Cryogenic Thermal Studies on Terminations for Helium Gas Cooled Superconducting Cables

Chul Han Kim, Sung-Kyu Kim, Lukas Graber, and Sastry Pamidi
Center for Advanced Power Systems
The Florida State University
<table>
<thead>
<tr>
<th>Benefits</th>
<th>Challenges</th>
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<tr>
<td>➢ Wide operating temperature (20 K–80 K)</td>
<td>➢ Low heat capacity of helium gas – requires high pressures and flow rates for heat removal</td>
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<td>➢ Enhanced superconducting properties at lower temperatures</td>
<td>➢ Helium gas has low dielectric strength – dielectric design has to depend on the solid dielectric medium</td>
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<td>➢ Lower temperatures allow higher power densities when necessary</td>
<td>➢ Little experience on helium gas cooled superconducting power devices</td>
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<td>➢ Larger temperature gradients can be maintained without a phase change</td>
<td>➢ Commercial cryocoolers are inefficient – technological developments necessary</td>
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<td>➢ Easier to integrate with other superconducting devices operating under helium gas cooling</td>
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<td>➢ Increased flexibility in power system design optimization</td>
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Cryogenic Helium Circulation Systems

Operating Pressure: up to 250 psi, Expected flow rate: up to 10 g/s

Stirling System
340 W @ 50 K
Cryozone Bohmwind Fan

AL 330
Cryo Fan
Current Phase – Validate cryogenic and thermal issues

- Monopole
- Current rating: 3 kA and @ 77 K (up to 10 kA @ 40 K)
- Voltage rating: 1 kV

Long-term Goal

- 100 MW -10 kA @ 50 K; voltage rating: ± 5 kV

2G HTS - Cryoflex insulation – Cable built by Ultera
These terminations are meant to be versatile for testing various cables.

Future terminations for the Navy applications will be much smaller and GHe cooled.
Schematic of cryogenic thermal experimental set up

- Upper bushing
- Lower bushing
- Flexible cryostat 1-m or 30-m
- HTS cable
- Inlet termination
- Outlet termination
- Cryogenic helium circulation system
- He inlet
- He outlet
Thermal Mapping of The Terminations Tanks and Cryostat Assembly

GHe In

GHe Out

30 m Cable Cryostat
$\Delta T$ Across the Terminations and the Cryostat Without The Cable

![Diagram showing temperature sensors and cryostat](image)
Variation of Temperature Across the Terminations
Without LN2 on the top sections

![Diagram showing temperature rise and flow rate for 1 m and 30 m cryostats with temperature sensors and cryostat terminations marked.]
Estimated Heat Leak From The Termination Tanks

With LN2

Heat Leak (W)

Mass Flowrate (g/s)

inlet Termination (30 m)

Outlet Termination (30 m)

1 m or 30 m cryostat

GHe In

GHe Out
Thermal Model

Parameters Used to estimate heat flux from different sources

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<tr>
<th>Parameter</th>
<th>Termination</th>
<th>Copper Current Lead</th>
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<td>(Apparent) thermal conductivity $k$ [W/(m·K)]</td>
<td>1.7 x 10^{-3}</td>
<td>647</td>
</tr>
<tr>
<td>Surface area (cross section) $A$ [m²]</td>
<td>1.25</td>
<td>5.1 x 10^{-4}</td>
</tr>
<tr>
<td>Thickness (length) [mm]</td>
<td>25.4</td>
<td>477</td>
</tr>
<tr>
<td>Temperature difference $\Delta T$ [K]</td>
<td>250</td>
<td>27</td>
</tr>
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\[
\dot{Q}_{tot} = 2\dot{Q}_{termination} + \dot{Q}_{cryostat} + 2\dot{Q}_{connector}
\]

\[
= 2\left( k_{term} \frac{A_{term} \Delta T_{term}}{d_{term}} + k_{Cu} \frac{A_{Cu} \Delta T_{Cu}}{d_{Cu}} \right) + \dot{Q}_{cryostat} + 2\dot{Q}_{connector}
\]

\[
= 2\left(20 \text{ W} + 19 \text{ W}\right) + 30 \text{ W} + 2(10 \text{ W}) = 128 \text{ W}
\]
HTS Cable Installation
The Cable Performed Well

Current

Voltage – HTS layers

Voltage – Copper layers
Summary

- Hybrid termination design concept used for testing GHe cooled HTS DC Cable
- The heat load from terminations is acceptable (~ 20 W each)
- $\Delta T$ of 4 K is achieved across the 30 m cable system for GHe mass flow rate of 5 g/s or higher
- Simple thermal models used to predict the heat load from the terminations and the cable cryostat
- Measured heat loads from the terminations are similar to those from the model
- 30 m cable performed well in GHe up to 3 kA and 1 kV–First demonstration of gaseous helium cooled HTS cable