Commissioning and Operational Results of the 12 GeV Helium Compressor System at JLab

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Background

- The compressor system is often considered
- An off-the-shelf, commercially available sub-system,
- Not worth the same level of consideration as compared to the cold box...however, *it should!*...since it,
  - Provides the cold box the “potential energy” (exergy) and,
  - *At least half* of the input power is lost in the compressor system
Background

- And, where do all the mega-watts go?...
- Our environment via the evaporative cooling towers!
Background

• Helium refrigeration systems are very power intensive processes (and are usually more efficient the larger the system)
  – Large 4.5-K helium refrigeration system
    • Inverse COP ~250 W/W
  – Large 2-K helium refrigeration system
    • Inverse COP ~750 to 950 W/W
• System design of the anticipated loads is an estimate
• It is therefore of great importance to design the cryogenic system with considerable flexibility, balanced with cost and good efficiency for the primary operating mode(s)
Background

The internal (Jlab) development of 12 GeV compressor system was brought about by:

(1) A key motivating factor

- Having to deal with the inevitable load variances and,
- An awareness of the inherent energy intensiveness of these systems
- Was ‘birthed’ at the SSCL, with several refinements and applications (to existing systems) occurring at JLab
(2) Observations of existing compressor systems
• Have had the benefit of operating screw compressors used in helium refrigerators, for the past 35 years, encompassing a wide range of
  – Sizes (100 to ~2000 kW)
  – Compressor manufacturers
  – Skid packagers
• This provided a broad range of experience
Background

(3) Fortuitous opportunity

- Provided by NASA Johnson Space Center’s (JSC) request to the JLab Cryogenics Group to design and specify a 12 kW 20-K helium refrigeration system for the James Webb program which was pivotal.

- The development of the 12 GeV compressor system would not have been possible without the courageous support of the NASA-JSC project team.

- This refrigeration system provided a demonstration of new wide range compressor design concept which afforded an acceptable level of risk to the JLab 12 GeV project.
## Background

- Compressor skids are completely designed by JLab and ‘built-to-print’ by industry (skid specifications below, previously presented)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Units</th>
<th>HP</th>
<th>MP</th>
<th>LP</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Units</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td></td>
<td>Howden</td>
<td>Howden</td>
<td>Howden</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WLViH 321/193</td>
<td>WLVi 321/165</td>
<td>WLVi 321/193</td>
<td></td>
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<tr>
<td>Displacement</td>
<td>[m³/s]</td>
<td>1.774</td>
<td>1.577</td>
<td>1.774</td>
<td>(a)</td>
</tr>
<tr>
<td>Motor Rating</td>
<td>[kW]</td>
<td>1864</td>
<td>671</td>
<td>671</td>
<td>(b)</td>
</tr>
<tr>
<td>Motor Service Factor</td>
<td></td>
<td>1.15</td>
<td>1.15</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>Weight (Est.)</td>
<td>[t]</td>
<td>30</td>
<td>22</td>
<td>20</td>
<td>(c)</td>
</tr>
<tr>
<td>Oil Charge (Est.)</td>
<td>[ℓ]</td>
<td>1400</td>
<td>1100</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Water Flow (Est.)</td>
<td>[ℓ/s]</td>
<td>61</td>
<td>23</td>
<td>21</td>
<td>(d)</td>
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<tr>
<td>Oil Cooler</td>
<td>Type</td>
<td>AEU: Shell (Oil, 1 pass) &amp; Tube (Water, 2 pass)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duty</td>
<td>[kW]</td>
<td>1671</td>
<td>617</td>
<td>617</td>
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<tr>
<td></td>
<td>(UA)</td>
<td>[kW/K]</td>
<td>77.6</td>
<td>29.4</td>
<td>31.2</td>
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<tr>
<td>Helium After-Cooler</td>
<td>Type</td>
<td>AEU: Shell (Water, 1 pass) &amp; Tube (Helium, 2 pass)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Duty</td>
<td>[kW]</td>
<td>448</td>
<td>184</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>(UA)</td>
<td>[kW/K]</td>
<td>20.4</td>
<td>8.44</td>
<td>4.66</td>
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<tr>
<td>Oil Pump Motor</td>
<td>[kW]</td>
<td>5.59</td>
<td>3.73</td>
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<tr>
<td>Rotor Oil Injection Filter</td>
<td>abs.]</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>(f)</td>
</tr>
<tr>
<td>Bearing Oil Injection Filter</td>
<td>abs.]</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>(f)</td>
</tr>
<tr>
<td>Helium Pressure Rating</td>
<td>[barg]</td>
<td>22.4</td>
<td>12.1</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>Oil Pressure Rating</td>
<td>[barg]</td>
<td>26.5</td>
<td>15.5</td>
<td>15.5</td>
<td></td>
</tr>
</tbody>
</table>

Notes:  
(a) at 59.17 Hz;  
(b) Westinghouse 4160 V;  
(c) Metric tonnes;  
(d) At 8.3 K temperature difference;  
(e) (UA) is the net thermal rating;  
(f) 98% efficiency
Commissioning and Operational Envelope

- Two key compressor skid features that allow a wide range of operation
  - Bulk oil removal design
  - Oil management
Commissioning and Operational Envelope

- Range of conditions tested during commissioning

<table>
<thead>
<tr>
<th>Compressor Stage</th>
<th>Suction Pressure [bar]</th>
<th>Discharge Pressure [bar]</th>
<th>Pressure Ratio</th>
<th>BVR (^{(a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP Stage</td>
<td>1.06</td>
<td>3.55 to 6.08</td>
<td>3.33 to 5.71</td>
<td>2.2 to 3.2</td>
</tr>
<tr>
<td>MP Stage</td>
<td>1.06 to 3.04</td>
<td>3.55 to 6.08</td>
<td>2.00 to 3.33</td>
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<tr>
<td>HP Stage (^{(c)})</td>
<td>1.07 to 5.47</td>
<td>13.37 to 18.75</td>
<td>3.00 to 16.98</td>
<td>2.2 to 5.0 (^{(b)})</td>
</tr>
</tbody>
</table>

\(^{(a)}\) BVR increments were 0.2

\(^{(b)}\) Not every BVR setting was used for each test point due to manufacturer maximum suction pressure limitations (for a given BVR)

\(^{(c)}\) HP stage can be operated as a (swing) LP or MP stage; under these conditions the suction pressure can be as low as \(~1.04\) bar, the discharge pressure as high as \(~18.7\) bar, and the pressure ratio \(~18\)
Commissioning and Operational Envelope

- Range of conditions tested during commissioning

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### Commissioning and Operational Envelope

- Range of conditions operated since commissioning

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<tr>
<td>LP Stage</td>
<td>1.04 to 1.22</td>
<td>3.40 to 7.03</td>
<td>3.17 to 6.55</td>
</tr>
<tr>
<td>MP Stage</td>
<td>1.12 to 2.26</td>
<td>3.37 to 7.07</td>
<td>2.48 to 5.58</td>
</tr>
<tr>
<td>HP Stage (^{(c)})</td>
<td>3.19 to 5.78</td>
<td>7.25 to 20.04</td>
<td>2.27 to 3.70</td>
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\(^{(c)}\) Same note as in table 3

LP BVR set to 2.4 for operation; MP and HP BVR set to 2.2 for operation
Commissioning and Operational Envelope

- Range of conditions operated since commissioning

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Minor Component Improvements

- Installation of a helium after-cooler (A/C) liquid level gauge
  - Modification utilized existing ports on the compressor A/C’s and allows a local visual check to adjust the oil drain in order to minimize the helium bypass
- Modification of A/C oil drain line
  - Increased the size of the line (including check valve and needle valve) to prevent blockage from fabrication debris and incorporates o-ring seal unions to allow easy removal if necessary
Minor Component Improvements

• Elimination of HP stage super-feed injection flex-hose
  – Original flex-hose was a convoluted metal braided hose and developed a crack at the weld between the cuff and bellows
  – Line was replaced with hard-tubing to prevent fatigue of thin metal but allow adequate flexibility

• Oil pump VFD modification
  – Allowed the oil pump to ride through small power cycle interruptions.
Minor Component Improvements

• Ability to de-pressurize LP and MP stage suction lines
  – Helium discharge check valve will tend to leak at a greater rate than the helium suction check valve
  – Can result in a high initial gas charge in the LP and MP stages which can cause difficulties during a re-start
  – Connections were made to existing ports to de-pressurize the trapped volume of helium gas to reduce the starting torque.

• Heat shield between compressor PLC cabinet and the coolers and BOS
  – Although no know issues resulted from not having the shield, one was installed to protect local control system.
Minor Component Improvements

• Elimination of cooling oil control valve positioner
  – Valve supplies cooling oil to the super-feed port
  – Original positioner would stop functioning
  – Less critical on the LP and MP stages, but will cause a shut-down of the HP stage very quickly
  – Upgraded positioner developed a similar problem
  – These were replaced with an I/P

• All of these have been incorporated into drawings for future skids, such as MSU-FRIB project
Summary

• Present development is a culmination of many years of experience, observation, questioning and opportunities presented and taken

• 12 GeV compressor skid design has allowed a very wide range of operation and a full implementation of the Floating Pressure Process

• With ~15,000 hours of operation (by the beginning of the 2015 summer) this design has proven to be efficient, reliable and easily maintained
Further Development

• The energy intensiveness of ~250 W/W for 4.5-K refrigeration and ~750-950 W/W for 2-K refrigeration and,

• The fact that half of the input power is lost in the compression system warrants continued R&D

• Further work is planned to develop alternate BOS designs and investigate methods and processes to improve efficiency
  – Specifically in regards to:
    • Oil choice, oil injection temperature and oil injection method on the isothermal efficiency and,
    • Behavior of the helium-oil mix in the compression process and the effect of dissolved helium in the bulk oil flow.
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Thank you for your attention