SSC-N-503
LBL-23946

High-T_C Superconductor and Its Use in Superconducting Magnets

Michael A. Green

Engineering Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

February 1988

This work was supported by the Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

High-T_c Superconductor and Its Use in Superconducting Magnets

Michael A. Green
Engineering Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

ABSTRACT

The discovery of the high-critical-temperature superconductor is a very important solid-state-physics event.[1] The popular press, and to a lesser extent some of the scientific journals, has claimed wonderful things will unfold because of the discovery of high-critical-temperature superconductors (high-T_c). Many of the proposed uses for the high-T_c superconductor involve the creation of a magnetic field using superconducting coils. This report will assess what is known about the high-T_c superconductors and take a realistic look at their potential use in various kinds of superconducting magnets.

Based on what is known about high-T_c superconductors, one can make a "wish list" of things that will make such materials useful for magnets. Then, the following question is asked. If one had a high-T_c superconductor with the same properties as modern niobium-titanium superconductor, how would the superconductor work in a magnet environment? Finally, this report will show the potential impact of the ideal high-T_c superconductor on: 1) accelerator dipole and quadrupole magnets, 2) superconducting magnets for use in space, and 3) superconducting solenoids for magnetic resonance imaging.

1. What Is Known about the High-T_c Oxide Superconductor?

The high-T_c oxide superconductors are an extension of a group of superconductors known as the perovskite class of superconductors[2] that includes materials such as WO_3ReO_3, $SrTiO_3$,[3] and $Ba(PbBi)O_3$. The last material has been known for some years, but it has a critical temperature of only 10 K. Perovskites have been studied for some years since many people thought that they might have some unusual superconducting or magnetic properties.[4] The discovery of a perovskite-type superconductor with a critical temperature above 35 K is considered to be a very important advance in metallurgy and solid-state physics.

The high-T_c oxide superconductors, which are not true perovskite structures, are more complex than perovskites, yet they exhibit similar properties. The high-T_c superconductors, at this time, appear to be divided into two types--the lanthanum-strontium type and the barium-yttrium type.[5] It might be argued that the two types are really subsets of a single type of metal/copper-oxide superconductor with oxygen as the most important element. The superconductor that has received the greatest attention has been the $RBa_2Cu_3O_{7-x}$, where R is yttrium or one of the Lanthanide rare earths. (There have been unverified reports from China that superconductivity can be obtained without the Lanthanide or yttrium.)[6]

a. Value of T_c

Superconductors of the lanthanum-strontium type have been reported to have critical temperatures as high as 50 K (based on zero resistance); the yttrium-barium types have been reported to have critical temperatures as high as 313 K.[7] The most consistent zero-resistance temperature measured by numerous investigators has been around 93 K for the yttrium-barium type superconductor. Studies of $YBa_2Cu_3O_{7-x}$ suggest that the superconductor may consist of granules of superconductor with T_c well above 100 K.[8] These granules appear to be connected by resistive regions. The production of a superconductor that has zero resistance above 90 K requires that the conductor be oxygenated[9] during the processing. (Some of the highest-T_c conductors have some of the oxygen replaced by fluorine. The zero-resistance T_c of these conductors is not consistently the same value. Fresh samples may exhibit a high-T_c temperature, but as the sample ages and is thermal cycled, the T_c drops to the ~90 K temperature measured by everyone else.[7])

b. Value of H_{c2}

There are many claims for high upper critical fields (H_{c2}) for the oxide-type superconductors. These claims should be examined carefully; many are based on measurements of the point at which the resistance of the conductor just begins to change. Other investigators base their claim for a particular value of H_{c2} on a definition of superconductivity based on zero apparent resistivity. The latter definition is the only one important to the person considering the use of the high-T_c oxide superconductor for generating a magnetic field. There have been few, if any, direct measurements of H_{c2} at low temperatures (e.g., 4.2 K) for these materials. The claims of high values of H_{c2} are based on extrapolations based on a measurement of dH_{c2}/dT at or near T_c and on the experimental observations in other materials that high T_c implies that H_{c2} is high also.

If one extrapolates dH_{c2}/dT for the onset of the drop in resistivity, one might get $\mu_0 H_{c2}$ at T = 0 K as high as 360 tesla, based on a linear extrapolation model. (If one uses an extrapolation model that many conventional superconductors follow,[10] one gets a value of $\mu_0 H_{c2}$ = 260 tesla at T = 0.) On the other hand, if one extrapolates dH_{c2}/dT based on measurements of zero resistance near T_c, the value of $\mu_0 H_{c2}$ at T = 0 K would be in the 14- to 20-tesla range, depending on the extrapolation model. The rather low predicted value of zero-resistance $\mu_0 H_{c2}$ at T = 0 K probably can be explained using a granular model, where regions of high-H_{c2} superconductor are surrounded by regions of low-H_{c2} superconductor.[8,11] There is evidence that the zero-resistance dH_{c2}/dT slope for one type (Y-Ba-Cu-O) makes a sharp change at about 60 K; i.e., below 60 K the value of H_{c2} increases more rapidly than it does above 60 K. If this were true for all types of Y-Ba-Cu-O, the estimated value for the zero-resistance H_{c2} would be much higher. (The material that K. Noto et al. examined might have a value of H_{c2} in the 55- to 80-tesla range depending on the model used for the extrapolation.[12]) It is expected that the value of the superconductor H_{c2} is a function of crystal orientation.[13]

c. H_{c1} Measurements

Measurements of $\mu_0 H_{c1}$ by the National Bureau of Standards on Y-Ba-Cu-O superconductor show two (or more) phases of the superconductor.[14] (H_{c1} is the lower critical field.) One phase has a value of $\mu_0 H_{c1}$ of 0.016 tesla to 0.035 tesla at T = 0 K, whereas the other phase has a zero-temperature $\mu_0 H_{c1}$ of 0.0014 tesla to 0.0030 tesla. (The variation is based on the model used to extrapolate the value of $\mu_0 H_{c1}$ at T = 0 K from measurements of dH_{c1}/dT at or near T_c.) The measured value of H_{c1} should be compared to $\mu_0 H_{c1}$ = 0.014 tesla for Nb-Ti, $\mu_0 H_{c1}$ = 0.018 tesla for Nb_3Sn, and $\mu_0 H_{c1}$ = 0.037 tesla for V_3Ga.

d. Critical-Current Density

The potential for high critical-current density (J_c) has been demonstrated by IBM in samples of oriented multicrystal Y-Ba-Cu-O on a strontium titanate substrate.[15] The IBM measured values were J_c(4.2 K, 0 T) = 5×10^{10} A m^{-2} and J_c(77 K, 0 T) = 10^9 A m^{-2}. Bulk samples of Y-Ba-Cu-O have yielded much lower measured values for the critical current. Measurements of critical current by direct voltage measurements of a sample yield measured critical-current densities that are an order of magnitude or more lower than those obtained by magnetization.[16,17] (The IBM oriented-film measurements were made using magnetization methods.)

Measurements of critical current at fields above zero using voltage-drop measurements show a sharp reduction in the critical-current density at 77 K (by more than one order of magnitude at fields as low as 0.1 tesla[17,18]). One explanation for this could be that an increase in the magnetic field inhibits Type II tunneling between granules in the bulk superconductor; thus, there is a reduction of critical current in the sample when the field is increased even a moderate amount. The critical-current density does not decrease as rapidly with field when the temperature is 4.2 K.

It is clear that critical-current density in the bulk high-T_c superconductors is not well understood. Perhaps dramatic improvement in bulk critical-current density can be expected as research on the high-T_c superconductors continues. On the other hand, large changes in critical-current density may take a long time to achieve. (The A-15[19] and Chevrel Phase[20] conventional superconductors have not developed as rapidly as their potential suggested they would.)

e. Mechanical Properties

The mechanical properties of the high-T_c oxide superconductors have been described as ranging from the consistency of chalk to the brittleness of porcelain. Conventional A-15 superconductors such as Nb_3Sn and V_3Ga, which can be produced in multifilamentary form in a ductile metal matrix, have limited usefulness because they are sensitive to strain. Nb_3Sn starts to lose current-carrying capacity irreversibly with strain rates as low as 0.8 percent. This depends on the state of precompression and on whether the strain is compressive or tensile.[21] The high-T_c copper oxide materials are probably more strain sensitive than the A-15 materials (Nb_3Sn, V_3Ga, etc.). The high-T_c superconductor can be expected to have only limited usefulness unless it is manufactured in a wind-and-react configuration. It also appears that the high-T_c superconductors will have to be encapsulated to prevent the diffusion of oxygen from them.

f. Usable Forms of the High-T_c Superconductor

At present, there is no form of high-T_c copper oxide superconductor that can be used to make superconducting magnets, although there are a number of experiments in progress that might yield a usable superconductor for magnets. The experiments have taken two forms: 1) Metal tubes are fabricated with powdered components within them. The tubes are drawn into wires and then are reacted.[22] 2) Thin films of superconductor are produced on a substrate.

The tube experiment has been tried with the components of Y-Ba-Cu-O superconductor in copper and silver tubes. After being fabricated, drawn, and reacted, the Y-Ba-Cu-O superconductor in the copper matrix was not superconducting at 77 K.[23] When copper is heated to the 700- to 1000-K reaction temperature, it pulls oxygen out of the reaction, which depletes the superconductor of its oxygen. The material fabricated within the silver tube was superconducting at 77 K, but its properties were not as good as the bulk superconductor annealed in an oxygen atmosphere.[22]

The IBM experiment is an example of the thin-film-on-a-substrate technique. Films as thick as 400 μm have been produced,[15] and the thin-film material may well become the first usable form of the high-T_c copper oxide superconductor. It is desirable, however, that this thin-film material be combined with a metal matrix.

2. What Properties Are Needed for a Good Superconducting Magnet Conductor?

It is useful to look at the desirable properties of a superconductor for use in superconducting magnets. The ideal magnet superconductor has the following characteristics:

1) The superconductor should be divided into many fine filaments transposed within a good conducting matrix material. The diameter of the filaments is set by stability criteria. In most cases twisted superconductor is suitable.

2) The matrix material should have a high thermal conductivity and a low electrical resistivity. The required matrix electrical resistivity is set by ac loss and quench-protection criteria.

3) The matrix material should have a high mass density so that the integral of J^2 dt = F* is maximized between the operating temperature (T_{op}) and room temperature, as shown below:

$$F^* = \int_{T_{op}}^{300} \frac{C}{\rho}\, dT = \int_0^{\infty} J^2\, dt \quad ,$$

where C is the specific heat per unit volume, ρ is the electrical resistivity, T is temperature, J is the matrix current density (defined as the current divided by the matrix area without superconductor), and t is time.

4) The superconductor and matrix material should be ductile and have approximately the same hardness as the superconductor to permit them to be co-drawn.

5) The conductor should not lose its superconducting properties as it is strained (say up to 1 percent strain). One should be able to bend it over a small radius.

6) The superconductor/matrix should have high ultimate breaking stress in tension (e.g., greater than 3×10^{8} N m^{-2}). The elastic modulus of the conductor should be high (preferably greater than 5×10^{10} N m^{-2}.)

Niobium titanium in a copper matrix has all of the above characteristics. Multifilamentary Nb_3Sn and V_3Ga in a bronze matrix meets all of the above criteria except No. 5. These conductors, however, cannot be bent in the reacted state, and their stress and strain capabilities are limited.[21]

It is unlikely that the high-T_c superconductor can be fabricated in a nice filamentary form that meets the criteria set out previously. At best, a conductor similar to multifilamentary Nb_3Sn and V_3Ga can be produced. In order to produce a multifilamentary form of the high-T_c ceramic oxide superconductor, many steps of processing will be required. Magnets built from the conductor will probably be of the wind-and-react variety except, possibly, for very large solenoid magnets.

The earliest and most likely form of the high-T_c ceramic oxide superconductor that could be used to fabricate superconducting magnets is a thin-film of superconductor on a substrate. It may be possible to slit the superconducting film along the length of the ribbon in order to subdivide the ribbon. The need for such slitting is dependent on the anisotropic character of the high-T_c oxide conductor. It is the author's opinion that the high critical-current densities required for a usable magnet superconductor ($J_c \geq 10^{10}$ A m^{-2}) can only be obtained in the thin-film form.

It may be possible to fabricate a thin-film ribbon form of the conductor that can be clad with copper or aluminum. A prereacted clad-ribbon conductor may be possible, provided the high-T_c oxide superconductor is at the neutral axis of bending for the conductor. (This is similar to the Nb_3Sn ribbon conductor.) A usable wind-and-react conductor with the matrix material built in will be more difficult to fabricate because the matrix material will tend to act as a getter for oxygen. An aluminum-matrix conductor will be especially difficult because the reaction temperature for the high-T_c superconductor is above the melting temperature for aluminum.

A normal metal-clad-ribbon high-T_c oxide superconductor will probably exhibit some of the following undesirable characteristics: 1) The stability of the conductor will be a potential problem unless the flux lines are parallel to the thin-film surface. 2) Winding will be limited by strain. (There will be only one preferred winding direction.) 3) The clad high-T_c oxide superconductor will probably have to be well cooled with the liquid cryogen. For magnets more than ~10 cm in diameter, cryostability may be the only option. The postulated clad high-T_c superconductor can be expected to have characteristics similar to diffusion-process Nb_3Sn ribbons in limited use today.

One of the major research difficulties with the high-T_c oxide superconductors is increasing the transport critical-current density. (This is even more difficult if one wants to use these materials at liquid-nitrogen temperature and above.) Not only must the J_c go up at zero field, but a mechanism for tying the superconducting grains together must be found to prevent the large fall off in J_c as the field is increased. (This is particularly true for conductors to be used at liquid-nitrogen temperatures or above.) It is likely that high J_c will be demonstrated by magnetization (the IBM oriented-film ribbon has demonstrated that acceptably high J_c is possible), but the real problem will be getting a conductor capable of carrying large transport currents. (This can be achieved by increasing the transport current J_c and by increasing the fraction of superconductor in the clad-ribbon conductor.)

If one looks at superconductor development from a historical perspective, the achievement of a usable magnet superconductor will be long in coming. If one is an optimist (most people involved with superconducting magnets are optimists), one should ask the following questions (assuming that a ductile fully transposed multifilamentary conductor in a copper matrix exists): Is it desirable to use the high-T_c superconductor? What will the problem areas be for superconducting magnets?

The next section of this report will discuss various aspects of magnet design that assume the existence of a usable form of the high-T_c superconductor.

3) Factors Which Affect the Use of High-T_c Superconductors in Magnets

The usefulness of high-T_c superconductors in magnets can be examined if one assumes that the high-T_c superconductor has mechanical and current carrying properties which are similar to present generation niobium titanium. To determine the potential usefulness of the new material, the following assumptions have been made:

1) The high-T_c oxide conductor can be fabricated in a transposed multifilamentary form in pure-copper or pure-aluminum matrices.
2) The conductor filaments are fine enough to ensure both adiabatic and dynamic stability.
3) The critical-current density in the high-T_c superconducting filament is at least 10^{10} A m^{-2} (10 000 A mm^{-2}) at its operating temperature and field. (A lower superconductor J_c would be usable, but not if it's below ~10^{9} A m^{-2}.)
4) The superconductor will be operated in a bath of boiling cryogenic working fluid. (High-current-density conductors could be indirectly cooled from a boiling cryogenic working fluid. This section of this report will consider whether cryostability is needed.)
5) The multifilamentary high-T_c superconductor is ductile with an ultimate stress comparable to multifilamentary Ni-Ti.

The previous sections indicate that we are far from achieving the assumptions previously stated. The question is whether the high-T_c oxide superconductor is useful for magnet fabrication even if it has ideal properties similar to Nb-Ti.

In order to determine the potential usefulness of the high-T_c oxide superconductor, the following factors are examined:

1) Five potential working fluids are evaluated for use with the high-T_c oxide superconductors. They (and their 1-atm. boiling temperatures) are helium (T = 4.2 K), hydrogen (T = 20.3 K), neon (T = 27.1 K), nitrogen (T = 77.4 K) and refrigerant 14 (tetrafluoromethane, T = 144.2 K). All of these working fluids could be used with high-T_c superconductors with critical temperatures up to ~240 K. (Assuming that a conductor with a reliable T_c of 240 K exists.)
2) Refrigeration input power is evaluated for the five working fluids at their 1-atm. boiling temperatures.
3) The critical filament diameters for adiabatic and dynamic stability are calculated assuming isotropic properties and a critical-current density of 10^{10} A m^{-2}.
4) Longitudinal and transverse quench velocities are calculated for high-T_c oxide conductors in copper and aluminum matrices. (The matrix current density is assumed to be 3 x 10^8 A m^{-2}.)
5) The burnout integral of J^2 dt is calculated for conductor in copper and aluminum matrices at the 1-atm boiling temperatures of the five working fluids. The maximum allowable hot-spot temperature is set at 400 K. (The matrix current density is assumed to be 3 x 10^8 A m^{-2}.)
6) The enthalpy change per unit volume is calculated for various conductors. The minimum quench propagation volume for a matrix current density of 3 x 10^8 A m^{-2} is also calculated. From these factors,

the quench energy is generated. The effect of putting the liquid cryogen in direct contact with the superconductor is also shown.

7) Cryostability criteria (based on the simple Stekly and Whetstone model) are calculated for the high-T_c superconductors in pure copper (RRR = 100 and RRR = 300) and pure aluminum (RRR = 1000) matrices operating in the five boiling working fluids.

8) Magnetization effects are discussed.

These eight factors will yield a constructive picture of the potential usefulness of the high-T_c oxide superconductors if they exist in an ideal form for constructing superconducting magnets.

a. The Five Working Fluids

Table 1 summarizes the most important properties of helium, hydrogen (para hydrogen), neon, nitrogen, and tetrafluoromethane (R-14). The properties listed in Table 1 are boiling temperature at 1 atm, liquid density at the boiling point, heat of vaporization at the boiling point, enthalpy change of the fluid from the liquid state at the boiling point to gas at 300 K, the usable design nucleate boiling heat flux at 1 atm, and several other parameters. The first four gasses are the lowest-temperature cryogenic fluids. The choice of R-14 was arbitrary. It is a commonly available, safe refrigerant that has the lowest boiling temperature of the fluorocarbon refrigerants.

Helium is the refrigerant of the conventional superconductor. It has good heat-transport properties. Its heat of vaporization is low, but its specific heat is high. Its critical pressure and the density difference between liquid and gas are also low. Helium has two liquid states. The second liquid state (Helium II), which occurs at 2.17 K or below, has some very interesting properties that make it an ideal refrigerant for aerospace applications. In addition, Helium II is finding increasing application as a coolant for conventional superconductors. From a safety standpoint helium has many outstanding properties. It is nontoxic and nonflammable, and because of its low critical pressure it is a relatively safe cryogenic fluid as long as the Dewar design pressure is high enough.

Hydrogen is a very interesting fluid with extremely good refrigeration and heat-transfer properties. It is characterized by its low density, extremely high specific heat, and the highest heat of vaporization of the five fluids. At its low boiling temperature (20.3 K) pure copper and pure aluminum will have a low resistivity. Hydrogen is nontoxic odorless and colorless but it burns over a very wide range of concentrations in air. Therefore, special safety precautions must be taken because of its extreme flammability. (Hydrogen is lighter than air and does not radiate much heat when it burns.)

Neon is an expensive substitute for hydrogen with a boiling temperature 7 K higher. It has the worst cryogenic properties of any of the five fluids. (Only helium has a lower heat of vaporization, but helium has five times the specific heat of neon.) The total available refrigeration in neon is the second lowest of the five fluids. Because neon is expensive; a ground-based system would have to have an extensive neon recovery system. Neon is odorless, nontoxic, and nonflammable. Therefore, handling neon is only slightly more hazardous than handling nitrogen.

TABLE 1. PROPERTIES OF FIVE LIQUEFIED GASSES THAT MIGHT BE USED TO COOL A SUPERCONDUCTING MAGNET

		Helium	Hydrogen	Neon	Nitrogen	R-14
<u>Basic Properties</u>						
Chemical Formula		He	H_2	Ne	N_2	CF_4
Molecular Weight		4	2	20	28	88
Melting Temperature at 1 atm	(K)	--[a]	13.91	24.66	63.29	123.2
Boiling Temperature at 1 atm	(K)	4.22	20.28	27.10	77.35	144.2
Triple-Point Temperature	(K)	2.17[a]	13.81[b]	~ 24.6	~ 63.30	~ 123
Critical Temperature	(K)	5.19	33.25	44.45	126.1	227.5
Critical Pressure	(atm)	2.26	12.8	26.9	33.5	37.0
<u>Other Properties</u>						
Liquid Density at Boiling Point	(kg m^{-3})	125	70.8	1205	810.9	3034
Heat of Vaporization at 1 atm	(J g^{-1})	20.8	441.3	86.6	198.1	177.8
Specific Heat C_p at 300 K	(J g^{-1} K^{-1})	5.19	14.55	1.036	1.030	0.707
Enthapy Change of Gas from Boiling Point to 300 K	(J g^{-1})	1540.6	4188[c]	286.6	233.3	~ 110
Maximum Effective Refrigeration from Liquid to Gas at 300 K	(J g^{-1})	1561.4	4629[c]	369.2	431.4	~ 288
Maximum Nucleate Boiling Heat Flux at 1 atm	(W cm^{-2})	0.8	9.5	~ 16	19.0	~ 22
Usable Design Nucleate Boiling Heat Flux at 1 atm	(W cm^{-2})	0.27	3.5	~ 5	6.0	~ 7
Nucleate Boiling Temperature Difference at 1 atm	(K)	0.5	2.7	~ 3.5	11	>10

[a]Helium has no solid phase in contact with liquid; 2.17 K is the lamda point where two liquid phases and gas coexist.

[b]Para hydrogen; hydrogen at room temperature is virtually all ortho hydrogen.

[c]Includes the heat of conversion from para hydrogen to ortho hydrogen.

Nitrogen is the most commonly used cryogenic fluid and is widely available in large quantities. Nitrogen has the second largest heat of vaporization of the five fluids. The total available refrigeration, however, is not much higher than that of liquid neon. Its most attractive feature is its wide availability. The potential use of liquid nitrogen as a coolant is one of the major reasons for the recent popular interest in high-T_c superconductors. Nitrogen is colorless, odorless, nonflammable, and nontoxic and is relatively safe to handle.

R-14, also known by the trade names of Freon 14 or Genitron 14, has the lowest boiling point of the commercial refrigerants. It can easily be incorporated in a conventional closed-cycle refrigeration plant and is commonly available in large quantities. It has the lowest available refrigeration and has a heat of vaporization comparable to nitrogen. Of the five fluids it has the worst heat-transfer properties (except peak nucleate boiling heat flux). R-14 has a slight odor and low toxicity (6 on the Underwriters Scale), but it is heavier than air.

The cryogenic properties of liquid helium, hydrogen, nitrogen, and neon are found in Ref. 24. Properties of R-14 are found in Refs. 25 and 26. Peak useful nucleate boiling heat flux for helium, hydrogen, and nitrogen are from Refs. 27 and 28. A usable design nucleate boiling heat flux of about one third of the peak heat flux can be used in all cases without specialized surface preparation on the boiling heat transfer surface. No measured peak nucleate boiling heat fluxes were found for neon or R-14. A method given by Ciechelli and Bonilla was used to calculate the peak heat flux.[29,30]

b. Refrigeration Input Power

The primary advantage of high-T_c superconductors is the elimination of liquid-helium refrigeration (and liquid helium). This, however, is a double-edged sword. The elimination of liquid-helium temperatures could also mean the elimination of the associated high vacuum, which helps insulate the cryogen container and the refrigeration system. (All other gases are pumped by a surface at liquid helium temperature.)

Increasing the operating temperature of the superconductor does substantially reduce the input power to a refrigerator per unit output refrigeration. For an ideal Carnot refrigerator the ratio of input power to refrigeration generated is as follows[21,22]:

$$\frac{\text{Input Power}}{\text{Output Refrigeration}} = \frac{1}{\beta} = \frac{T_H - T_C}{T_C} \quad , \tag{1}$$

where β is the refrigerator coefficient of performance; T_C is the temperature from which the heat is pumped (the cold-end temperature); and T_H is the temperature of the sink to which the heat is pumped (in this case T_H is the heat-rejection temperature, which is usually room temperature, ~300 K).

Table 2 presents the ratio of input power to refrigeration in a Carnot refrigerator at the boiling temperature T_b of the five working fluids from Table 1. The ratio of input power to refrigeration given in Table 2 is based on the assumption that the sink temperature T_H is 300 K. From Table 2 one can see that increasing the operating temperature from 4.2 K to 20.3 K reduces the ideal input power by a factor of 5. Increasing the operating temperature to 77.3 K results in nearly a factor-of-25 reduction in the ratio of input power to refrigeration compared with operation at liquid-helium temperatures.

A real refrigerator has only a fraction of the efficiency of an ideal Carnot refrigerator, and the efficiency of a refrigerator η is often stated in terms of percent of Carnot. This efficiency η is a function of the output refrigeration and is only a very weak function of the refrigeration temperature. For a real refrigerator, the ratio of input power to refrigeration can be calculated using the following relationship:

$$\frac{\text{Input Power}}{\text{Output Refrigeration}} = \frac{1}{\eta\beta} = \frac{T_H - T_C}{\eta\, T_C} \quad , \qquad (2)$$

where β, T_H, and T_C are previously defined, and η is the refrigerator efficiency stated in terms of a percentage of Carnot. Strobridge[33] investigated a large number of cryogenic refrigerators and determined their efficiency. A curve was generated of refrigeration efficiency (percent of Carnot) as a function of output refrigeration. Using the Strobridge calculation, Table 3 was generated. This table presents the projected ratio of input power to output power as a function of refrigeration output for refrigerators operating at the boiling temperatures of the five working fluids from Table 1. The numbers presented in Table 3 have a 30- to 50-percent error bar attached to them since there is considerable scatter in the refrigeration efficiency data on the Strobridge curve.

TABLE 2. INPUT POWER AT 300 K FOR A PERFECT CARNOT REFRIGERATOR FOR FIVE BOILING FLUIDS

Fluid	T_b (K)	Input Power per Watt of Refrigeration (W)
Helium	4.22	70.4
Hydrogen	20.3	13.7
Neon	27.1	10.1
Nitrogen	77.3	2.88
R-14	144.2	1.08

TABLE 3. THE INPUT POWER REQUIRED PER WATT OF REFRIGERATION VERSUS WORKING FLUID AND REFRIGERATOR SIZE[33]

Working Fluid	T_b (K)	Input Compressor Power (W per W of Refrigeration)		
		1-W Refrigerator	100-W Refrigerator	10000-W Refrigerator
Helium	4.22	~ 3600	~ 950	~ 370
Hydrogen	20.3	~ 1000	~ 170	~ 90
Neon	27.1	~ 750	~ 125	~ 65
Nitrogen	77.3	~ 140	~ 26	~ 12
R-14	144.2	~ 50	~ 12	~ 5

If one looks at the rated capacity of a Koch 1400 refrigerator[34] at 4.6 K, one finds that the calculated ratio of input power to refrigeration is quite close to the measured value. For a 1-W refrigerator at 4.6 K, the ratio is 3200; a 100-W refrigerator has a ratio of about 850. A Koch 1400 with one 25-kW compressor and no precooling is rated at 23-W (the ratio is 1087). With two 25-kW compressors the refrigeration increases to 57-W (the ratio drops to 877). These numbers agree with Table 3.

Regarding refrigeration, it is useful to point out that there is a tendency to reduce the quality of the insulation when the temperature goes up. The heat leak into a liquid-nitrogen cryostat can easily be an order of magnitude higher than for a liquid-helium cryostat. One should resist the tendency to be sloppy with the insulation if one is really concerned about reductions of refrigerator input power. In short, the savings of refrigeration input power and refrigeration may not be as large as one might initially think.

c. Filament Diameters for Adiabatic and Dynamic Stability

For the high-T_c superconductor or any other superconductor to be used in a high-current-density configuration, the superconducting filaments must be small enough to ensure stability. Superconductors used in cryostable magnets will perform better if the filament diameter is below the adiabatic and dynamic stability limit.

The concept of adiabatic stability comes from the concept of the critical-current model, which says that a superconductor in an electric field must carry its critical current.[35] (i.e., a superconductor has a resistivity that is proportional to the electric field.) The critical current is a function of temperature and magnetic induction (B). The energy stored within a superconducting filament due to circulating currents (at critical-current density) is proportional to filament diameter d_f squared and critical-current density in the superconductor $J_c(B,T)$ squared. In conventional Nb-Ti, flux-jump instability will occur when the shield magnetic induction from the center to the edge of the filament is of the order of 0.25 tesla.[36] According to the paper by Wilson et al.,[37] the superconductor will be stable if the following conditions prevail:

$$d_f J_c \leq \left[\frac{\pi^2}{4\mu_0} \; C_{sc} \; J_c^{-1} \left(\frac{dJ_c}{dT} \right)^{-1} \right]^{1/2} , \qquad (3)$$

where d_f is the filament diameter, J_c is the critical current in the superconductor, μ_0 is the permeability of air ($\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}), C_{sc} is the specific heat per unit volume of the superconductor (conservative calculations would use C_{sc} at the conductor operating temperature), and

$$\left(J_c^{-1} \; \frac{dJ_c}{dT} \right)^{-1} \approx \frac{T_c}{2} . \qquad (3a)$$

The specific heat of the superconductor is somewhat complicated to calculate because it contains both a term for specific heat of the normal state and a superconducting magnetization term.[38] High-T_c superconductors have a much smaller magnetization term relative to the specific heat of the normal material, so it is reasonable to use the normal-state specific heat in equations.

Wilson[37] and Hart[39] have both suggested that stability could be increased by increasing C_{sc} and by increasing T_c. A conductor that has a positive dJ_c/dT will be stable regardless of the filament diameter. The high-T_c superconductor will have a larger $d_f J_c$ product because both T_c and C_{sc} are larger. The adiabatic stability for the high-T_c conductor is expected to be enhanced.

Multifilamentary conductors are not flux-jump stable unless the filaments are transposed within the superconductor. Up to a certain size a simple twist is sufficient to ensure that the conductor is stable against circulating currents from filament to filament. The twist pitch required for stable operation of a multifilamentary conductor is a function of the matrix material resistivity and the rate of magnet flux change that the conductor sees. (The minimum twist pitch is about 5 times the mean diameter of the conductor matrix.) In general, a higher-resistivity matrix material will result in a more-stable conductor for given rate of magnetic flux change. For a typical multifilamentary conductor the twist pitch ℓ_{tp} should be

$$\ell_{tp} < \left[\frac{8\,\rho_1\,J_c\,d_f}{\dot{B}}\left(\frac{1}{r+1}\right)^{1/2}\frac{d_s}{d_s+d_f}\right]^{1/2} , \qquad (4)$$

where ℓ_{tp} is the critical twist pitch that causes doubling of the superconductor ac loss in a magnetic induction changing at the rate $\dot{B}=dB/dt$, ρ_1 is the matrix resistivity, J_c is the superconductor critical-current density, r is the normal metal-to-superconductor ratio, d_f is the filament diameter, and d_s is the average distance between filaments.

Twisting does not ensure stability against self-field effects,[40] but self field is usually not a problem if the magnetic induction difference from one side of a conductor to the other is less than about 0.5 tesla. There are several criteria that govern self-field instability if the induction difference from side to side is greater than 0.5 tesla. The conductor will nearly always be stable against self-field effects if the minimum conductor dimension is about 2 mm or less[41] and the filament diameter is smaller than indicated by Eq. (3). The larger the matrix the smaller the filaments should be. Increasing the matrix-to-superconductor ratio enhances self-field stability.

The last form of stability that is important on the superconductor level is dynamic stability. The principle behind dynamic stability is that the thermal diffusivity of matrix material must be much greater than the thermal diffusivity of the superconductor. On the other hand, the magnetic diffusivity of the superconductor must be much larger than the magnetic diffusivity of the matrix material.[42,43] For effective dynamic stability, the filaments of superconductor must be relatively small, and the matrix material should have a high thermal conductivity (and a low electrical resistivity). According to the dynamic-stability criteria given by Wilson et al.[37]:

$$d_f J_c \leq \left[\frac{8\, k_{sc}\, r}{\rho_1} \left(J_c^{-1} \; \frac{dJ_c}{dT} \right)^{-1} \right]^{1/2} \quad \text{and} \qquad (5)$$

$$\left(J_c^{-1} \; \frac{dJ_c}{dt} \right)^{-1} \approx \frac{T_c}{2} \quad . \qquad (5a)$$

where J_c is the superconductor critical-current density, d_f is the filament diameter, k_{sc} is the thermal conductivity of the superconductor, ρ_1 is the resistivity of the matrix material, and r is the ratio of matrix material to superconductor.

Equation (5) takes a form very similar to Eq. (3). When the matrix material is made from pure copper, the product of $J_c d_f$ will decrease as the operating temperature rises (k_{sc} is almost constant except at the lowest temperatures) because the matrix resistivity increases. The dynamic stability diameter (like the adiabatic stability diameter) increases with T_c, but it decreases as one increases the operating temperature because of the matrix resistivity term.

Table 4 presents estimates for the adiabatic and dynamic stability diameters based on calculations made using Eqs. (3) and (5). The specific heat used was the superconductor specific heat at the operating temperature. If T_c is much higher than the operating temperature, this assumption will yield a conservative result in most cases. There is a great deal of uncertainty in the value of the critical dynamic stability diameter since the thermal conductivity of the superconductor is not known. An estimate of the thermal conductivity was made using the thermal conductivity of various rare-earth salts,[44] whose thermal conductivities vary over a wide range. The value chosen was an approximate midpoint value, and there is a factor of two to three uncertainty in the dynamic stability diameter for the high-T_c oxide superconductor. Table 4 uses Nb-Ti, Nb_3Sn, and three high-T_c superconductors for comparison: High TC-1, one of the lanthanum-strontium superconductors, with a T_c of 40 K; High TC-2, a yttrium-barium

TABLE 4. ESTIMATED ADIABATIC AND DYNAMIC STABILITY DIAMETERS FOR Nb-Ti, Nb_3Sn, AND THREE HIGH-T_c SUPERCONDUCTORS AT VARIOUS OPERATING TEMPERATURES

Superconductor	T_c (K)	T_o (K)	C_{sc} J m^{-3} K^{-1}	k_{sc} W m^{-1} K^{-1}	ρ_1[a] (Ω m)	Adiabatic d_f (μm)	Dynamic d_f (μm)
Nb-Ti	9.4	4.2	5×10^3	0.1	1.5×10^{-10}	57.3[b]	59.7[b]
Nb_3Sn	18	4.2	5×10^3	0.1	1.5×10^{-10}	29.7	31.0
High TC-1	40	20	5×10^4 [c]	1.0[c]	1.6×10^{-10}	140	141
High TC-2	93	20	5×10^4 [c]	1.0[c]	1.6×10^{-10}	216	218
High TC-2	93	77	8×10^5 [c]	1.0[c]	2.0×10^{-9}	863	62
High TC-3	240	20	5×10^4 [c]	1.0[c]	1.6×10^{-10}	343	346
High TC-3	240	77	8×10^5 [c]	1.0[c]	2.0×10^{-9}	1373	98

__Note__: Copper-to-superconductor ratio $r = 2$; $J_c = 10^{10}$ A m^{-2} for all conductors except Nb-Ti; $\mu_o = 4\pi \times 10^{-7}$.

[a]Copper matrix with a residual resistance ratio of 100.

[b]Based on a superconductor $J_c = 3.75 \times 10^9$ A m^{-2} for Nb-Ti.

[c]Approximate, based on typical salts of the Lathanides. The thermal conductivity varies over a factor of 20. The midpoint value is given.

superconductor, with a T_c of 93 K; and High TC-3, one of the postulated (as yet nonexistent) near-room-temperature superconductors, with a T_c of 240 K.

Table 4 shows a general trend. The higher the T_c, and operating temperature, of the superconductor the larger the adiabatic stability critical diameter, but the dynamic stability critical diameter decreases with increasing operating temperature. In general, the high-T_c superconductor should be more stable with respect to thermal excursions caused by flux jumps, conductor motion, and pulses of external heat. The increased stability of the conductor is both a blessing and a curse since a very stable superconductor does not propagate quenches well.

d. Longitudinal and Transverse Quench Propagation Velocity

The usefulness of a high-T_c oxide superconductor in a high-current-density superconducting magnet without good cooling (a magnet that is not cryostable) depends on the rate of quench propagation and the integral of matrix current density squared with time before burnout. This subsection deals with quench propagation velocity. The next subsection deals with burnout integral.

The method used to calculate quench propagation velocities is one suggested by Cherry and Gittleman[45] that was modified slightly by Eberhard et al.[46] in 1977. This method does not calculate quench propagation velocity accurately, but it can be used to compare the order of magnitude of the quench velocities in high-T_c superconductors. The longitudinal quench propagation velocity can be calculated using an equation of the following form:

$$V_L \approx 0.6\ J_o \left(\frac{\rho_1\ \alpha_L}{\Delta H}\right)^{1/2} \quad , \tag{6}$$

where J_o is the superconductor/matrix current density, ρ_1 is the electrical resistivity of the matrix material at T_c, α_L is the thermal diffusivity of the matrix in the longitudinal direction at T_c, and ΔH is the enthalpy change in the conductor (per unit volume) needed to raise the conductor temperature from the operating temperature to the critical temperature T_c (H, J).

The ratio of the transverse quench velocity V_T (the normal-region propagation from turn to turn or layer to layer) to longitudinal quench velocity V_L (along the wire) is given as follows:

$$\nu = \frac{V_T}{V_L} \approx \left(\frac{\alpha_T}{\alpha_L}\right)^{1/2} \quad , \tag{7}$$

where α_T is the thermal diffusivity in the transverse direction at T_c, and α_L is the thermal diffusivity in the longitudinal direction at T_c; α_T and α_L are given as follows:

$$\alpha_L \approx \frac{k_M}{C_M} \qquad \text{and} \tag{7a}$$

$$\alpha_T \approx \frac{k_T}{C_T} \quad , \tag{7b}$$

where k_M is the matrix-material thermal conductivity at T_c, and c_M is the matrix-material volume specific heat at T_c; k_T is the transverse thermal conductivity at T_c, and C_T is the volume specific heat at T_c for the matrix and insulation; k_T and C_T can be estimated using the following relationships:

$$\frac{1}{k_T} \approx \frac{X_M}{k_M} + \frac{X_i}{k_i} \qquad \text{and} \qquad (7c)$$

$$C_T \approx C_M X_M + C_i X_i \quad , \qquad (7d)$$

where X_M is the thickness fraction of the matrix metal in the transverse direction, and X_i is the thickness fraction of the insulation, k_M and k_i are the thermal conductivity of the matrix material and the insulation material, and C_M and C_i are the volume specific heats of the matrix material and the insulation material at T_c.

If one assumes that $C_M = C_i$, that the insulation is relatively thin compared to the matrix material ($X_i \leq 0.25$), and that the $k_i << k_M$, one gets the following simplified expression for the transverse quench-velocity ratio:

$$\nu \approx \left(\frac{k_i}{x_i\, k_m}\right)^{1/2} \quad . \qquad (8)$$

Equations (7) and (8) ignore the superconductor. Both equations are independent of the ratio of normal metal to superconductor. The rationale for this is that superconductor in the normal state is a poor conductor of heat and electricity. Therefore, the superconductor plays almost no role in transporting either form of energy. The specific heat of the superconductor, however, does count, and this component is allowed for, in part, by using the total J for the superconductor/matrix.

Table 5 contains specific-heat, thermal-conductivity, and resistivity data for RRR = 100 copper, RRR = 1000 aluminum, and a General Electric TSV vinyl modified phenolic varnish insulation.[47] Table 6 shows calculated quench velocities and quench-velocity ratios (transverse quench velocity to longitudinal quench velocity) ν for Nb-Ti, Nb_3Sn, and the three high-T_c superconductors from Table 4. These calculations were made with these superconductors in a RRR = 100 copper matrix and in a RRR = 1000 aluminum matrix. The velocities were calculated at zero field with a superconductor/matrix current density $J_o = 3 \times 10^8$ A m^{-2}. The velocity-ratio calculation assumes that the TSV varnish has one-tenth of the thickness of the total package ($X_i = 0.1$).

The calculated longitudinal quench propagation velocity given for Nb-Ti in Table 6 is somewhat higher than the 4–6 m s^{-1} measured for Nb-Ti in a copper matrix at near zero field with a matrix plus superconductor current density of 3×10^8 A m^{-2}.[48,49,50,51] Measurements of quench velocity in multifilamentary Nb_3Sn conductor indicate that its quench velocity is a factor of 2.5 to 4 lower than for multifilamentary Nb-Ti.[50,51] Measurements of Nb-Ti in an aluminum matrix indicate a faster quench propagation velocity for a given matrix current density.[50,51] The discrepancy between measurement and the calculations given in Table 6 for

TABLE 5. PROPERTIES OF COPPER, ALUMINUM, AND TSV (GENERAL ELECTRIC VINYL MODIFIED PHENOLIC VARNISH) AS A FUNCTION OF T_c[a]

Temperature (K)	Volume Specific Heat ($J\ m^{-3}\ K^{-1}$)	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	α ($m^2\ s^{-1}$)	Electrical Resistivity ($\Omega\ m$)
Copper Matrix RRR = 100				
9.4	6.7×10^3	1300	0.195	1.5×10^{-10}
18	6.2×10^4	2200	0.049	1.5×10^{-10}
40	5.3×10^5	1300	2.45×10^{-3}	3.5×10^{-10}
93	2.2×10^6	480	2.18×10^{-4}	3.5×10^{-9}
240	3.3×10^6	400	1.21×10^{-4}	1.3×10^{-8}
Aluminum Matrix RRR = 1000				
9.4	3.2×10^3	7900	2.46	2.5×10^{-11}
18	1.7×10^4	7200	0.423	2.5×10^{-11}
40	2.1×10^5	2400	0.011	2.7×10^{-10}
93	1.2×10^6	330	2.75×10^{-4}	4.5×10^{-9}
240	2.3×10^6	240	1.05×10^{-4}	2.2×10^{-8}
TSV				
9.4	2.9×10^4	0.08	2.8×10^{-6}	--
18	7.8×10^4	0.10	1.3×10^{-6}	--
40	2.7×10^5	0.16	6.0×10^{-7}	--
93	7.5×10^5	0.24	3.2×10^{-7}	--
240	1.6×10^6	0.35	2.2×10^{-7}	--

[a]Sources for the properties data are in Refs. 24 and 47.

TABLE 6. CALCULATED VALUES OF LONGITUDINAL QUENCH VELOCITY AND QUENCH-VELOCITY RATIOS FOR VARIOUS SUPERCONDUCTORS AT VARIOUS OPERATING TEMPERATURES AT A CURRENT DENSITY OF 3 x 10^8 A m^{-2}

Superconductor	T_c (K)	T_o (K)	α (m^2 s^{-1})	ΔH (J m^{-3})	V_L[a] (m s^{-1})	Velocity Ratio υ
Copper Matrix RRR = 100						
Nb-Ti	9.4	4.2	0.194	0.017 x 10^6	7.4	0.025
Nb_3Sn	18	4.2	0.049	0.176 x 10^6	1.2	0.021
High TC-1	40	20	2.45 x 10^{-3}	5.12 x 10^6	0.074	0.035
High TC-2	93	20	2.18 x 10^{-4}	70.3 x 10^6	0.019	0.071
High TC-2	93	77	2.18 x 10^{-4}	12.5 x 10^6	0.044	0.071
High TC-3	240	77	1.21 x 10^{-4}	454 x 10^6	0.011	0.094
High TC-3	240	144	1.21 x 10^{-4}	310 x 10^6	0.013	0.094
Aluminum Matrix RRR = 1000						
Nb-Ti	9.4	4.2	2.46	0.008 x 10^6	15.8	0.010
Nb_3Sn	18	4.2	0.423	0.107 x 10^6	1.8	0.012
High TC-1	40	20	0.011	1.05 x 10^6	0.30	0.026
High TC-2	93	20	2.75 x 10^{-4}	35.6 x 10^6	0.034	0.085
High TC-2	93	77	2.75 x 10^{-4}	11.3 x 10^6	0.059	0.085
High TC-3	240	77	1.04 x 10^{-4}	289 x 10^6	0.016	0.121
High TC-3	240	144	1.04 x 10^{-4}	201 x 10^6	0.019	0.121

[a]The current density in the superconductor/matrix material is 3 x 10^8 A m^{-2} (300 A mm^{-2}). See Table 5 for the electrical resistivity. Insulation thickness is 0.1 of the total thickness.

Nb-Ti is caused by the high specific heat of Nb-Ti,[38,49] which was ignored in the calculation, and by the presence of insulation and cryogen, which also tend to reduce longitudinal quench propagation velocity.

The calculated quench propagation velocity ratios given in Table 6 reflect the fact that matrix resistivity does have an effect on the quench velocity from turn to turn. (To first order, matrix resistivity has no effect on the quench velocity along the wire because α_L increases as ρ_1 decreases so that the product of ρ_1 and α_L is nearly constant.)

From Table 6 it is clear that a multifilamentary high-T_c superconductor will propagate quenches at a substantially lower rate than does Nb-Ti. A T_c = 93 K superconductor being operated at 77 K will have a normal-region volume growth rate that is between five and six orders of magnitude smaller than for Nb-Ti at 4.2 K. In some cases, this has serious implications for the design of high-current-density magnets and their quench-protection systems.

e. The Integral of Current Density Squared at the Hot Spot

The second factor that affects the usefulness of high-T_c superconductors in a high-current-density magnet coil is the integral of current density in the matrix squared with time. This is the same integral used to size electronic components used in pulsed service. This concept was developed for superconductors by Cherry and Gittleman,[48] and Mattock and James[52] applied the concept to quench protection of superconducting magnets.

The maximum allowable integral of current density in the superconductor/matrix squared can be calculated as follows:

$$F^* = \int_{T_O}^{T_D} \frac{C(T)}{\rho(T)}\, dT = \frac{r+1}{r} \int_0^{\infty} J_O(t)^2\, dt \quad , \tag{9}$$

where T is temperature, T_O is the operating temperature, T_D is the maximum allowable design hot-spot temperature (usually T_D = 300-400 K), $C_M(T)$ is the matrix-material volume specific heat (as a function of temperature), $\rho_M(T)$ is the matrix-material electrical resistivity (also as a function of temperature), r is the metal-to-superconductor ratio, $J_O(t)$ is the current density across the superconductor plus matrix cross section (which is a function of time), and t is time.

F* in Eq. (9) is a figure of merit that determines the time needed to dump the current from a superconductor before its hot-spot temperature reaches the design hot-spot temperature T_D. The temperature T_D may be determined by stress or by the temperature at which the insulation starts to degrade. Equation (9) is conservative in that the contribution of the insulation is not included in the specific heat.

Table 7 shows the value of F* for various superconductor operating temperatures and design hot-spot temperatures in matrices of RRR = 100 copper, RRR = 300 copper, and RRR = 1000 aluminum. The operating temperatures chosen are 4.2 K, 20.2 K, 77.3 K, and 144 K. From Table 7 one can see that the higher operating temperatures associated with the high-T_c superconductor will reduce the value of F* to the maximum allowable temperature T_D. Consequently, the high-T_c superconductors suffer a double penalty in a quench situation. Not only is the volume growth of the normal zone five to six orders of magnitude smaller, but also the margin of safety is smaller than for Nb-Ti or Nb_3Sn at liquid-helium temperature.

TABLE 7. THE VALUE OF F^* (THE INTEGRAL OF J^2 dt) AS A FUNCTION OF DESIGN MAXIMUM TEMPERATURE T_D, OPERATING TEMPERATURE T_O, AND THE MATRIX MATERIAL

T_O (K)	F^* (A^2 m^{-4} s) T_D = 300 K	F^* (A^2 m^{-4} s) T_D = 400 K
Copper Matrix RRR = 100		
4.2	14.9×10^{16}	16.6×10^{16}
20.2	14.5×10^{16}	16.2×10^{16}
77.3	8.7×10^{16}	10.0×10^{16}
144	4.0×10^{16}	5.7×10^{16}
Copper Matrix RRR = 300		
4.2	16.9×10^{16}	18.6×10^{16}
20.2	16.3×10^{16}	18.0×10^{16}
77.3	8.8×10^{16}	10.1×10^{16}
144	4.0×10^{16}	5.7×10^{16}
Aluminum Matrix RRR = 1000		
4.2	6.0×10^{16}	6.8×10^{16}
20.2	5.7×10^{16}	6.5×10^{16}
77.3	3.0×10^{16}	3.8×10^{16}
144	1.5×10^{16}	2.3×10^{16}

Quench-protection systems for high-T_c superconductors used in high-current-density magnets will have to be much more sophisticated than those used on today's high-current-density superconducting magnets. A completely passive fail-safe quench protection system,[53,54] such as used today with some types of Ni-Ti magnets, may not be possible. If one is to build high-stored-energy high-current-density magnets from high-T_c superconductor, the quench-protection system will have to be integrated with the magnet design. There are probably many instances when quench protection is not practical.

f. Energy Required to Initiate a Quench and the Minimum Propagation Zone

From the previous sections, one can see that quenches do not propagate rapidly in the high T_c superconductor. Also, the margin to burnout is smaller with the high T_c superconductor. Since the specific heat of the conductor is higher at the higher operating temperatures of the high T_c superconductors, the energy to initiate the quench should be much higher for these superconductors.

Two factors affect the energy needed to initiate a quench in a superconductor. They are; 1) the enthalpy change needed to drive the conductor normal, and 2) the minimum quench propagation zone volume. The product of the enthalpy change to quench and the minimum propagation zone volume yields the quench energy needed to initiate the quench in a magnet and keep it propagating.

The enthalpy change to quench has been defined differently by different authors. Some define this enthalpy change as the enthalpy change needed to completely turn the superconductor normal so that it carries no current in the superconducting state. (To do this one must increase the temperature from the operating temperature to the critical temperature T_c). Another definition of the quench enthalpy change is to define it as the enthalpy changes needed to just turn the superconductor normal. The second definition which is the conservative one will be used here.

The enthalpy change to initiate a quench ΔH_M^* is defined as follows

$$\Delta H_M^* = \int_{T_O}^{T^*} C_M(T)dT \qquad (10)$$

where $C_M(T)$ is the volume specific heat a function of temperature of the matrix material; ΔH_M^* is the quench initiation enthalpy change per unit volume in the matrix material; T_O is the operating temperature; and T^* is the quench initiation temperature T^* is defined using the following equation

$$T^* = T_O + 0.2\ (T_c - T_O) \qquad (10a)$$

where T_c is the zero field, zero current density critical temperature.

The definition of T^* given by equation 10a is typical for superconductor in a magnet which operates at 83 to 87 percent of critical current along the load line for conventional niobium-titanium and niobium-tin superconductor. (The operation of a superconducting magnet at 85 percent of its critical current along the load line is a reasonable engineering design goal. Most successful superconducting magnets operate at currents less than 85 percent of critical current along the load line.)

Table 8 shows calculations of the energy per unit volume which must be added to initiate a quench where ΔT is defined as 0.2 $(T_c - T_o)$. From Table 8 one can see that conventional superconductors have rather low quench initiation energies (around 1000 J m^{-3} for Nb-Ti and around 5000 J m^{-3} for Nb_3Sn).

Conventional superconducting magnets benefit from having the cryogens in direct contact with the windings. The equation for quench initiation energy when the cryogen is in the winding is given as follows

$$\Delta H_T^* = X_M \, \Delta H_M^* + (1 - X_M) \, C_f (T^* - T_o) \tag{11}$$

where T_o, T^* and ΔH_M^* are defined as they were for Equation 10; X_M is the volume fraction of the metal; and C_f is the volume specific heat for the liquid cryogen. (For helium $C_f \approx 5.6 \times 10^5$ J m^{-3} K^{-1}, for hydrogen $C_f \approx 7.0 \times 10^5$ J m^{-3} K^{-1}, and for nitrogen $C_f \approx 16.5 \times 10^5$ K^{-1}).

From Table 8, one can see that the addition of 10 percent liquid helium to the superconductor will dramatically increase the quench initiation energy for per unit volume superconductors operating in liquid helium. (For Nb-Ti the increase is about a factor of 50; for Nb_3Sn the increase is closer to a factor of 35.) The addition of 10 percent liquid hydrogen to a high T_c superconductor will increase the quench initiation energy per unit volume by a factor of 1.7 to 3.3 depending on the superconductor T_c and the matrix material. When one operates the high T_c conductors at nitrogen temperature, there is almost nothing gained from adding the cryogen to the conductor package. Table 8 shows that, in general, increasing T_c and increasing the operating temperature T_o both tend to increase the energy per unit volume

TABLE 8. QUENCH INITIATION ENTHALPY AS A FUNCTION T_c, OPERATING TEMPERATURE AND MATRIX MATERIAL

Superconductor	T_c (K)	Operating Temp (K)	ΔT (K)	Quench Initiation Enthalpy ($J\ m^{-3}$) Copper matrix	Aluminium matrix
Superconductor Alone					
Niobium titanium	9.4	4.2	1.04	1.26×10^3	0.97×10^3
Niobium tin	18	4.2	2.76	4.37×10^3	4.78×10^3
High TC-1	40	20	4.0	3.20×10^5	1.29×10^5
High TC-2	93	20	14.6	1.32×10^6	0.99×10^6
High TC-2	93	77	3.2	5.17×10^6	2.81×10^6
High TC-3	240	77	32.6	7.00×10^7	3.96×10^7
High TC-3	240	144	19.2	5.30×10^7	3.38×10^7
Superconductor Plus the Cryogen					
90% Nb-Ti, 10% He	9.4	4.2	1.04	5.73×10^4	5.70×10^4
90% Nb_3Sn, 10% He	18	4.2	2.76	1.53×10^5	1.53×10^5
90% HighTC-1, 10%H_2	40	20	4.0	5.96×10^5	4.24×10^5
90% HighTC-2, 10%H_2	93	20	14.6	2.31×10^6	2.02×10^6
90% HighTC-2, 10%N_2	93	77	3.2	5.18×10^6	3.06×10^6

needed to initiate a quench. Table 8 suggests that increased operating temperature will result increased resistance to quench initiation. One should be careful with this conclusion until one has looked at the volume of a minimum quench propagation zone.

The minimum propagation zone length MPZ length is defined as the minimum length of superconductor which has to be driven normal in order for the quench to grow. If the length of superconductor driven normal is less than the minimum propagation length the resistive heating will be drawn away by conduction and the superconductor will return to the superconducting state.[55,56] The equation for the minimum propagation length in the superconductor alone l_{sc} along the conductor suggested by Wilson[57] takes the following form;

$$l_{sc} = \left[\frac{2\, k_{sc}\, (T^* - T_o)}{J_c^2\, \rho_{sc}}\right]^{1/2} \qquad (12)$$

where k_{sc} is the thermal conductivity of the superconductor; ρ_{sc} the normal state resistivity of the superconductor; T^* is the critical temperature defined by Equation 10a; T_o is the operating temperature and J_c is the critical current density for the superconductor.

A typical normal state resistivity for niobium titanium is about 6.5×10^{-7} Ωm and the thermal conductivity of niobium titanium is about 0.1 $Wm^{-1}\,K^{-1}$. Using these values and and $T^*-T_o = 1.04$ K and a J_c of about 2×10^9 A m^{-2}, one get minimum propagation lengths of about 2.8×10^{-7} m. If one applies Equation 12 to Y-Ba-Cu-O superconductor with $\rho \approx 2 \times 10^{-8}$ Ωm,[11] $k_{sc} \approx 1.0$ W m^{-1},[44] $J_c \approx 10^{10} Am^{-2}$, and $T^*-T_o = 14.6$ K, one gets a minimum propagation length of about

1.2×10^{-7} m. The energy required to initiate a quench in Y-Ba-Cu-O alone is greater than that of Nb-Ti. It is clear that Y-Ba-Cu-O like niobium titanium must be put into a good conducting metal matrix such as copper or aluminum.

If one puts the niobium titanium superconductor into copper (which has $k_M = 650$ W m^{-1} K^{-1} and $\rho_M = 1.6 \times 10^{-10}$ Ωm), the minimum propagation length goes up to the order of 10^{-2} m when the overall matrix current density J_o is 3×10^{8} A m^{-2}. An approximate equation for the minimum propagation length for a superconductor in a metal matrix takes the following form;

$$l_M \approx \frac{r}{r+1}\left[\frac{2\, k_M\, (T^* - T_o)}{J_o^{\,2}\, \rho_M}\right]^{1/2} \qquad (13)$$

where r is the matrix to superconductor ratio; k_M is the matrix thermal conductivity, ρ_M is the matrix resistivity; and T^* and T_o are defined as before.

Table 9 shows the parameters needed to calculate the minimum propagation length along a superconductor in a RRR = 100 copper matrix and an RRR = 1000 aluminum matrix. From Table 9, one can see that the MPZ length increases with temperature up to temperatures of 20 to 30 K. Above 30 K the MPZ length goes down for a given value of $T^* - T_o$ because the matrix resistivity goes up and the matrix thermal conductivity goes down. The RRR = 1000 aluminum matrix has a longer MPZ length than does the RRR = 100 copper matrix at temperature below about 50 K. It is interesting to note that the MPZ lengths shorter for the high T_c superconductors at nitrogen temperature than the same conductors at liquid hydrogen temperatures. From a quench initiation standpoint, a high T_c superconductor at a liquid nitrogen temperature is better in a copper matrix than in an aluminum matrix.

TABLE 9. MINIMUM PROPAGATION LENGTH FOR VARIOUS SUPERCONDUCTORS IN A RRR = 100 COPPER AND RRR = 1000 ALUMINUM MATRIX

	T_c (K)	Operating temp (K)	ΔT (K)	k_M ($W\ m^{-}K^{-1}$)	ρ_M (Ωm)	MPZ length (m)*
RRR = 100 Copper						
Niobium-titanium	9.4	4.2	1.04	850	1.57×10^{-10}	0.0098
Niobium-tin	18	4.2	2.76	800	1.57×10^{-10}	0.0177
High TC-1	40	20	4.0	2200	1.75×10^{-10}	0.0334
High TC-2	93	20	14.6	1400	2.00×10^{-10}	0.0477
High TC-2	93	77	3.2	570	2.20×10^{-9}	0.0043
High TC-3	240	77	32.6	400	3.00×10^{-9}	0.0098
High TC-3	240	144	19.2	420	7.20×10^{-9}	0.0050
RRR = 1000 Pure Aluminum						
Niobium-titanium	9.4	4.2	1.04	4300	2.43×10^{-11}	0.0640
Niobium-tin	18	4.2	2.76	5000	2.43×10^{-11}	0.1123
High TC-1	40	20	4.0	6500	3.60×10^{-11}	0.1267
High TC-2	93	20	14.6	3200	5.20×10^{-11}	0.1427
High TC-2	93	77	3.2	410	3.00×10^{-9}	0.0031
High TC-3	240	77	32.6	250	4.50×10^{-9}	0.0063
High TC-3	240	144	19.2	260	1.20×10^{-8}	0.0030

* $\frac{r}{r+1} \approx 1$ and $J_o \approx 3 \times 10^8 A\ m^{-2}$

The minimum propagation zone (MPZ) length which is given by Equation 13 applies only in the direction of current flow in the conductor. The minimum propagation zone is an reality three dimensional the minimum propagation length in a direction perpendicular to the conductor direction takes the following form when heat flow is blocked along the conductor;

$$l_{M\perp} \simeq \frac{r}{r+1} \left[\frac{2\, k_i}{x_i} \; \frac{(T^* - T_o)}{J_o^2\, \rho_M} \right]^{1/2} \tag{14}$$

where r, T^*, T_o, J_o, and ρ_m are previously defined. k_i is the thermal conductivity of the insulation between turns and x_i is the fraction of the conductor thickness which is insulation. Equation 14 can be restated using Equation 8. This restatement takes the following form;

$$l_{M\perp} \simeq \nu \, l_M \tag{15}$$

where ν is the transverse quench velocity ratio defined by Equation 8.

The minimum propagation zone volume can approximately be stated using the following relationship

$$\underset{\text{volume}}{\text{MPZ}} \simeq 8\, \nu^2\, l_M^3 \tag{16}$$

where l_M is the minimum propagation length along the conductor defined by Equation 13. The quench initiation energy for the superconductor can be stated as follows

$$\begin{matrix}\text{quench}\\ \text{initiation}\\ \text{energy}\end{matrix} \approx \Delta H_M^* \begin{pmatrix}\text{MPZ}\\ \text{volume}\\ \end{pmatrix} \quad (17)$$

where ΔH_M^* is defined by Equations 10 or 11 and the MPZ volume is defined by Equation 16. The quench initiation energy calculated by Equation 17 should be regarded as a figure of merit for comparing various superconductor matrix combinations.

Table 10 shows the estimated MPZ volume and quench initiation energy for superconductor with RRR = 100 copper and RRR = 1000 aluminum stabilizers with and without cryogen in the windings. Table 10 shows that the high T_c superconductors will require much more energy to initiate a quench than does conventional niobium titanium or niobium tin superconductors. The high T_c superconductor will have substantially higher quench initiation energies when they are operated with liquid hydrogen as coolant. At temperatures below 40 to 50 K, the use of a RRR = 1000 aluminum stabilizer will result in higher quench initiation energy than the use of a RRR = 100 copper stabilizer. Finally, the high T_c superconductors require the use of a low electrical resistivity stabilizer just as much as the conventional superconductors do.

While the high T_c superconductors will be substantially more stable than conventional superconductors when they are in a conducting matrix. There is a question whether they are stable enough to be operated at high current densities without quench protection. Since the high T_c superconductors are more stable, they propagate quenches poorly (see the previous subsection d). In addition, higher operating temperatures will result in loss integral of current density squared with time to burnout. (See the previous subsection e). Therefore it can be argued that really reliable high T_c superconducting

TABLE 10. CALCULATED MINIMUM PROPAGATION VOLUME AND QUENCH INITIATION ENERGY FOR VARIOUS SUPERCONDUCTORS AT VARIOUS OPERATING TEMPERATURES AT A CURRENT DENSITY $J_O = 3\times10^8$ A m^{-2}

Superconductor	T_C (K)	T_O (K)	RRR = 100 Copper: MPZ** volume (m^3)	RRR = 100 Copper: Quench** energy (J)	RRR = 1000 Aluminum: MPZ** volume (m^3)	RRR = 1000 Aluminum: Quench** energy (J)
Superconductor Alone						
Niobium titanium	9.4	4.2	4.70×10^{-9}	5.92×10^{-6}	2.10×10^{-7}	2.04×10^{-4}
Niobium tin	18.0	4.2	1.95×10^{-8}	8.52×10^{-5}	1.63×10^{-6}	7.79×10^{-3}
High TC-1	40	20	3.65×10^{-7}	0.1168	1.10×10^{-5}	1.419
High TC-2	93	20	4.37×10^{-6}	5.768	1.68×10^{-4}	166.3
High TC-2	93	77	3.21×10^{-9}	0.0166	1.72×10^{-9}	4.83×10^{-3}
High TC-3	240	77	6.65×10^{-8}	4.655	2.93×10^{-8}	1.160
High TC-3	240	144	8.84×10^{-9}	0.4685	3.16×10^{-9}	0.1068
Superconductor Plus Cryogen*						
90% Nb-Ti, 10% He	9.4	4.2	4.70×10^{-9}	2.69×10^{-4}	2.10×10^{-7}	0.0120
90% Nb_3Sn, 10% He	18.0	4.2	1.95×10^{-8}	2.98×10^{-3}	1.63×10^{-6}	0.2494
90% HighTC-1, 10%H_2	40	20	3.65×10^{-7}	0.2175	1.10×10^{-5}	4.664
90% HighTC-1, 10%H_2	93	20	4.37×10^{-6}	10.095	1.68×10^{-4}	339.4
90% HighTC-2, 10%N_2	93	77	3.21×10^{-9}	0.0166	1.72×10^{-9}	5.26×10^{-3}

*The matrix plus superconductor volume is 90% of the total volume; the cryogen occupies 10% of the total volume.

**Based on $T^* \approx 0.2\ (T_C - T_O)$

magnets will need to be cryostable. The cryostability of high T_c superconductors in a metal matrix is delt with in the next subsection.

g. Cryostability of High-T_c Superconductors in a Metal Matrix

The use of high-T_c superconductors in high-current-density magnets is characterized by substantially reduced quench propagation rates and reduced values of F*. As a result, cryostability will be extremely important. This subsection compares the characteristics of cryostability for superconductors that operate in the five boiling working fluids--helium, hydrogen, neon, nitrogen, and R-14.

There are many definitions of cryostability ranging from transient cryostability[36,41] to fully cryostable[58] with superconductor filaments that have a diameter less than the adiabatic or the dynamic stability critical diameter, whichever is less. The definition of cryostability used in this subsection is a conservative one. The conductor assumed for these studies has the following characteristics:

1) The filaments are small enough to be both adiabatically and dynamically stable.
2) Heat transfer to the cryogenic fluid is by nucleate boiling at the conductor surface. There is no conduction along the conductor.
3) The assumed nucleate boiling heat-transfer rate is the usable design nucleate boiling heat flux in Table 1 (about one-third of the maximum nucleate boiling heat flux). This heat flux is suitable for use with narrow channels.

4) The difference between the operating temperature and the critical temperature of the superconductor when it is at design magnetic field and design current is at least 1.5 times the difference between the nucleate boiling temperature and the bath temperature.[59]

5) For the case calculated here, the superconductor/matrix area is set arbitrarily to 10^{-4} m^2 (1 cm^2). The boiling heat-transfer area is 10^{-2} m^2 per meter of superconductor length (1 cm^2 per centimeter of conductor length). Heat transfer to the bath can only occur across the boiling heat-transfer area.

6) Full Stekly stability is assumed such that when the superconductor is completely normal, the heat generated in the matrix by the current is carried across the boiling heat-transfer surface to the cryogen bath.

The above criteria are conservative and will serve very well to calculate a figure of merit for estimating cryostability of superconductors in various boiling cryogenic fluids.

The cryostability criterion defined by Stekly[58] and Whetstone[60] takes the following form:

$$\alpha = \frac{I^2 R}{A_T \phi_B} \quad , \tag{18}$$

where I is the current in the conductor, R is the resistance of the conductor per unit length, A_T is the heat-transfer area of the conductor per unit length, and ϕ_B is usable design nucleate boiling heat flux (about one-third of the maximum nucleate boiling heat flux). The resistance per unit length is defined as follows:

$$R = \frac{r + 1}{r} \frac{\rho_M}{A_C} \quad , \tag{18a}$$

where r is the ratio of normal metal to superconductor, ρ_M is the matrix-material resistivity, and A_c is the cross-sectional area of the superconductor/matrix. For our study we will assume that r is large so that (r + 1)/r approaches 1.

Using the Stekly stability criterion, the conductor is stable when α is less than, or equal to, 1. When α is greater than 1, the conductor is unstable. The limit of stability occurs when heat generation (the numerator of the right side of Eq. (18)) equals heat transfer (the denominator of the right side of Eq. (18)). The cryostable current density in the superconductor plus matrix J_S can be determined by the following relationship:

$$J_S = \left(\frac{r}{r + 1} \frac{A_T}{A_C} \frac{\rho_B}{\rho_M} \right)^{1/2} \quad . \tag{19}$$

The stable current density J_S is in fact the figure of merit that one is looking for in comparing cryostability in various working fluids at various temperatures.

Table 11 presents J_S as a function of working fluid and matrix material. Three matrix materials are assumed: RRR = 100 copper, RRR = 300 copper, and RRR = 1000 aluminum. The resistivity ρ_M given in Table 11 is based on conditions with no field. (Magnetoresistance is less important at high temperatures than at low temperatures.) Table 11 is based on the assumption that the heat-transfer area per unit length $A_T = 10^{-2}$ m^2 per meter and that the conductor cross-sectional area $A_c = 10^{-4}$ m^2.

TABLE 11. STABLE CONDUCTOR CURRENT DENSITY AS A FUNCTION OF MATRIX MATERIAL AND CRYOGENIC WORKING FLUID.

Fluid	Temperature (K)	ϕ_B (W m^{-2})	ρ_M[a] (Ω m)	J_S[b] (A m^{-2})
Copper Matrix RRR = 100				
He	4.2	2 700	1.57×10^{-10}	4.15×10^{7}
H_2	20.3	35 000	1.65×10^{-10}	1.46×10^{8}
Ne	27.1	50 000	2.00×10^{-10}	1.58×10^{8}
N_2	77.4	60 000	2.00×10^{-9}	5.48×10^{7}
R-14	144.2	70 000	7.00×10^{-9}	3.16×10^{7}
Copper Matrix RRR = 300				
He	4.2	2 700	5.18×10^{-11}	7.22×10^{7}
H_2	20.3	35 000	5.98×10^{-11}	2.42×10^{8}
Ne	27.1	50 000	9.00×10^{-11}	2.36×10^{8}
N_2	77.4	60 000	1.90×10^{-9}	5.62×10^{7}
R-14	144.2	70 000	7.00×10^{-9}	3.16×10^{7}
Aluminum Matrix RRR = 1000				
He	4.2	2 700	2.43×10^{-11}	1.05×10^{8}
H_2	20.3	35 000	3.05×10^{-11}	3.39×10^{8}
Ne	27.1	50 000	5.00×10^{-11}	3.16×10^{8}
N_2	77.4	60 000	2.70×10^{-9}	4.71×10^{7}
R-14	144.2	70 000	1.10×10^{-8}	2.52×10^{7}

[a]Resistivity at zero induction, magnetoresistance is ignored in the calculations.

[b]$A_T/A_C = 100$, and $r \gg 1$.

Thus the factor A_T/A_C = 100. The usable design boiling heat flux Φ_B in Table 11 comes from Table 1; ρ_M is the matrix resistivity as a function of temperature. The ratio r of normal metal to superconductor is large, so that $r/(r + 1) \approx 1$.

From Table 11 one can see that the stable current density for the fully stabilized high-T_c superconductor is about the same in nitrogen or helium. Significant improvements can be made in cryostability (as can be seen from the J_s calculation) if the high-T_c superconductor is operated in liquid hydrogen or neon. The RRR = 1000 aluminum makes an excellent stabilizer. However, RRR = 1000 aluminum has very poor mechanical properties,[47] so there is no advantage in the use of very pure aluminum in liquid nitrogen or R-14. The use of R-14 is not at all justified from a cryogenic stability standpoint.

h. Magnetization and AC Loss

To first order, the magnetization of a superconductor is a function of its critical current density and the filament diameter.[37] For a given product of filament diameter times critical current density, the magnetization in the conductor should be the same per unit superconductor volume. The ac loss should also be the same.

With conventional superconductors one can measure the true critical current density using transport current methods (except at low fields). The critical current density measured this way can be applied to magnetization calculations, provided the conventional superconductor is of good quality. The high-T_c superconductors may turn out to be quite different. The measured transport current density is an order of magnitude (or more) lower than the current density measured by magnetization.[17] This is probably related to the granular structure of the high-T_c oxide superconductors.[8,11]

Magnets with quantities of high-T_c superconductor adequate to carry the required transport current may have much larger magnetization (and the field errors associated with magnetization) and ac loss than similar magnets built with conventional superconductors. Filament size and the magnetization associated with it will still be very important in accelerator magnets. There is a limit, however, to how much one can reduce the magnetization by reducing the filament size. One eventually runs into proximity coupling and the effect of H_{c1}.[61,62] Since H_{c1} for high-T_c oxide superconductors is probably larger than for Nb-Ti, the lower limit of magnetization-induced field errors can be expected to be larger than for a similar magnet built with Nb-Ti.

4. What Are the Potential Impacts of High-T_c Oxide Superconductors on Magnets for Accelerators, the ASTROMAG Experiment, and Magnetic Resonance Imaging?

This section deals with the use of high-T_c superconductors in the generation of a magnetic field with a superconducting magnet. Three types of superconducting magnets are considered: high-current-density small-bore (≈40- to 60-mm coil diameter) accelerator dipoles and quadrupoles, a large two-coil solenoid or toroid (about 2 m in diameter) for astrophysics detectors in space (for up to 2 years), and medium-sized (about 1-m warm-bore diameter) solenoids for magnetic-resonance imaging.

a. Dipoles and Quadrupoles for Accelerators

Accelerator magnets represent one class of superconducting magnets for which much research and development money has been spent. The superconducting super collider (SSC) magnets represent at least one form of modern accelerator magnet design.[63] The SSC dipole magnet will be 17 m long and will have a coil inside diameter of 40 mm. This dipole, which will generate a 6.6-tesla central induction, is characterized by high-current-density windings (the design current density for the superconductor/matrix is 5.5 x 10^8 A m^{-2} for the inner coil and 6.5 x 10^8 A m^{-2} for the outer coil). The high-current-density coils with their support collars are put into a circular iron shield with a 112-mm bore.

Because the SSC is a storage ring, the required field uniformity at a radius of 10 mm is about 1 part in 10 000. The magnetic fields produced by superconductor magnetization are a serious problem at the injection induction of 0.33 tesla.[62,64] Even with a Nb-Ti superconductor, the performance of the prototype SSC dipoles has been limited by stress and strain in the coil package. The propagation of a quench in a magnet coil is an important consideration for accelerators such as the SSC.

The factors that favor the use of high-T_c superconductor in accelerators are savings in the capital cost of the refrigeration plant and in the cost of electric power needed to operate the refrigeration plant over the life of the machine.[65]

The high-current-density requirements of the SSC dipoles and other accelerator dipoles are dictated by the amount of superconductor needed to produce a particular field in a particular volume. A reduction of the current density by a factor of two increases the volume and mass of the superconductor by more than a factor of two. This effect is worse when the magnet aperture is small. An increase in the magnetic field will require the superconductor to be operated at an even higher current density than required by most present accelerator magnet designs. As the field increases, the stresses increase as the square of the field. Even if the high-T_c superconductor has very high critical fields, the central field in an accelerator dipole is unlikely to increase much above 10 to 12 tesla.[46]

Quench protection becomes a serious problem in high-current-density dipoles or quadrupoles using a high-T_c superconductor since cryostability and the use of pure aluminum RRR = 1000 are precluded in accelerator magnets such as the SSC magnets because the current density achievable in the matrix is not high enough. (Very pure aluminum also has very poor mechanical properties.[47])

If high-T_c superconducting dipoles and quadrupoles can be built, it is likely that they can only be built using a wind-and-react technique; the brittleness of the high-T_c superconductor will be the limiting factor. An aluminum matrix probably cannot be used in a wind-and-react dipole because the reaction temperature is above the melting temperature of the aluminum. Wind-and-react dipoles are difficult to build even with conventional superconductors such as multifilamentary Nb_3Sn. Therefore, it is reasonable to expect high-T_c superconductors to be even more difficult to fabricate.

The use of high-T_c superconductor can potentially save refrigeration, but this savings is not as large as one might think. For example, most of the heat leak into the SSC magnet cryostats is already intercepted at higher temperatures, where the ratio of input power to refrigeration is at least an order of magnitude lower. The heat leak per unit length can be expected to go up because the cryostat vacuum is unlikely to be as good as it is in a liquid-helium cryostat.

In addition, the use of high-T_c superconductor will cause major accelerator vacuum problems for colliding-beam machines such as the SSC because liquid helium provides cryopumping over the full length of the magnet for the accelerator vacuum. Replacing the cold-bore vacuum system with a conventional vacuum system is difficult (if it can be done at all), and it may cost more than the savings in refrigeration capital cost and electric-power cost.[67]

b. Superconducting Magnet Coils for the ASTROMAG Experiment

The ASTROMAG experiment would have a superconducting magnet that produces the magnetic field needed to analyze charged particles from deep space.[68] Since ASTROMAG is a space experiment, reduction of the experiment mass is critical. The requirement of minimum mass can be met using high-current-density superconducting coils since the mass of the coils is directly proportional to their stored energy[69] (for quench protection and stress reasons). The mass of the cryogen storage vessel is also proportional to the stored energy, and, to first order, the masses of the stored cryogen and the magnet vacuum vessel are also directly proportional to stored energy.

The ASTROMAG superconducting magnet with a conventional Nb-Ti superconducting coil would be cooled with superfluid helium (helium II) at 1.8 K. The advantages of helium II over helium I (helium above the lamda point temperature of 2.17 K) are as follows. 1) Helium II can be circulated through the coils using a thermal mechanical pump, which has no moving parts.[70,71] A magnet cooled with helium I would require either a continuously operating mechanical pump, or the coils must be in the helium I bath. 2) Helium II can be separated from helium gas through a porous plug. This is important because phase separation is a problem with any cryogenic fluid being used in space. If liquid is fed into the shields instead of gas, the mass consumption of cryogen goes up. 3) Helium II permits one to operate a Nb-Ti magnet with a large critical-current margin. This makes the magnet less likely to quench.

Table 1 compares the properties of various cryogens. The most important figure of merit is the total refrigeration available in the cryogen per unit mass. The fluid with the largest available refrigeration is liquid hydrogen, and hydrogen is an ideal cryogen for cooling space-based cryostats (a hydrogen-cooled ASTROMAG magnet might require 240 kg of hydrogen in place of the 700 kg of helium proposed for a two-year lifetime in space). Unfortunately, under current NASA safety regulations, liquid hydrogen cannot be used on the shuttle or the space station. Helium has much more available refrigeration than neon, nitrogen, or R-14. The mass of these gases needed to cool the ASTROMAG magnet for two years is neon, 2900 kg; nitrogen, 2500 kg; and R-14, 3800 kg. (These estimates do not include the extra heat leak associated with the increased area of the cold-mass supports needed to carry the extra mass of cryogen.)

A superconductor with a combined aluminum and copper matrix material could be used for the ASTROMAG magnet coils if they operate in either boiling hydrogen or neon. The mass of these coils would be dictated by considerations of stored energy per unit mass. Unfortunately hydrogen is not an allowable working fluid for space, and neon has too little available refrigeration per unit mass. Reliable liquid-nitrogen refrigerators, expected to be available for use in space in the next few years,[72] would eliminate the need for

2500 kg of liquid nitrogen. Magnets of high-T_c superconductor will probably have to operate as cryostable conductors in boiling nitrogen. The nucleate boiling heat-transfer coefficient to boiling nitrogen in space is probably lower than it would be under "normal" gravity. (The difference in density between gas and liquid ensures good flow of nitrogen at the boiling surface.) Even under the best of circumstances the mass of a nitrogen-cooled aluminum-matrix conductor would be more than for a coil made with conventional Nb-Ti superconductor (2800 kg versus 1500 kg). The coil mass in a cryostable coil scales as total current instead of total current squared.

The high-T_c superconductor might be potentially attractive for use in space provided one can operate the magnet with liquid hydrogen as the coolant or a reliable liquid-neon refrigerator can be built. The larger the superconducting magnet and the larger its stored energy, the larger the potential attractiveness of the high-T_c superconductor--provided liquid hydrogen is the coolant.

c. Solenoids for Magnet Resonance Imaging

Magnets for magnetic resonance imaging (MRI)[73] for the human body have a warm bore about 1 m in diameter. The fields generated by such magnets must be accurate to better than 2 parts in 10^4, before correction. After correction, the field must be accurate to between 1 part in 10^5 and 1 part in 10^7 (depending on the type of imaging done and whether spectroscopy is done). The useful field region of such a magnet is nearly spherical, with a radius between 100 and 150 mm. In the 0.5-tesla and 1.5-tesla magnets being produced today, the current density in the coils is not important. As the central field of an imaging magnet rises, however, current density may become more important, but a requirement for cryostability probably doesn't have a large effect on the magnet.

The brittleness of the superconductor is a factor. Whether a prereacted superconductor could be used is not known. A bend radius of 0.5 m is near a lower limit for multifilament Nb_3Sn, so one would expect the high-T_c conductor to be difficult to wind in the prereacted state.

The elimination of purchased liquid helium would be desirable. Replacing the liquid helium with liquid hydrogen would not be desirable in a hospital setting, however, because of hydrogen's flammability. Liquid nitrogen is heavy, and large masses would be needed, compared with liquid helium. Because of liquid nitrogen's low cost (about $0.25 per kilogram in large quantities), its use is desirable. The use of a liquid-nitrogen refrigerator would also be very attractive.

Three other potential negative factors, beside the present unavailability of a usable high-T_c superconductor, in any form, are the following. 1) It will probably be difficult to make truly persistent joints in a high-T_c superconductor.[74] (One might argue that a liquid-nitrogen-cooled MRI magnet does not have to operate in the persistent mode, but heat leak is not the only factor that favors the operation of MRI magnets in the persistent mode. The stability of the field also favors persistent operation.) 2) The expected increase in superconductor magnetization could have a very detrimental effect on the quality of the magnetic field within the imaging volume.[75] 3) A persistent switch may be more difficult to build with the high-T_c materials. A greater mass of the material would be required, and the total heat needed to open the switch would be about four orders of magnitude higher than for a conventional persistent switch made from Nb-Ti.

5. Concluding Comments

This report presents a realistic evaluation of the prospects for the use of high-T_c superconductors for the generation of magnetic fields. It seems clear that to delay scientific projects using superconducting magnets until the new superconductors are available is not warranted, based on the technical knowledge available today. Furthermore, many of the projected uses for high-T_c superconductor in magnets (e.g., levitated trains, superconducting motors and generators) reported in the popular press are not likely to materialize unless a ductile form of the material is found that is so stable that one never has to worry about quenches.

If the high-T_c superconductor is not attractive for use in the three types of magnets described in this report, what, in the author's view, are the potential uses for the high-T_c oxide superconductor?

1) Very large cryostable superconducting magnets that must run with low current densities in the matrix may become possible if a usable form of the superconductor can be found.
2) The high-T_c superconductors could be useful in the current leads for conventional superconducting magnets between liquid helium and room temperature. Currents leads using this technology would require less refrigeration.
3) Superconducting electronic applications using thin films of high-T_c superconductor might be possible. The use of squids is often dictated by noise considerations. A nitrogen temperature squid will be noisier than a liquid helium temperature squid. Some people might argue that high T_c superconducting electronics will be useful but others might argue against this view. It may be too early to tell.

4) The high-T_c superconductor might be usable for high-voltage dc superconducting transmission lines operating at either liquid-hydrogen or liquid-nitrogen temperatures. The use of high T_c superconductor in A.C transmission lines appears to be less likely at this time.

5) The high-T_c superconductors may well be used in specialized magnets that can operate within the limitations of the material. For example, small low-current-density, low-stored-energy magnets may become possible. For small experiments the use of liquid nitrogen as a coolent is very desirable.

6) There may be possible uses for high-T_c superconductors that have not been conceived. If the research on high T_c superconductors, is not done, these uses for the material are not likely to appear.

High T_c superconductors have brought much excitement into the field of superconductivity and solid state physics. The work has only begun; it is not realistic to believe that high T_c superconductors will have a real commercial use for many years. There is a great deal of fundamental research that must be done in order to understand the basic properties of the new materials. From this research, the first practical applications for high-T_c superconductor will come.

Some Additional Notes

This report was originally written in September of 1987. Since that time, there have been reports of hints of high T_c superconductivity at temperatures as high as 500 K. It should be emphasized that this is not a zero resistivity temperature. There is a new five component copper oxide material which has consistent T_c of around 120 K.[76]

The critical current density of various samples has gone up.[77] Bulk melted polycrystalline samples have achieved critical current densities as high as 8 x 10^7 A m^{-2} at zero field and 77 K. At 1 Tesla J_c drops to about 10^7 A m^{-2}. Oriented superconductors are beginning to show some promise. These conductors have J_c values approaching single crystal values. 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.[78] The increase in J_c in the last 6 months has been quite promising. The fabrication of the superconductor into usable form for magnets still has not been achieved.

Acknowledgments

The author talked to many people during the preparation of this report and would like to acknowledge information gained from the following: C. E. Taylor and R. M. Scanlan of the Lawrence Berkeley Laboratory, D. C. Larbalestier of the University of Wisconsin, J. W. Ekin of the National Bureau of Standards in Boulder, Colorado, A. K. Ghosh of Brookhaven National Laboratory, E. W. Collings of Battelle Columbus Laboratory, and T. Geballe of Stanford University. There are numerous other people who contributed to the thought processes contained in this report as well. The author thanks the people in and out of the Lawrence Berkeley Laboratory who have reviewed this work and have offered suggestions.

This work was supported by the Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

1. J. G. Bednorz and K. A. Miller, Z Phys B 64, p. 189, 1986.

2. Theodore Geballe, from a talk given at the Lawrence Berkeley Laboratory, May 1987.

3. J. F. Scholey et al., Phys Rev Lett 12, p. 474, 1964.

4. A. L. Robinson, "Antiferromagnetism Observed in La_2CuO_4," Science 235, p. 778, 1987.

5. M. K. Wu et al., "Superconductivity at 93 K in a New Mixed Phase Y-Ba-Cu-O Compound System at Ambient Pressure," Phys Rev Lett 58, p. 908, 1987.

6. From a short discussion with Chinese researchers at the University of Wisconsin, June 19, 1987.

7. M. Kumada "Observation of Zero Resistivity up to 313 K in Y-Ba-Cu-F-O," *presented* at the *10th International Conference on Magnet Technology*, Boston MA, 21-24 September 1987.

8. X. Cai et al., "Experimental Evidence for Granular Superconductivity in Y-Ba-Cu-O at 100 to 160 K," Phys Rev Lett, June 29, 1987.

9. A. L. Robinson, "An Oxygen Key to the New Superconductor," Science 236, p. 1063, 1987.

10. M. S. Lubell, "Empirical Scaling Formulas for Critical Current and Critical Field for Commercial Nb-Ti," IEEE Transactions on Magnetics MAG-19, No. 3, p. 754, 1983.

11. D. C. Larbalestier, et al., "Experiments Concerning the Connective Nature of Superconductivity in $YBa_2Cu_3O_7$," University of Wisconsin SMRG-47, submitted to the Journal of Applied Physics, April 1987.

12. K. Noto et al., "31.1 Tesla Hybride Magnet and Superconducting Materials Research held at HFLSM, Tohoku University," presented at CEC/ICMC87 St. Charles IL, 15-18 June 1987; to be published in Advances in Cryogenic Engineering 34, Plenum Press, New York, 1988.

13. D. O. Welch et al., "On the Anisotropy of H_{c2} and the Breadth of Resistive Transition of Polycrystalline $YBa_2Cu_3O_{7-x}$ in a Magnetic Field," Phys Rev B, August 1, 1987.

14. R. B. Goldfarb et al., "Evidence for Two Superconducting Components in Oxygen-Annealed Single Phase Y-Ba-Cu-O," Cryogenics 27, p. 475, September 1987.

15. A. L. Robinson, "IBM Superconductor Leaps Current Hurdle," Science 236, p. 1189, June 5, 1987.

16. A. K. Ghosh et al., "Magnetization Studies of High T_c $YBa_2Cu_3O_7$," to be published in Advances in Cryogenic Engineering 33, Plenum Press, New York, 1987.

17. J. R. Thompson et al., "Magnetization Studies of the High T_c Compound $Y_1Ba_2Cu_3O_z$," to be published in Advances in Cryogenic Engineering 34, Plenum Press, New York, 1988; Proceedings of the ICMC Conference at St. Charles, IL, June 1987.

18. J. W. Ekin et al., "Evidence for Anisotropy Limitation on Transport Critical-Current in Polycrystalline $Y_1Ba_2Cu_3O_x$," submitted to the J Appl Phys, June 26, 1987.

19. K. Kamata et al., "High Field Superconducting Critical Values of Titanium Bronze Multifilamentary Nb_3Sn Conductors," IEEE Transactions on Magnetics MAG-23, No. 2, p. 637, March 1987.

20. D. W. Capone et al., "High Field Properties of $SnMo_6S_8$ and $PbMo_6S_8$ Ribbon Prepared Using the Vapor Transport Technique," IEEE Transactions on Magnetics MAG-23, No. 2, p. 1752, March 1987.

21. J. W. Ekin, "Strain Dependence of Critical Current and Critical Field in Multifilamentary Nb_3Sn Composites," IEEE Transactions on Magnetics MAG-15, No. 1, p. 197, 1979.

22. K. Togano et al., "High Temperature Superconductivity in the Ba-Y-Cu Oxide System," to be published in Advances in Cryogenic Engineering 34, Plenum Press, New York, 1988.

23. D. C. Labalestier, private communication on the state of experiments to produce high-T_c multifilamentary oxide superconductor, June 19, 1987.

24. V. J. Johnson, "Properties of Materials at Low Temperatures (Phase 1)," Part 1, The WADD Compendium, Pergamon Press, New York, 1961.

25. K. Raunjevie, Handbook of Thermodynamic Tables and Charts, McGraw Hill, New York, 1975.

26. Handbook of Chemistry and Physics, 58th Edition, CRC Press, Cleveland, OH, 1978.

27. D. N. Lyon, "Boiling Heat Transfer and Peak Nucleate Boiling Heat Fluxes in Saturated Liquid Helium Between the Lamda and Critical Temperature," Adv Cryo Eng 10, No. 2, p. 372, 1964.

28. E. G. Birentari and R. V. Smith, "Nucleate and Film Boiling Design for O_2, N_2, H_2 and He," Advances in Cryogenic Engineering 10, Plenum Press, New York, p. 325, 1964.

29. Frank Kreith, Principles of Heat Transfer, International Textbook Company, Scranton, PA, 1960.

30. M. T. Ciechelli and C. F. Bonilla, "Heat Transfer to Liquids Under Pressure," AICHE Trans, Vol. 41, 1945.

31. H. B. Callen, Thermodynamics, John Wiley and Sons, New York, 1962.

32. J. B. Jones and G. A. Hawkins, Engineering Thermodynamics, John Wiley and Sons, New York, 1960.

33. T. R. Strobridge, "Refrigeration for Superconducting and Cryogenic Systems," IEEE Transactions on Nuclear Science NS-16, No. 3, p. 1104, 1969.

34. Koch Process Systems Model 1400 Helium Refrigerator Data Sheet, Koch Industries, Westborough, MA, 1983.

35. C. P. Bean et al., "A Research Investigation of the Factors that Affect the Superconducting Properties of Materials," AFML-TR-65-431 Airforce Materials Laboratory, Wright Patterson Air Force Base, Ohio, 1964.

36. E. W. Collings, The Applied Superconducting Metallurgy and Physics of Titanium Alloys, Plenum Press, New York, 1986.

37. M. N. Wilson, C. R. Walters, J.D. Lewin, and P. F. Smith, "Experimental and Theoretical Studies of Filamentary Superconducting Composites, Part 1, Basic Ideas and Theory," J Phys: Applied Physics, Vol. 3, p. 1517, 1970.

38. P. H. Eberhard and E. Grossman, "Specific Heat of Superconductors," LBL Physics Note 862, September 1978.

39. H. R. Hart, Jr., "Magnetic Instabilities and Solenoid Performance, Applications of the Critical State Model," Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators, BNL 50155 (C55), p. 571, 1968.

40. J. L. Duchatean and B. Turck, J Appl Phys, Vol. 46 (11), p. 4989, 1975.

41. M. N. Wilson, "Stabilization of Superconductors for Use in Magnets," IEEE Transactions on Magnetics MAG-13, No. 1, p. 440, January 1977.

42. P. F. Chester, Rep. Prof. Phys. 30, Part 2, p. 361, 1967.

43. H. Brechna, "Materials and Conductor Configurations in Superconducting Magnets," Proceedings of the 1968 Summer Study on Superconducting Devices and Accelerators, BNL 50155 (C55), p. 478, 1968.

44. Thermal Conductivity of Solids at Room Temperature and Below, National Bureau of Standards Nomograph 131, September 1973.

45. W. H. Cherry and J. I. Gittleman, "Thermal and Electrodynamic Aspects of the Superconductive Transition Process," Solid State Electronics 1, 287, 1960.

46. P. H. Eberhard et al., "Quenches in Large Superconducting Magnets," Proceedings of the 6th International Conference on Magnet Technology, Bratislava, Czechoslovakia, Lawrence Berkeley Laboratory Report LBL-6718, August 1977.

47. Handbook on Materials for Superconducting Machinery, Metals and Ceramics Center, Battelle Columbus Ohio Laboratories, MEK-HB-04, November 1974.

48. P. H. Eberhard et al., "The Measurement and Theoretical Calculation of Quench Velocities in Large Fully Epoxy Impregnated Superconducting Coils," IEEE Transactions on Magnetics MAG-17, No. 5, p. 1803; also Lawrence Berkeley Laboratory Report LBL-12337, March 1981.

49. M. A. Green, "PEP Detector Development, Large Superconducting Solenoid, Copper Stabilized vs. Aluminum Stabilized Superconductor," LBL Engineering Note M5044A, January 1978.

50. M. Scherer and P. Turowski, "Investigation of the Propagation Velocity of a Normal Conducting Zone in Technical Superconductors," Cryogenics 16, pp. 515-520, September 1978.

51. P. Turowski, Institute fur Technische Physik Kernforschungszentrum Karlsruhe, private communication on quench propagation velocity measurements, 1976.

52. B. J. Maddock and G. B. James, "Protection and Stabilization of Large Superconducting Coils," Proc. IEEE 115 4, p. 543, April 1968.

53. M. A. Green, "Design Condition for Fail Safe Quenching of a High Current Density Superconducting Solenoid with a Shorted Secondary Circuit," Lawrence Berkeley Laboratory Report LBL 14859, September 1982.

54. M. A. Green, "The Role of Quench Back in Quench Protection of a Superconducting Solenoid," Cryogenics 22, p. 659, December 1984.

55. S. L. Wipf, Los Alamos Scientific Laboratory Report, LA 7275 (1978)

56. A. P. Martinelli, Proceedings of the 1972 Applied Superconductivity Conference, Anapolis MD IEEE, New York p. 331.

57. M. N. Wilson "Superconducting Magnets" Clarendon Press Oxford, 1983.

58. Z. J. J. Stekly and Z. L. Zar, "Stable Superconducting Coils," IEEE Transactions NS-12, June 1965.

59. M. A. Green, "The Importance of Heat Transfer in the Stabilization of Superconductors," Proceedings of MT-2, Oxford University, Oxford, England, July 11-14, 1967.

60. C. N. Whetstone et al., "Thermal Stability for Ti-22 at % Nb Superconducting Wires and Cables," IEEE Transactions on Magnetics, MAG-2, No. 3, 1966.

61. A. K. Ghosh et al., "Anomalous Low Field Magnetization in Fine Filament Superconductor," IEEE Transaction on Magnetics, MAG-23, No. 2, 1987.

62. M. A. Green, "Modeling of Proximity Coupling Between Superconducting Filament in Superconducting Dipole Magnets," to be published in Advances in Cryogenic Engineering 33, Plenum Press, New York, 1987.

63. Superconducting Super Collider Conceptual Design, Report SSC-SR-2020, March 1986.

64. M. A. Green, "Field Generated Within the SSC Magnets Due to Persistent Currents in the Superconductor," Proceedings of the Workshop on Accelerator Physics, Ann Arbor, MI, Lawrence Berkeley Laboratory Report LBL-17249, December 1983.

65. M. S. McAshan and P. VanderArend, "A Liquid Nitrogen Temperature SSC," Report SSC-127, April 1987.

66. R. Perin, "Magnet Research and Development for the CERN Large Hadron Collider," CERN SPS/86-9 (EMA), LHC Note 41, May 9, 1986.

67. R. Meuser, T. Elioff, N. Travis, and J. Zelver "Potential Effect of the New High Temperature Superconductor on SSC Costs," SSC-N-347, May 1987.

68. Interim Report of the ASTROMAG Definition Team on the Particle Astrophysics Magnet Facility, ASTROMAG, NASA-GSFC, 1986.

69. M. A. Green, "Basic Parameters of the Strawman Magnet Configuration for ASTROMAG," an unpublished report presented at the ASTROMAG Definition Team Meeting at NASA-GSFC, December 1986.

70. M. D. Pirro and S. Castles, "Superfluid Helium Transfer Flight Demonstration Using the Thermomechanical Effect," Cryogenics 26, p. 84, February 1986.

71. A. Hofmann et al., "Operational Characteristics of Loops with Helium II Flow Driven by Fountain Effect Pumps," to be published in Advances in Cryogenic Engineering 33, Plenum Press, New York, 1987.

72. S. H. Castles, "Goddard Space Flight Center Cryogenics Research Program," presented at the Space Cryogenics Workshop, University of Wisconsin, Madison, WI, June 21-23, 1987.

73. R. E. Schwall, "MRI-Superconductivity in the Marketplace," IEEE Transactions on Magnetics MAG-23, No. 2, 1987.

74. J. W. Ekin et al., "Method for Making Low Resistivity Contacts to High T_c Superconductors," submitted to Appl Phys Lett, October 1987.

75. John Purcell, private communication about the measurement of magnetization effects in conventional Nb-Ti MRI magnets.

76. W. Hasenzahl, private communication on five component high T_C copper oxide superconductors.

77. M. Mitchell Waldrop "Superconductor's Critical Current at a New High" Science, Vol. 238, p. 1655, 18 December 1987.

78. T. H. Geballe and J. K. Hulm, "Superconductivity The State that Came in From the Cold", Science, Vol. 239, p. 367, 22 January 1988.