Cryogenic vacuum chamber testing of a conductively-cooled, high temperature superconducting rotor for a 1.4 MW electric machine for aeronautics applications

Justin J. Scheidler¹, Erik J. Stalcup¹, Thomas F. Tallerico¹, William Torres², Kirsten P. Duffy³, Tysen T. Mulder¹

¹ NASA Glenn Research Center  ² Wolf Creek Federal Services  ³ University of Toledo

This material is a work of the U.S. Government and is not subject to copyright protection in the United States.
Motivation

- Aviation impacts:
  - Climate: CO₂ (dominant), contrails (~\(\frac{1}{2}\) impact of CO₂), H₂O vapor, soot
  - Environment: Air quality – NOₓ (dominant), sulfur
  - Noise
  - Despite significant progress in efficiency, global CO₂ emissions from aviation growing at increasing rate

- 2 options:
  - Change fuel (e.g., jet A → SAF or H₂)
  - Electrify
  - NASA’s High-Efficiency Megawatt Motor (HEMM) sized as generator for NASA’s STARC-ABL concept
NASA’s High-Efficiency Megawatt Motor (HEMMM)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated continuous power</td>
<td>1.42 MW</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>6,800 rpm</td>
</tr>
<tr>
<td>Tip speed</td>
<td>107 m/s</td>
</tr>
<tr>
<td>Rated torque</td>
<td>2 kNm</td>
</tr>
<tr>
<td>Electromagnetic specific power</td>
<td>16 kW/kg goal</td>
</tr>
<tr>
<td>Efficiency goal</td>
<td>&gt; 98%</td>
</tr>
</tbody>
</table>

Copper stator (> 100 ºC)

Superconducting rotor coils & core (~ 60 K)

Housing

Slip ring

Rotating shaft with integrated cryocooler
HEMM’s Superconducting Rotor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure of rotor cavity</td>
<td>&lt; 1e-3 torr</td>
</tr>
<tr>
<td># poles (coils)</td>
<td>12</td>
</tr>
<tr>
<td>Superconductor</td>
<td>2(^\text{nd}) generation high temperature superconductor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil configuration</td>
<td>No-insulation quadruple pancake</td>
</tr>
<tr>
<td># turns per coil</td>
<td>600 (150 per layer)</td>
</tr>
</tbody>
</table>

Fe\(_{49.15}\)Co\(_{48.75}\)\(_2\) rotor core

Superconducting coil

Thermal bridge to cryocooler

Titanium structure

Fe\(_{49.15}\)Co\(_{48.75}\)\(_2\) rotor core

Superconducting coil

Thermal bridge to cryocooler

Titanium structure
Experimental Setup – Physical Assembly

- Used NASA Glenn’s ICE-Box

Gifford-McMahon cryocooler (100 W @ 25 K)

4x thermal straps (4.6 W/K total)

Sensor lead wire heat sink bobbins

Cold tip extensions (solid Cu 101)

Support plate (Al 6061)

3x support plate heaters

Shaft section (Ti-6Al-4V)

Rotor assembly

Pressure vessel (Ø 0.86 m x 1.22 m)

Scroll pump (1.6e-2 torr when cryocooler off)

4x thermal straps (4.6 W/K total)

Sensor lead wire heat sink bobbins

Cold tip extensions (solid Cu 101)

Support plate (Al 6061)

3x support plate heaters

Shaft section (Ti-6Al-4V)

Rotor assembly
Experimental Setup – Physical Assembly

ICE-Box’s cryocooler
Cold tip extensions
Back iron (solid Fe$_{49.15}$Co$_{48.75}$V$_2$)
Bolted interface
Thermal bridge
Bolted interface
Thermal bridge
Temporary alignment fixture
Cold tip extension
Experimental Setup – Physical Assembly

- Current terminal & threaded mount for RTD (1 of 2)
- Heat sunk copper terminal (1 of 11 on each axial face)
- Copper wire loop (1 of 9 on each axial face)
- Superconducting coils
- Empty coil fixture
Experimental Setup – Instrumentation

- Vacuum feedthrough channels
  - 15 resistive temperature detectors (RTDs)
  - 9 Type E thermocouples
  - 4 voltage probes
  - 2 heaters
  - 1 pair high current leads
Experimental Setup – Instrumentation

Coil L

Coil C

Coil R

Shaft side of rotor

‘Free’ side of rotor

Legend

- Copper wire
- Green: Thermal interface material
- Yellow: Superconducting coils
- Brown: Screwed copper terminals
Experimental Results – Electrical

• Current slowly ramped between set points (~ 0.5 – 0.7 A/min) to minimize heating in coils
• Each data point taken after voltage and temperature exhibited little variation (typically 30-45 minutes)
• 1st round of testing
  1. At 60.5 – 61.0 K
     1. Linear & stable voltage response up to 45 A, then ~7 mV jump while stabilizing at 50 A
     2. Linear & stable voltage up to 57.2 A (rated current)
  2. At 57.2 A
     1. Linear & stable voltage from 60.8 K to 62.0 K (rated temperature)
Electrical Results – Voltage Response

- 2nd round of testing
  - At 60.9 – 61.1 K
    - Linear & stable voltage up to ≥ 47.5 A on 4 separate occasions over 2 weeks

<table>
<thead>
<tr>
<th>Measured Resistance $R$, mOhm</th>
<th>Entire rotor</th>
<th>Coil L</th>
<th>Coil C</th>
<th>Coil R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.253</td>
<td>0.086</td>
<td>0.100</td>
<td>0.008</td>
</tr>
</tbody>
</table>
Electrical Results – Inductance

- 2nd round of testing
- At 60.9 – 61.1 K
  - Measured exponential time constant ($\tau$): average: 10.2 min | standard deviation: 1.2 min
  - Estimated inductance = 0.15 H (series $L$-$R$ circuit: $L=\tau R$)

** Electrical Results – Inductance**

- Long solenoid: $L = \frac{\mu N^2 A}{l}$
- Short solenoid: $L = \frac{\mu N^2 A [\sqrt{\pi l} - a]}{l}$

** Long solenoid:** $N = \# \text{ of turns } = 600$ | $A = \text{ cross-sectional area } = \frac{\pi}{4} (50.8)^2 \text{ mm}^2$ (mean diameter of end turns = 50.8 mm) | $a = \text{ radius of turn } = \frac{50.8}{2} \text{ mm}$ | $l = \text{ length } = 14 \text{ mm}$
• 2\textsuperscript{nd} round of testing

### Electrical Results – Inductance

**Voltage response to quasi-step 10 A decrease in current**

<table>
<thead>
<tr>
<th>Coil temperatures, K</th>
<th>Measured time constant, s</th>
<th>Measured resistance, mOhm</th>
<th>Estimated inductance, mH</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.8 to 57.4</td>
<td>628</td>
<td>0.253</td>
<td>159</td>
</tr>
<tr>
<td>104.3 to 105.6</td>
<td>$&lt; 0.2$</td>
<td>0.680</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>300</td>
<td>$&lt; 0.2$</td>
<td>0.557</td>
<td>$&lt; 0.1$</td>
</tr>
</tbody>
</table>
Steady-State Thermal Results

- Steady state: >90% of temperature sensors changing at rate < 0.2 K/hr
- Most tests: cold tip held at 45 K rather than 50 K (HEMM’s nominal)
- Allowable $\Delta T$ from cold tip to coils: 12 K

<table>
<thead>
<tr>
<th>Test Point</th>
<th>Rotor Current (A)</th>
<th>Support Plate Heater Enabled?</th>
<th>HEMM’s Cold Tip Temp. (K)</th>
<th>Coil Temp. (K)</th>
<th>$\Delta T$, Cold Tip to Coils (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
<td>Peak</td>
<td>Average</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>Yes</td>
<td>48.2</td>
<td>59.6</td>
<td>60.2</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>No</td>
<td>26.3</td>
<td>39.1</td>
<td>40.1</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>No</td>
<td>45.0</td>
<td>55.9</td>
<td>56.6</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>No</td>
<td>45.0</td>
<td>55.2</td>
<td>55.9</td>
</tr>
<tr>
<td>E</td>
<td>47.5</td>
<td>No</td>
<td>45.0</td>
<td>55.8</td>
<td>56.7</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>Yes</td>
<td>45.0</td>
<td>56.6</td>
<td>57.3</td>
</tr>
</tbody>
</table>

After improvements (to cleanliness, clamping force, instrumentation)

Measured peak $\Delta T$ from cold tip to coils (10.9 to 12.3 K) is acceptable, but with no margin.
Steady-State Temperature Gradients Across Interfaces

- Values shown for test points C – F (after improvements)
- In most cases, $\Delta T$ varied by $< 0.6$ K between test points
- Relative to uncorrelated model:
  - Current terminals hotter
  - Other interfaces similar

\[
\begin{align*}
\text{Cold tip to thermal bridge} & : \Delta T = 0.4 \text{ K} \\
\text{Thermal bridge to backiron} & : \Delta T < 5.1 \text{ K} \quad \text{(not directly measured)} \\
\text{Backiron through coil fixture to coil} & : \Delta T = \begin{cases} -0.1 \text{ K, Coil L} \\ 1.8 \text{ K, Coil C} \\ 1.2 \text{ K, Coil R} \end{cases} \\
\text{Current lead terminal to backiron} & : \Delta T = 11.8 \text{ K} \\
\text{Backiron torque web to shaft} & : \Delta T = 4.0 \text{ K} \\
\text{Coil-to-coil terminal to backiron} & : \Delta T = 4.9 \text{ K}
\end{align*}
\]
• Values shown for test points C – F (after improvements)
• **Relative to uncorrelated model:**
  • Shaft $\Delta T$ considerably lower
  • Dovetail part thermally coupled
  • Hoop less coupled

$\Delta T$ from cold tip to coils driven by elevated conduction from shaft & current leads
Conclusions

- Thermal & electromagnetic differences between HEMM & ICE-Box experiment are acceptably small [1]
- **Sustained 6 thermal cycles from 293 K to < 50 K throughout test campaign**
- Despite lack of magnetic sensors, **good confidence that superconducting coils operated as intended**
  - Linear & stable operation up to ≥ 45 A in 6 separate tests
  - Estimated inductance of rotor (0.15 H) had reasonable magnitude & went to ~0 above HTS transition temperature
- \( \Delta T \) from HEMM’s cold tip to coils acceptable but with no margin
  - Identified opportunities to reduce \( \Delta T \)

Stable operation of rotor at rated current (57.2 A) and rated temperature (62.0 K) demonstrated while conductively cooled with acceptable \( \Delta T \)

1\textsuperscript{st} ever demonstration of superconducting rotor cooled conductively without a cryogen

---

Acknowledgements

This work was funded by

- NASA’s Advanced Air Transport Technology (AATT) Project
- Electrified Aircraft Powertrain Technologies Subproject

Contact Info

Justin Scheidler  justin.j.scheidler@nasa.gov
Erik Stalcup  erik.j.stalcup@nasa.gov
Thomas Tallerico  thomas.tallerico@nasa.gov
William Torres  william.torres@nasa.gov
Kirsten Duffy  kirsten.p.duffy@nasa.gov
Simulated Thermal Response

- Radiation, conductive, and resistive heating loads are applied to ICE-Box model
- 4 W lower heat load in experiment due to lack of windage
  - Thus, generally lower temperatures in experiment
- End winding hoops operate at up to ~100 K due to missing coils

Predicted coil temperatures

<table>
<thead>
<tr>
<th></th>
<th>ICE-Box Test</th>
<th>HEMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>55.9 K</td>
<td>57.4 K</td>
</tr>
<tr>
<td>Average</td>
<td>55.3 K</td>
<td>57.2 K</td>
</tr>
</tbody>
</table>
Simulated Electromagnetic Response

- Rotor current & # turns same in both models
- Nonlinearity considered
- Using HEMM design method, critical current in ICE-Box test 2.1 A less than in HEMM
Simulated Electromagnetic Response

- Critical current calculation considers:
  - Temperature from previous slide
  - $I_c(77 \, K, s.f.)$ of conductor used to make each layer
- Stator back iron not added to experiment

Predicted critical current ($I_c$) distribution (units: A) with & without stator back iron
Instrumentation
Experimental Results – Electrical

- Current very slowly ramped between set points (about 0.5-0.7 A/min) to minimize heating in coils
- Each data point taken after voltage and temperature exhibited little variation (typically 30-45 minutes)
- Highest temperature in coils controlled to 60.5 to 61.0 K
- ~7 mV voltage jump occurred during 1st attempt at constant 50 A as temperature increased to 61.2 K
- 2nd characterization shows higher resistance but stable at the design current while conductively cooled

Electrical characterization of the entire rotor before (left) & after (right) voltage jump
Experimental Results – Electrical

- After stably operating at 57.2 A and 60.9 K, current held fixed, and temperature slowly raised in increments to 62.0 K
- Linear response & increase in voltage (1.40%) suggest superconductivity maintained to 62.0 K (HEMM design limit)

**Voltage across the superconducting rotor during a temperature excursion at 57.2 A**

![Graph showing voltage across the superconducting rotor during a temperature excursion at 57.2 A. The graph includes a line equation: y = 0.260x + 4.993 and R² = 0.990.]

<table>
<thead>
<tr>
<th>Temperature of central superconducting coil (CU6), K</th>
<th>Voltage, mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.8</td>
<td>20.80</td>
</tr>
<tr>
<td>61</td>
<td>20.85</td>
</tr>
<tr>
<td>61.2</td>
<td>20.90</td>
</tr>
<tr>
<td>61.4</td>
<td>20.95</td>
</tr>
<tr>
<td>61.6</td>
<td>20.99</td>
</tr>
<tr>
<td>61.8</td>
<td>21.00</td>
</tr>
<tr>
<td>62</td>
<td>21.05</td>
</tr>
<tr>
<td>62.2</td>
<td>21.10</td>
</tr>
<tr>
<td>21.15</td>
<td>21.10</td>
</tr>
<tr>
<td>21.20</td>
<td>21.20</td>
</tr>
</tbody>
</table>

**Predicted increase in resistance (thus voltage) per linear interpolation of cryogenic data**

<table>
<thead>
<tr>
<th>Material</th>
<th>Change in resistance (&amp; voltage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu (very high purity)</td>
<td>5.53%</td>
</tr>
<tr>
<td>OFHC copper (annealed)</td>
<td>3.88%</td>
</tr>
<tr>
<td>OFHC copper (60% cold work)</td>
<td>3.54%</td>
</tr>
<tr>
<td>Less pure Cu wire</td>
<td>&lt; 3.5%</td>
</tr>
</tbody>
</table>
Steady-State Thermal Results – Test Point E

- Dovetail: 61.2 K (TC)
- Backiron: 54.2 K to 55.5 K (RTDs)
- Retaining Hoop: 81.9 K (TC)
- Current Terminals on Backiron: 63.9 K to 67.5 K (TCs)
- Shaft: 292.6 K (TC)
- Cold Tip: 45.0 K (RTD)
- Shaft: 214.9 K (TC)
- Thermal Bridge: 45.4 K (RTD)
- Thermal Bridge (on clamp ring): 49.7 K (RTD)
- Coils (on terminals): 54.4 K to 56.7 K (RTDs)
- Current Jumper: 60.2 K (TC)
- Retaining Hoop: 81.9 K (TC)
- Current Terminals on Backiron: 63.9 K to 67.5 K (TCs)
- Shaft: 292.6 K (TC)
- Cold Tip: 45.0 K (RTD)
- Thermal Bridge: 45.4 K (RTD)
- Thermal Bridge (on clamp ring): 49.7 K (RTD)
- Coils (on terminals): 54.4 K to 56.7 K (RTDs)
- Current Jumper: 60.2 K (TC)
- Dovetail: 61.2 K (TC)
- Backiron: 54.2 K to 55.5 K (RTDs)
- Retaining Hoop: 81.9 K (TC)
- Current Terminals on Backiron: 63.9 K to 67.5 K (TCs)
- Shaft: 292.6 K (TC)
- Cold Tip: 45.0 K (RTD)
- Thermal Bridge: 45.4 K (RTD)
- Thermal Bridge (on clamp ring): 49.7 K (RTD)
- Coils (on terminals): 54.4 K to 56.7 K (RTDs)
- Current Jumper: 60.2 K (TC)
- Dovetail: 61.2 K (TC)
- Backiron: 54.2 K to 55.5 K (RTDs)
- Retaining Hoop: 81.9 K (TC)
- Current Terminals on Backiron: 63.9 K to 67.5 K (TCs)
- Shaft: 292.6 K (TC)
- Cold Tip: 45.0 K (RTD)
- Thermal Bridge: 45.4 K (RTD)
- Thermal Bridge (on clamp ring): 49.7 K (RTD)
- Coils (on terminals): 54.4 K to 56.7 K (RTDs)
- Current Jumper: 60.2 K (TC)

TC = thermocouple
RTD = resistance temperature detector

National Aeronautics and Space Administration
M2Or3J-02 – Cryovac testing of conductively-cooled superconducting rotor
### Steady-State Thermal Results

#### Notable temperature differences at each test point (location 1 minus location 2)

<table>
<thead>
<tr>
<th>Location 1</th>
<th>Location 2</th>
<th>Test Point</th>
<th>Uncorrelated model (test point E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold tip at cold tip/bridge interface</td>
<td>ICE-Box cryocooler cold tip (facility)</td>
<td>A</td>
<td>12.77</td>
</tr>
<tr>
<td>Thermal bridge at cold tip/bridge interface</td>
<td>Cold tip at cold tip/bridge interface</td>
<td>B</td>
<td>8.77</td>
</tr>
<tr>
<td>Thermal bridge (clamp ring) at bridge/backiron interface</td>
<td>Thermal bridge at cold tip/bridge interface</td>
<td>C</td>
<td>10.79</td>
</tr>
<tr>
<td>Large support plate, near heater</td>
<td>Shaft near interface with Al support plate</td>
<td>D</td>
<td>10.12</td>
</tr>
<tr>
<td>Shaft near interface with Al support plate</td>
<td>Shaft at shaft/backiron interface</td>
<td>E</td>
<td>11.01</td>
</tr>
<tr>
<td>Shaft at shaft/backiron interface</td>
<td>Backiron at shaft/backiron interface</td>
<td>F</td>
<td>11.72</td>
</tr>
<tr>
<td>Backiron at shaft/backiron interface</td>
<td>Backiron axial face, coil C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current lead terminal A</td>
<td>Backiron pole OD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current lead terminal B</td>
<td>coil L, free end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil-to-coil terminal, coil C, free end</td>
<td>coil C, free end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil terminal</td>
<td>coil L, shaft end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>coil C, free end</td>
<td>coil L, shaft end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>coil R, free end</td>
<td>coil R, shaft end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold tip at cold tip/bridge interface</td>
<td>Cold tip at cold tip/bridge interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal bridge (clamp ring) at bridge/backiron interface</td>
<td>Thermal bridge (clamp ring) at bridge/backiron interface</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are in °C.
Predicted Performance of HEMM’s Cryocooler

\[ y = 2.1x - 65.7 \]
Cryovac testing of conductively-cooled superconducting rotor