturing & assembly, including drive & controller

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

• BP1 & BP2 complete
  – Stage 1 LMRC built and tested –
  – Compression Ratio and Flow near the goals

• BP3 (FY2019) –
  – Working with new partner (Libertine) to built a new motor
  – New motor will be adapted to an existing compression chamber from BP2
  – New LMRC design will help reach the original & new goals

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Norm Shade
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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.)
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

<table>
<thead>
<tr>
<th>Stage</th>
<th>Max. Internal Operating Press. (psig)</th>
<th>Temp. Range (°F)</th>
<th>Size (in.)</th>
<th>Material</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,125</td>
<td>-15 to 400</td>
<td>3/32</td>
<td>V1238-95 Fluorocarbon</td>
<td>Parker Hannifin</td>
</tr>
<tr>
<td>2</td>
<td>4,101</td>
<td>-15 to 400</td>
<td>3/32</td>
<td>V1238-95 Fluorocarbon</td>
<td>Parker Hannifin</td>
</tr>
<tr>
<td>3</td>
<td>14,069 (inner seal**)</td>
<td>-15 to 400</td>
<td>1/8</td>
<td>Inconel 718 w/gold plate</td>
<td>Parker Hannifin</td>
</tr>
</tbody>
</table>
Materials selected for each of the compressor components, and the significant mechanical and physical properties for each part of Libertine's existing motor design spec's*

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
<th>TENSILE STRENGTH</th>
<th>YIELD STRENGTH</th>
<th>ENDURANCE STRENGTH</th>
<th>MAGNETIC PROPERTIES</th>
<th>COEFFICIENT OF EXPANSION (77-212°F)</th>
<th>YOUNG S MODULUS</th>
<th>INFORMATION SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Casing</td>
<td>A-286 Sol &amp; Age (AMS 5737B)</td>
<td>145 ksi</td>
<td>95 ksi</td>
<td>61 ksi</td>
<td>Non-Magnetic (1.007Mu)</td>
<td>9.17 x 10^-6</td>
<td>28.8 x 10^6 psi</td>
<td>1.27</td>
</tr>
<tr>
<td>Magnet Spacers</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>2.4 x 10^6</td>
<td>32 x 10^6 psi</td>
<td>4.6</td>
</tr>
<tr>
<td>Piston Rod</td>
<td>A-286 Sol &amp; Age (AMS 5737B)</td>
<td>145 ksi</td>
<td>95 ksi</td>
<td>61 ksi</td>
<td>Non-Magnetic (1.007Mu)</td>
<td>9.17 x 10^-6</td>
<td>28.8 x 10^6 psi</td>
<td>1.27</td>
</tr>
<tr>
<td>Magnet Retainer</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>2.4 x 10^6</td>
<td>32 x 10^6 psi</td>
<td>4.6</td>
</tr>
<tr>
<td>Piston Holder</td>
<td>Incoloy 903 Sol &amp; Age</td>
<td>190 ksi</td>
<td>160 ksi</td>
<td>68 ksi</td>
<td>Magnetic</td>
<td>4.0 x 10^-4</td>
<td>21.35 x 10^6 psi</td>
<td>6.14</td>
</tr>
<tr>
<td>or Carpenter CTX-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piston</td>
<td>Sapphire</td>
<td>58 ksi</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>2.4 x 10^6</td>
<td>32 x 10^6 psi</td>
<td>4.6</td>
</tr>
<tr>
<td>Cylinder</td>
<td>A-286 Sol &amp; Age (AMS 5737B)</td>
<td>145 ksi</td>
<td>95 ksi</td>
<td>61 ksi</td>
<td>Non-Magnetic (1.007Mu)</td>
<td>9.17 x 10^-6</td>
<td>28.8 x 10^6 psi</td>
<td>1.27</td>
</tr>
<tr>
<td>Head</td>
<td>AISI 316 Annealed</td>
<td>85 ksi</td>
<td>36 ksi</td>
<td>25 ksi</td>
<td>Non-Magnetic (1.000Mu)</td>
<td>8.83 x 10^-6</td>
<td>28.8 x 10^6 psi</td>
<td>3.18</td>
</tr>
<tr>
<td>Suction/Discharge Valves</td>
<td>A-286 Sol &amp; Age (AMS 5737B)</td>
<td>145 ksi</td>
<td>95 ksi</td>
<td>61 ksi</td>
<td>Non-Magnetic (1.007Mu)</td>
<td>9.17 x 10^-6</td>
<td>28.8 x 10^6 psi</td>
<td>1.27</td>
</tr>
<tr>
<td>Rider Bands</td>
<td>PEEK (PTFE filled)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Seal Rings</td>
<td>Filled PTFE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Seal Springs</td>
<td>Bairsy (Cold Drawn &amp; aged)</td>
<td>350/330 ksi</td>
<td>NA</td>
<td>NA</td>
<td>Non-Magnetic</td>
<td>NA</td>
<td>29.6 x 10^6 psi</td>
<td>8</td>
</tr>
<tr>
<td>Valve Retainer Bolting</td>
<td>AISI 316 ASTM F593 Gr 2 Cond. Cr</td>
<td>100 ksi</td>
<td>65 ksi</td>
<td>34 ksi</td>
<td>Non-Magnetic (1.000Mu)</td>
<td>8.83 x 10^-6</td>
<td>28.8 x 10^6 psi</td>
<td>22</td>
</tr>
<tr>
<td>Valve Springs</td>
<td>Bairsy (Cold Drawn &amp; aged)</td>
<td>350/120 ksi</td>
<td>NA</td>
<td>NA</td>
<td>Non-Magnetic</td>
<td>NA</td>
<td>29.6 x 10^6 psi</td>
<td>8</td>
</tr>
<tr>
<td>Piston Travel Screw Rings</td>
<td>Bairsy (Cold Drawn &amp; aged)</td>
<td>330/330 ksi</td>
<td>NA</td>
<td>NA</td>
<td>Non-Magnetic</td>
<td>NA</td>
<td>29.6 x 10^6 psi</td>
<td>8</td>
</tr>
<tr>
<td>or AISI 316 (Cold Drawn)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valve Poppets</td>
<td>PEEK (Unfilled)</td>
<td>13-15 ksi</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>25.7 x 10^-4</td>
<td>20.21</td>
<td></td>
</tr>
<tr>
<td>Valve Nose Gasket</td>
<td>Cooper (OSHC) Cl10020/Cl10100</td>
<td>31.9 ksi</td>
<td>10 ksi</td>
<td>6 ksi</td>
<td>Non-Magnetic (0.999Mu)</td>
<td>NA</td>
<td>NA</td>
<td>3.17</td>
</tr>
<tr>
<td>Valve Retainer</td>
<td>A-286 Sol &amp; Age (AMS 5737P)</td>
<td>145 ksi</td>
<td>95 ksi</td>
<td>61 ksi</td>
<td>Non-Magnetic (1.007Mu)</td>
<td>9.17 x 10^-6</td>
<td>28.8 x 10^6 psi</td>
<td>1.27</td>
</tr>
<tr>
<td>Cylinder Cooling Jacket</td>
<td>Aluminum 6061-T6</td>
<td>40 ksi</td>
<td>35 ksi</td>
<td>12.4 ksi</td>
<td>Non-Magnetic (1.000Mu)</td>
<td>13.1 x 10^-6</td>
<td>10.0 x 10^6 psi</td>
<td>9.10, 17</td>
</tr>
<tr>
<td>Cool Housing</td>
<td>Brass, Nickel, Iron Casting</td>
<td>60 ksi</td>
<td>40 ksi</td>
<td>37 ksi</td>
<td>Magnetic (450Mu)</td>
<td>6.6 x 10^-6</td>
<td>24.9 x 10^6 psi</td>
<td>14.12</td>
</tr>
<tr>
<td>External Bolting</td>
<td>Alloy Steel A193-B7</td>
<td>125 ksi</td>
<td>105 ksi</td>
<td>61.2 ksi</td>
<td>Magnetic</td>
<td>6.78 x 10^-6</td>
<td>29.7 x 10^6 psi</td>
<td>14.3</td>
</tr>
<tr>
<td>Bolting for Piston</td>
<td>17-4PH H1150-S or 17-4PH H1159-M</td>
<td>125 ksi</td>
<td>105 ksi</td>
<td>62.5 ksi</td>
<td>Magnetic</td>
<td>6.65 x 10^-6</td>
<td>28.5 x 10^6 psi</td>
<td>1.3</td>
</tr>
<tr>
<td>Holder &amp; Magnet Retainer</td>
<td></td>
<td>115 ksi</td>
<td>75 ksi</td>
<td>57.5 ksi</td>
<td>Magnetic</td>
<td>6.65 x 10^-6</td>
<td>28.5 x 10^6 psi</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Piston material is zirconia based ceramic.

* All items were checked to be compatible in high pressure H2 environment.