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HIGH Tc SUPERCONDUCTORS: WILL THEY REPLACE HELIUM TEMPERATURE SUPERCONDUCTORS FOR MAGNETS?

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During the last two years, the maximum zero resistance critical temperature for superconductors has risen from 23 K to temperatures above 120 K. This paper presents a sober view of the usefulness of the high Tc materials for generating magnetic fields in superconducting devices. The high Tc materials are compared to conventional niobium titanium superconductors in the following areas: critical current density, adiabatic and dynamic stability, normal region propagation velocity, burn out integral, energy per unit volume to quench and the maximum cryogenic stability current density. A look at the whole picture suggests that for most superconducting magnet applications, conventional conductors would be the superconductors of choice for magnets.

THE PROPERTIES OF HIGH Tc MATERIALS

The high Tc oxide superconductors are an extension of a group of superconductors known as the perovskite class of superconductors. The discovery of a copper oxide perovskite-type superconductor with a Tc above 35 K is considered to be an important advance in solid-state physics and superconductivity. The high Tc superconductors are more complex than the true perovskite structure. The lanthanum-strontium (Tc = 40 K) and the yttrium-barium (Tc = 93 K) types of superconductors have a single copper oxide plane. The more recent five component superconductors have two or three copper oxide layers. It appears that having more copper oxide layers means a higher Tc and perhaps better stability.

The five component high Tc superconductors can have zero resistivity critical temperatures as high as 125 K. The Y Ba2 Cu3 O7-x superconductors have a consistent zero resistance Tc of 93 K. Studies of this conductor suggest that this type of superconductor may have granules of superconductor with a Tc above 100 K. These granules appear to be connected by resistive regions. The production of a high Tc superconductor that has zero resistance above 90 K requires that the superconductor be oxygenated during processing.

The claims for high Hc2 for the high Tc superconductor should be examined carefully. Many of the claims are based on measurements where the resistance begins to change or an apparent Meissner effect is seen. The only value of Hc2 which really counts for magnets is when the resistivity is zero. The highest values of Hc2 are found in single crystals with the magnetic field in a direction parallel to the plane of the copper oxide planes. The Jc superconductor is also anisotropic. The Jc is two orders of magnitude higher in the direction perpendicular to the copper oxide planes in the superconductor than in a direction parallel to the copper oxide planes. At least one type of bulk sintered Y-Ba-Cu-O superconductor makes a sharp change in d Hc2/d T at about 60 K. Based on the WHH theory, the estimated T = 0 value of Bc2 for this conductor is about 60 T (Bc2 = \mu_0 Hc2).

Table 1 compares the properties of Nb-Ti and Y Ba2 Cu3 O7-x. The Jc for the high Tc superconductors has improved considerably since their discovery. The melted cast Y-Ba-Cu-O conductor has higher values of Jc at
77 K than do the bulk sintered samples (particularly when a magnetic field is present). The thin film superconductors show the most promise for critical current densities which approach the values of conventional superconductors.

The high Tc superconductors are brittle ceramics, whereas niobium titanium is both strong and ductile. Niobium titanium can be codrawn in copper; the high Tc superconductor cannot be drawn into fine filaments. When one compares Nb-Ti with the high Tc superconductor, one should look at Nb3Sn or V3Ga as compared to Nb-Ti. Both Nb3Sn and V3Ga have very critical current densities (as high as $10^5$ A/mm$^2$ at 2 T for V3Ga at 4.2 K), but they are brittle. Both Nb3Sn and V3Ga can be made in fine filament form, yet for many uses one prefers to pay more for 1.8 K refrigeration and use Nb-Ti rather than use Nb3Sn or V3Ga at 4.2 K. The conductor brittleness and the difficulty of forming multifilamentary superconductor are the high Tc superconductors biggest detriments. At this time there is no usable form of the high Tc superconductor which can be used to make useful superconducting magnets.

Table 1. Properties of Nb-Ti and Y Ba$_2$Cu$_3$O$_{7-x}$ Superconductors

<table>
<thead>
<tr>
<th></th>
<th>Nb-Ti</th>
<th>Y-Ba-Cu-O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of Material</strong></td>
<td>Metal Alloy</td>
<td>Ceramic</td>
</tr>
<tr>
<td><strong>Critical Temperature (K)</strong></td>
<td>9.4</td>
<td>93</td>
</tr>
<tr>
<td><strong>Density (kg m$^{-3}$)</strong></td>
<td>6700</td>
<td>6380$^b$</td>
</tr>
<tr>
<td><strong>Specific Heat at Top (J m$^{-3}$ K$^{-1}$)</strong></td>
<td>$5.76 \times 10^3$</td>
<td>$1.0 \times 10^6$</td>
</tr>
<tr>
<td><strong>Thermal Conductivity at Top (W m$^{-1}$ K$^{-1}$)</strong></td>
<td>0.275</td>
<td>$-13$</td>
</tr>
<tr>
<td><strong>Thermal Contraction Coefficient at 300 K</strong></td>
<td>$-10^{-5}$</td>
<td>$1.3 \times 10^{-5}$</td>
</tr>
<tr>
<td><strong>Total Thermal Contraction Coefficient 300 K - T$_{top}$</strong></td>
<td>$-2.0 \times 10^{-3}$</td>
<td>$-2.3 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Elastic Modulus at Top (G Pa)</strong></td>
<td>83</td>
<td>90 - 110</td>
</tr>
<tr>
<td><strong>Ultimate Strength at Top (M Pa)</strong></td>
<td>$\sim 2200$</td>
<td>Variable</td>
</tr>
<tr>
<td><strong>Ductility</strong></td>
<td>Ductile</td>
<td>Brittle</td>
</tr>
</tbody>
</table>

$^a$ For Nb-46.5 w% Ti.

$^b$ Void-free sample, typical sintered samples are lower than this value.

FACTORS WHICH AFFECT THE HIGH USE OF HIGH T$_c$ SUPERCONDUCTORS IN SUPERCONDUCTING MAGNETS

If one wants to assess the usefulness of high T$_c$ superconductor in magnets, one should compare the superconductor with the same value of J$_c$ (say 4000 A mm$^{-2}$, which can be achieved in Nb-Ti at a field of 5 T and 4.2 K). One should also assume that the high T$_c$ superconductor is in fine enough filaments so that adiabatic and dynamic stability is achieved. Table 2 compares the properties of liquid helium hydrogen and nitrogen which would be used to cool high T$_c$ superconductor. Table 3 compares niobium titanium with high T$_c$ superconductor. In Table 3 it is assumed that niobium titanium operates at 4.2 K (in liquid helium) and Y-Ba-Cu-O operates at 20.4 K (in liquid hydrogen) and at 77 K (in liquid nitrogen). Included in Table 3 are comparisons of adiabatic stability diameter, dynamic stability diameter, normal region propagation velocity along the conductor,
Table 2. Properties of Three Liquid Gases That Can Be Used to Cool Superconductor

<table>
<thead>
<tr>
<th></th>
<th>Helium</th>
<th>Hydrogen</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 atm Boiling Temperature (K)</td>
<td>4.22</td>
<td>20.3</td>
<td>77.4</td>
</tr>
<tr>
<td>Critical Temperature (K)</td>
<td>5.19</td>
<td>33.3</td>
<td>126.1</td>
</tr>
<tr>
<td>1 atm Liquid Density (kg m⁻³)</td>
<td>125</td>
<td>70.8</td>
<td>811</td>
</tr>
<tr>
<td>1 atm Heat of Vaporization (J g⁻¹)</td>
<td>20.8</td>
<td>442ᵃ</td>
<td>198</td>
</tr>
<tr>
<td>Gas Specific Heat (J g⁻¹ K⁻¹)</td>
<td>5.19</td>
<td>14.6</td>
<td>1.03</td>
</tr>
<tr>
<td>Available Refrigeration Liquid to 300 K (J g⁻¹)</td>
<td>1561</td>
<td>4629ᵇ</td>
<td>431</td>
</tr>
<tr>
<td>Design Nucleate Boiling Heat Fluxc (W m⁻²)</td>
<td>2500</td>
<td>30000</td>
<td>600000</td>
</tr>
<tr>
<td>Design Nucleate Boiling ΔTc (K)</td>
<td>0.5</td>
<td>1.7</td>
<td>6.8</td>
</tr>
</tbody>
</table>

ᵃ para hydrogen
ᵇ includes the para to ortho transition energy
ᶜ about 30 percent of the maximum nucleate boiling heat flux

Table 3. Properties of Niobium Titanium in Liquid Helium and a 93 K High Tc Superconductor in Liquid Hydrogen and Liquid Nitrogen

<table>
<thead>
<tr>
<th></th>
<th>Nb-Ti in Helium</th>
<th>High Tc in Hydrogen</th>
<th>High Tc in Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature (K)</td>
<td>4.22</td>
<td>20.3</td>
<td>77.4</td>
</tr>
<tr>
<td>Critical Temperature (K)</td>
<td>9.35</td>
<td>~ 93</td>
<td>~ 93</td>
</tr>
<tr>
<td>Adiabatic Stability Diameter (µm)ᵃ</td>
<td>53.7</td>
<td>539</td>
<td>2156</td>
</tr>
<tr>
<td>Dynamic Stability Diameter (µm)ᵃ</td>
<td>56.0</td>
<td>1220</td>
<td>328</td>
</tr>
<tr>
<td>Longitudinal Quench Velocity (m s⁻¹)ᵇ,c</td>
<td>30.5</td>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>Ratio of Transverse to Longitudinal Quench Velocity RRR = 300 Cu Matrix</td>
<td>0.018</td>
<td>0.020</td>
<td>0.066</td>
</tr>
<tr>
<td>Burnout Integral J² d T RRR = 300 Cu Matrix Operating Temperature to 400 K (A² m⁻⁴ s⁻¹)</td>
<td>18.6 x 10¹⁶</td>
<td>18.1 x 10¹⁶</td>
<td>10.1 x 10¹⁶</td>
</tr>
<tr>
<td>Enthalpy Change per Unit Volume to Quench without Cryogenc (J m⁻³)</td>
<td>1.26 x 10³</td>
<td>1.32 x 10⁶</td>
<td>5.17 x 10⁶</td>
</tr>
<tr>
<td>Enthalpy Change per Unit Volume to Quench with 10% Cryogen by Volumec (J m⁻³)</td>
<td>5.73 x 10⁴</td>
<td>2.31 x 10⁶</td>
<td>5.18 x 10⁶</td>
</tr>
<tr>
<td>Cryostability Matrix Current Density RRR = 300 Copperd (A mm⁻²)</td>
<td>72.2</td>
<td>242</td>
<td>56.2ᵃ</td>
</tr>
</tbody>
</table>

ᵃ Jc = 4000 A mm⁻² at low field, copper-to-superconductor ratio = 2
ᵇ Matrix J = 500 A mm⁻²
ᶜ At 85% of Jc along the load line
ᵈ For a typical cryostable conductor in boiling liquid
ᵉ Maximum value based on a 6.8 K boiling temperature difference
the integral of $J^2 \, dt$ needed to raise the conductor plus matrix temperature from
the operating temperature to 400 K, the energy per unit volume needed to initiate a
quench and the matrix current density in an RRR = 300 copper matrix in boiling
cryogen at one-third of peak nucleate boiling flux.

From Table 3 it is clear that the high $T_C$ superconductor is much more stable than
niobium titanium at 4.2 K. With increased superconductor stability comes reduced
normal region propagation velocity. The volume rate of normal region growth is
five to seven orders of magnitude smaller for the high $T_C$ material. Not only is
the volume normal region propagation rate much smaller for the high $T_C$
superconductor, but the margin of safety during a transition is smaller. As a
result, the concept of cryostability is much more important for high $T_C$
superconductors than it is for niobium titanium.

Table 2 shows the properties of liquid helium, hydrogen and nitrogen at their 1 atm
boiling points. Included in Table 2 is the usable design nucleate boiling heat
flux and the temperature difference between the surface and the fluid when heat is
being transferred at the usable nucleate boiling heat flux. The cryostable current
density given in Table 3 is based on the heat transfer rates shown in Table 2 and a
heat transfer area which is 100 times larger than the conductor current carrying
cross-section per meter of conductor length. The copper RRR is 300, and the
copper to superconductor ratio is large. From Table 3, cryostable operation of
high $T_C$ superconductor appears to be attractive in liquid hydrogen. Cryostable
current densities in liquid nitrogen appear to be attractive except that the
nucleate boiling temperature difference approaches 7 K. An increase of the
superconductor $T_C$ makes cryostable operation in liquid nitrogen more attractive.

HIGH $T_C$ SUPERCONDUCTOR AND ITS USE IN SPACE

High $T_C$ superconductor has been proposed for use in space because, it is said,
that low temperatures are easy to get in space. Unfortunately, temperatures below
200 K are difficult to achieve on the surface of the cryostat in low earth orbit.
Superconducting magnets in space are high current density devices, because the
reduction of coil and cryogenic system mass is essential. The cold mass of a high
current density superconducting space magnet system is directly proportional to the
energy stored in the magnetic field (for quench protection and stress reasons).

From Table 2, it is clear that the best coolant for space cooling is liquid or
solid hydrogen. There is over 4600 J per gram (including the para to normal
green hydrogen transition energy) available to cool the magnet and the shields. The
available refrigeration for helium is almost 1600 J g$^{-1}$, while the liquid
nitrogen has only 430 J g$^{-1}$. Hydrogen, because of extreme flammability, presents
safety problems which preclude its use on devices carried by manned space shuttles
or on the space station. As a result, under today's safety rules, helium is the
refrigerant of choice. Helium offers some additional advantages not found with
either hydrogen or nitrogen. The second liquid phase, which exists below the lamda
transition temperature of 2.17 K, can be circulated through a superconducting coil
using a thermal mechanical pump with no moving parts. Helium II can be phase
separated from the gas using a porous plug, and direct heat transfer to helium II
can be very good if the coil cryogenic system is properly designed.

In most situations, there is very little incentive to use anything but conventional
superconducting materials in space. The mechanical properties of niobium titanium
make it almost ideal to withstand the accelerations and vibrations during launch as
well as the magnetic forces.
ACKNOWLEDGMENTS

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7) J. W. Ekin, private communication on the behavior of single crystal high Tc superconductor.