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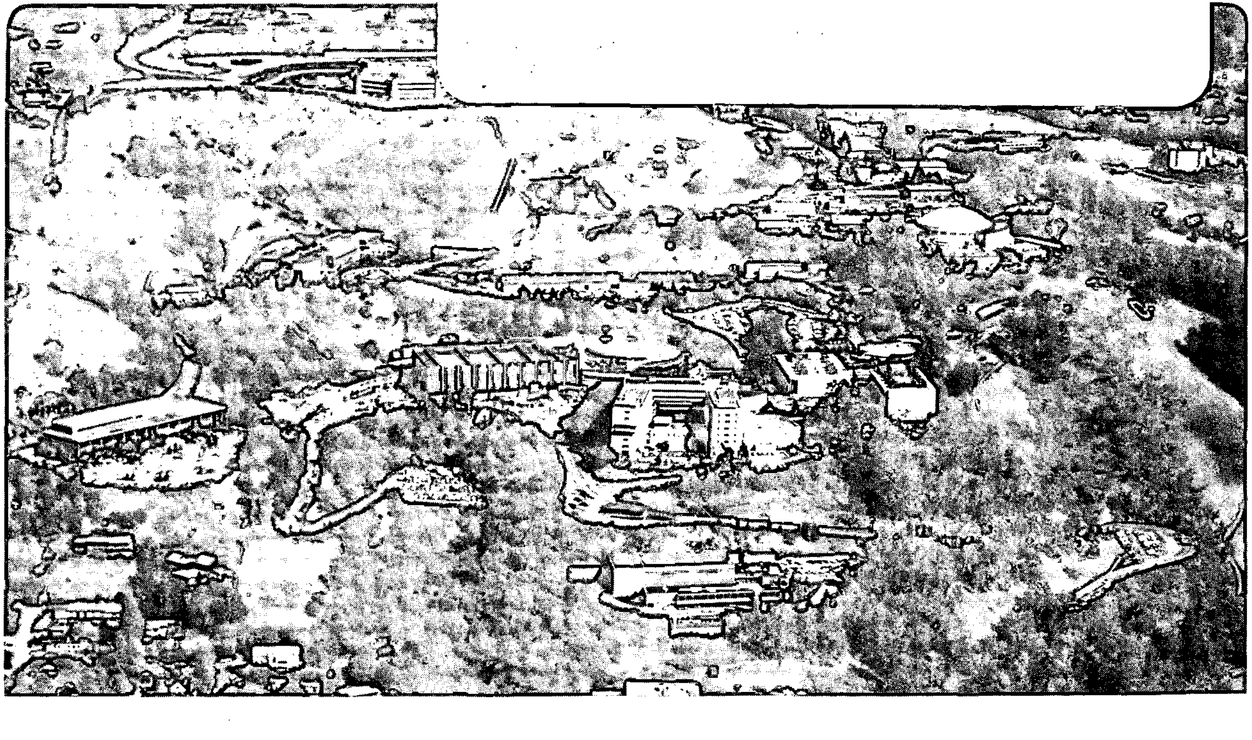

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HIGH T_c SUPERCONDUCTORS: WILL THEY REPLACE HELIUM TEMPERATURE SUPERCONDUCTORS FOR MAGNETS?

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During the last two years,[1] 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 T_c materials for generating magnetic fields in superconducting devices. The high T_c 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 T_c MATERIALS

The high T_c oxide superconductors are an extension of a group of superconductors known as the perovskite class of superconductors.[2] The discovery of a copper oxide perovskite-type superconductor with a T_c above 35 K is considered to be an important advance in solid-state physics and superconductivity. The high T_c superconductors are more complex than the true perovskite structure. The lanthanun-strantium ($T_c \simeq 40$ K) and the yttrium-barium ($T_c \simeq 93$ K) types of superconductors have a single copper oxide plane. The more recent five component superconductors have two or three copper oxide layers.[3] It appears that having more copper oxide layers means a higher T_c and perhaps better stability.

The five component high T_c superconductors can have zero resistivity critical temperatures as high as 125 K.[4] The $Y\ Ba_2\ Cu_3\ O_{7-x}$ superconductors have a consistent zero resistance T_c of 93 K. Studies of this conductor suggest that this type of superconductor may have granules of superconductor with a T_c above 100 K.[5] These granules appear to be connected by resistive regions. The production of a high T_c superconductor that has zero resistance above 90 K requires that the superconductor be oxygenated during processing.[6]

The claims for high H_{c2} for the high T_c superconductor should be examined carefully. Many of the claims are based on measurements where the resistance begins to change or an apparent Meisner effect is seen. The only value of H_{c2} which really counts for magnets is when the resistivity is zero. The highest values of H_{c2} are found in single crystals with the magnetic field in a direction parallel to the plane of the copper oxide planes.[7] The J_c superconductor is also anisotropic. The J_c 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 $d\ H_{c2}/d\ T$ at about 60 K.[8] Based on the WHH theory,[9] the estimated $T = 0$ value of B_{c2} for this conductor is about 60 T ($B_{c2} = \mu_0\ H_{c2}$).

Table 1 compares the properties of Nb-Ti and $Y\ Ba_2\ Cu_3\ O_{7-x}$.[10,11] The J_c for the high T_c superconductors has improved considerably since their discovery.[12] The melted cast Y-Ba-Cu-O conductor has higher values of J_c 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 T_c superconductors are brittle ceramics, whereas niobium titanium is both strong and ductile. Niobium titanium can be codrawn in copper; the high T_c superconductor cannot be drawn into fine filaments. When one compares Nb-Ti with the high T_c superconductor, one should look at Nb_3 Sn or V_3 Ga as compared to Nb-Ti. Both Nb_3 Sn and V_3 Ga have very critical current densities (as high as 10^5 A mm^{-2} at 2 T for V_3 Ga at 4.2 K),[13] but they are brittle. Both Nb_3 Sn and V_3 Ga 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 Nb_3 Sn or V_3 Ga at 4.2 K. The conductor brittleness and the difficulty of forming multifilamentary superconductor are the high T_c superconductors biggest detriments. At this time there is no usable form of the high T_c 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

	Nb-Ti[a] $T_{op} = 4.2$ K	Y-Ba-Cu-O $T_{op} = 77$ K
Type of Material	Metal Alloy	Ceramic
Critical Temperature (K)	9.4	93
Density (kg m^{-3})	6700	6380[b]
Specific Heat at Top (J m^{-3} K^{-1})	5.76×10^3	1.0×10^6
Thermal Conductivity at T_{op} (W m^{-1} K^{-1})	0.275	~13
Thermal Contraction Coefficient at 300 K	$\sim 10^{-5}$	1.3×10^{-5}
Total Thermal Contraction Coefficient 300 K - T_{op}	$\sim 2.0 \times 10^{-3}$	$\sim 2.3 \times 10^{-3}$
Elastic Modulus at T_{op} (G Pa)	83	90 - 110
Ultimate Strength at T_{op} (M Pa)	~2200	Variable
Ductility	Ductile	Brittle

[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

	Helium	Hydrogen	Nitrogen
1 atm Boiling Temperature (K)	4.22	20.3	77.4
Critical Temperature (K)	5.19	33.3	126.1
1 atm Liquid Density (kg m^{-3})	125	70.8	811
1 atm Heat of Vaporization (Jg^{-1})	20.8	442[a]	198
Gas Specific Heat (Jg^{-1} K^{-1})	5.19	14.6	1.03
Available Refrigeration Liquid to 300 K (Jg^{-1})	1561	4629[b]	431
Design Nucleate Boiling Heat Flux[c] (W m^{-2})	2500	30000	60000
Design Nucleate Boiling ΔT[c] (K)	0.5	1.7	6.8

[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 T_c Superconductor in Liquid Hydrogen and Liquid Nitrogen

	Nb-Ti in Helium	High T_c in Hydrogen	High T_c in Nitrogen
Operating Temperature (K)	4.22	20.3	77.4
Critical Temperature (K)	9.35	~93	~93
Adiabatic Stability Diameter (μm)[a]	53.7	539	2156
Dynamic Stability Diameter (μm)[a]	56.0	1220	328
Longitudinal Quench Velocity (ms^{-1})[b,c]	30.5	0.13	0.16
Ratio of Transverse to Longitudinal Quench Velocity RRR = 300 Cu Matrix	0.018	0.020	0.066
Burnout Integral J^2 d T RRR = 300 Cu Matrix Operating Temperature to 400 K (A^2 m^{-4} s)	18.6×10^{16}	18.1×10^{16}	10.1×10^{16}
Enthalpy Change per Unit Volume to Quench without Cryogen[c] (Jm^{-3})	1.26×10^{3}	1.32×10^{6}	5.17×10^{6}
Enthalpy Change per Unit Volume to Quench with 10% Cryogen by Volume[c] (Jm^{-3})	5.73×10^{4}	2.31×10^{6}	5.18×10^{6}
Cryostability Matrix Current Density RRR = 300 Copper[d] (A mm^{-2})	72.2	242	56.2[e]

[a] J_c = 4000 A mm^{-2} at low field, copper-to-superconductor ratio = 2

[b] Matrix J = 500 A mm^{-2}

[c] At 85% of J_c 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[16] 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.[17] 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.[17] 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).[18] 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 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.[19]

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.

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