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(1)

STABILITY PROJECTIONS FOR HIGH TEMPERATURE SUPERCONDUCTORS

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Superconductors at elevated temperatures will be much less susceptible to thermal instabilities than the classical superconductors at liquid helium temperatures. This is a consequence of the increased specific heat of all materials at elevated temperatures, and removes the need for the extremely fine degree of subdivision exemplified by present state-of-the-art copper stabilized multifilamentary superconducting composites. It should thus be possible to use simple monolithic high temperature superconducting structures, without direct connections to an external power source, to trap fields of at least 3 T at 77 K and thereby produce superconducting permanent magnets with energy products of 225 MG·Oe. The application of high temperature superconductors would be eased and expedited by removing the problems associated with current connections to ordinary conductors and, at the same time, eliminating the heat leak and refrigeration costs associated with current leads between ambient and cryogenic temperatures. The findings of this SBIR Phase I effort are contained in two papers: "Stability Projections for High Temperature Superconductors"

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Stability Projections for

High Temperature Superconductors[*]

by

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Abstract

The stability of the new high temperature superconducting oxides has been analyzed using the methodology developed over the last 25 years for conventional Type II superconductors. The results are presented in graphical form for the temperature range from 4 to 100 K. For a 90 K superconductor the first flux jump field peaks above 7 T* at 60 K. The adiabatic stability limit increases dramatically. The linear dimension of the minimum propagating zone increases by a factor of 3 to 5, and the quench propagation velocity drops by 4 orders of magnitude. The high temperature superconducting materials will, therefore, have much higher stability than conventional Type II superconductors; their high flux jump fields make ultra-fine multifilamentary conductors unnecessary, and improve the outlook for tape conductors; the energy to create a propagating zone is increased; but methods of coil protection will have to be modified.

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* Note added in Proof: For the 120 K superconductors announced after completion of this contract, the first flux jump field should exhibit a broad peak of 12 T between 70 and 80 K.

1. Background Information

Until 1986 superconductivity was known to exist only below 23 K and, up to the present, most practical applications of Type II superconductors have been at liquid helium temperatures. Applying superconducting technology requires the management of interacting thermal, electrical and mechanical constraints.

Thermal control is difficult because the specific heats of all materials are quite small at low temperatures, so that a small localized energy input may raise a region of a current carrying superconductor above its transition temperature. Whenever that occurs, the current must flow through normally resistive material until it is disconnected at its source, or until the energy of the source is dissipated in the resistive region. Clearly, this process can have catastrophic consequences if the stored energy is large, or if the resistive region remains small.

The basic triggering mechanism for the conversion of electrical into thermal energy arises from the impossibility of having a changing magnetic field ($\dot{B} \neq 0$) within a body of zero resistivity ($\rho = 0$). Therefore some finite resistivity and some energy dissipation **must always** be present whenever currents and fields are **changing** in a type II superconductor. Secondary problems stem from the brittleness of most superconductors and from the sizable forces experienced by the windings of all high field electromagnets. Slight mechanical failure, such as cracking or slipping in the support structure will also release energy locally.

The topic of superconductor stability is concerned with defining permissible energy inputs and with methods of modifying the configuration and components of a superconducting assembly to either limit the magnitude of potential energy inputs, or to make the assembly more tolerant of such inputs. The usual parts of a superconducting assembly are:

(1) The superconductor proper;

(2) Stabilizer and structural support material that provide some of the properties lacking in the superconductor, such as mechanical strength, heat capacity, and high normal state electrical and thermal conductivity; and

(3) Heat transfer material or cryogen filled channels that keep the structure at a predetermined safe operating temperature.

There are separate, independent and distinct approaches to improve stability by working on each of these three components. The management of the local energy input by controlling the dimensions of the superconductor is known as adiabatic stabilization; the slowing down of flux motion is called dynamic stabilization; and the provision of sufficient cryogenic cooling for thermal recovery of any, accidentally formed, normal region is termed cryostabilization. The latter includes both direct immersion in a liquid cryogen and indirect means.

The advent of High Temperature Superconductivity (HTSC) [1] [2] raises the obvious question of how the stability of the new materials differs from that of the classical ones. Some answers to that question have already been given by a number of people [3] [4] with a primary emphasis on 77 K operation. The projections developed in the present study are concerned with adiabatic stabilization and indirect cryogenic cooling, as described by the concept of the minimum propagating zone. Parameters controlling stability are then presented graphically as a function of temperature over the range from 4 to 100 K.

2. Materials

The ceramic, copper oxide, high temperature superconductors that have been discovered since 1986 are easily prepared in imperfect form, once the formula for the composition is established. The typical representative of the group has been the rare earth, Yttrium 1-2-3 compound $YBa_2Cu_3O_7$. The most striking property of these materials is, of course, the high transition or critical temperature, T_C, ranging up to 100 K and possibly higher. Equally exciting are the high upper critical fields, B_{c2}, which, for single crystals, rise from T_C with slopes of -0.5 and -2.3 T/K, depending on crystallographic direction. Extrapolations to 0 K give values above 100 T, well beyond fields that can be contained by even the strongest materials.

The limiting factor, to date, has been the low critical current densities, observed on bulk polycrystalline samples, typically between 1 and 10 A/mm^2 (10^6 to 10^7 A/m^2), or no more than the current carrying capacity of ordinary household wiring. Clearly, it may be some time before these superconductors can be used in an engineering environment. Nevertheless, the potential payoff is so large that a tremendous research and development effort is being mounted worldwide and there has been an avalanche of publications and conferences on high temperature superconductors. Just keeping track, not to mention assimilating this flood of information from a variety of disciplines, can be time consuming, at best.

2.1. Fabrication and Chemistry

Fabrication of materials with poor current densities is so simple that it can be done by anybody with access to a high school chemistry laboratory, but actual control of exact metal composition ratios and of oxygen content is crucial and complex. For practical, *i.e.* high current density, materials the main problem may well lie with the control of grain size and grain boundaries. The manufacture of oriented and textured materials would be an important first step in attacking this problem.

2.2. Physical Properties

Any prediction of the expected performance of the new materials over an extended range of temperatures requires a knowledge of a number of physical properties. In the following, we enumerate these properties, together with some available data or our best estimates.

2.2.1. Specific Heat per Unit Volume - From the specific heat measurements of Junod *et al.* [5] and Inderhees *et al.* [6] we derive a value of 10^6 J/m^3·K for the volumetric specific heat at 80 K. This is half the value for copper at the same temperature, and since the curves appear to be essentially parallel, we simply use the readily available reference data for copper divided by two.

2.2.2. Density - The crystallographic density of the Yttrium 1-2-3 compound is 6.38 g/cm^3.

2.2.3. Thermal Conductivity - Morelli, Heremans and Swets [7] report a thermal conductivity of about 0.5 W/m·K between 140 and 80 K, rising to a peak of 0.6 W/m·K at 55 K, and followed by a linear drop to 0.16 W/m·K at 15 K. This is only about 2 or 3 times as large as most glasses.

2.2.4. Normal State Electrical Resistivity - According to many reports, the bulk resistivity just above the transition temperature is an order of magnitude higher than most metallic resistance alloys, and ranges between 200 and 300 μΩ·cm for the better samples. Less perfect and thin film samples can be higher by factors of 5 to 10. We will use $2 \cdot 10^{-6}\ \Omega \cdot m$.

2.2.5. Critical Field - Measurements on single crystals by Worthington, Gallagher and Dinger [8] give upper critical fields, B_{c2}, that rise from a T_c of 89 K with slopes of -0.5 and -2.3 T/K, depending on the crystallographic direction. We will use -0.5 T/K as a conservative estimate to relate zero-current critical field and temperature. The average value in polycrystalline samples could, actually, be higher.

2.2.6. Critical Current Density - For presently available polycrystalline high temperature superconductors, bulk critical current densities are low. However, since real applications will only be interesting once critical current densities are increased by 2 or 3 orders of magnitude, we model our analysis with J_c as a "free" parameter and assume a linear drop from a "reference" value, J_{ref}, of 10^4 A/mm^2 (or 10^{10} A/m^2), at the reference temperature of 4 K, to zero at T^*, where T^* represents the "at-field" zero-current critical temperature defined in the previous section. This is the behavior observed with most Type II superconductors, so that for any operating temperature T_0:

$$J_c(T_0) = J_{ref} \cdot (T^* - T_0)/(T^* - T_{ref}) \qquad (1)$$

3. Stability Analysis

The understanding of stabilization of current carrying type II superconductors was achieved in a 15 year period starting in the mid sixties and has been summarized in Martin Wilson's definitive treatise, titled "Superconducting Magnets". [9] We extend the analytical relations given in Wilson's book to higher temperatures, making the still unproven assumption that the physics of flux motion and of flux pinning is the same for the high temperature materials as it is for conventional Type II superconductors.

3.1. Mathematical Formulation

The physical arguments that underlie the various stability, stabilization and protection concepts are discussed in detail in subsequent sections. Here we summarize the mathematical formulations (with page references to Wilson's book) for ready access and comparison:

Flux Jump Field (p. 135):

$$B_{fj} = \left(3\,\mu_0\,\gamma\,C\,(T^* - T_0)\right)^{0.5} \qquad (2)$$

Maximum Stable Radius or Half-Thickness (p. 134):

$$a = \frac{1}{J_c}\left(\frac{3\,\gamma\,C\,(T^* - T_0)}{\mu_0}\right)^{0.5} \qquad (3)$$

Radius of Minimum Propagating Zone, MPZ (modified from p. 76):

$$R = \frac{1}{J_m}\left(\frac{3\,k\;\Delta T}{\rho}\right)^{0.5} \qquad (4)$$

Quench Propagation Velocity (p. 206):

$$V = \frac{J_m}{\gamma\,C}\left(\frac{\rho\,k}{\Delta T}\right)^{0.5} \qquad (5)$$

Where:

C	= Specific Heat	---	$J\,kg^{-1}\,K^{-1}$
J_c	= Critical Current Density	---	$A\,m^{-2}$
J_m	= Average Current Density	---	$A\,m^{-2}$
k	= Thermal Conductivity	---	$W\,m^{-1}\,K^{-1}$
T^*	= Critical Temperature (at Field)	---	K
T_0	= Operating Temperature	---	K
ΔT	= Thermal Margin at Op. Temp.	---	K
γ	= Density	---	$kg\,m^{-3}$
μ_0	$= 4\pi \cdot 10^{-7}$		
ρ	= Average Resistivity	---	$\Omega\,m$

in the next two sections we describe the flux jump phenomenon and discuss means to avoid it. Subsequent sections cover the dynamics of normal zone propagation and its relation to coil protection.

3.1.1. Adiabatic Stabilization -- Flux Jump Fields

It was observed early in the development of superconducting magnets that thick sections and wide tapes exhibit a peculiar instability associated with the re-distribution of magnetic fields during current changes. Modern twisted, multi-filamentary, copper stabilized, superconducting wires and cables are designed so as to avoid these flux jumps.

The classical treatment of adiabatic stability starts with the Bean-London [10] [11] critical state model, which describes the response of a bulk Type II superconductor to changing external magnetic fields. The superconductor initially excludes the magnetic field from its interior by setting up shielding currents on its surface. However, once those currents exceed what can be carried within a London penetration depth, current transfers into the interior, where the current density is governed by the pinning strength, *i.e.* by the ability of various lattice imperfections to pin flux lines and keep them from moving.

Further increases in the applied magnetic field overcome the pinning and cause progressive penetration of magnetic flux. The induced shielding currents gradually move into the conductor, so that local current densities are either at their critical value or zero. Eventually the entire conductor will be fully penetrated **unless** there is a sudden, premature, catastrophic flux penetration - a flux jump. The jump is usually accompanied by local heating and results in unpredictable flux and current distributions. The objective then is to have the field fully penetrate the superconductor without triggering any flux jumps, and this must be done by limiting the energy stored in the induced currents.

The analysis treats a semi-infinite slab of superconductor with a field parallel to its surface . The conductor is at a uniform temperature, *i.e.* iso-thermal, but is also assumed to be thermally isolated, hence the term "adiabatic", which really means "worst-case". The following "feedback" cycle is considered:

> A small heat input produces a temperature rise, which causes a decrease in J_c, which then results in a redistribution of the shielding currents and additional heating from the associated flux motion.

Depending on the specific heat and the slope of the critical current density *vs.* temperature curve, the cycle will either accelerate or die out.

Equation (2) gives the first flux jump field, B_{fj}, as a function of the operating temperature, T_0. It is worth noting that the critical current density is not explicitly present, but does affect the depth of flux penetration for a given applied field. The higher the current density, the less the penetration depth. For subsequent flux jumps equation (2) can be generalized by replacing B_{fj} with the difference, ΔB, between the fields inside and outside the body of the superconductor.

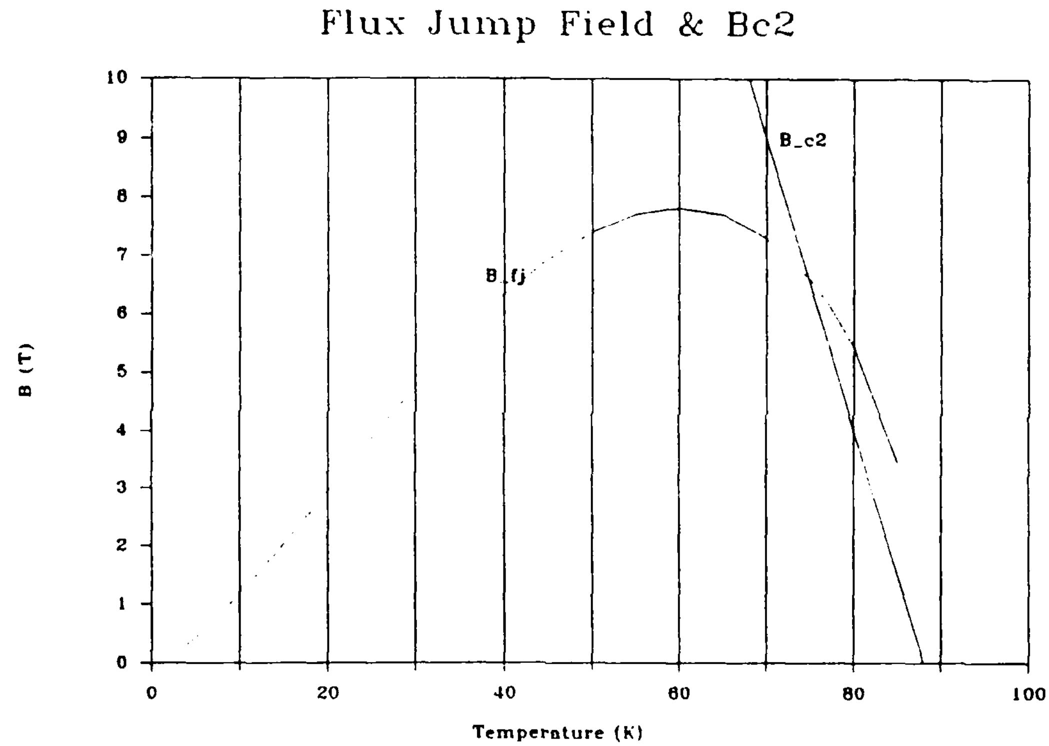

Fig. 1 *First flux jump and upper critical field limits for generic high temperature superconducting (HTSC) material with half the volumetric specific heat of copper, a [illegible] decrease in J_c and a T_c of 88 K.*

Figure 1 shows that for superconductors with a T_c near 90 K, the flux jump field peaks near liquid nitrogen temperature with the very high value of 7±2 T, depending on the magnitude of the specific heat of the material. The implications of this prediction on the possibility of developing superconducting "permanent" magnets is discussed in a separate note. [12]

3.1.2. Adiabatic Stabilization -- Critical Dimensions

If the slab discussed in the model is thin enough, it will be fully penetrated **before** the first flux jump takes place and it is said to be adiabatically stable. This concept is then used to derive the adiabatic stability criterion for a current carrying tape or wire of half-thickness or radius, a.

Equations (3) and (1) indicate that the maximum permissible dimension, perpendicular to a changing magnetic field, is proportional to the square root of the specific heat and inversely proportional to the square root of the product of the critical current density and its slope.

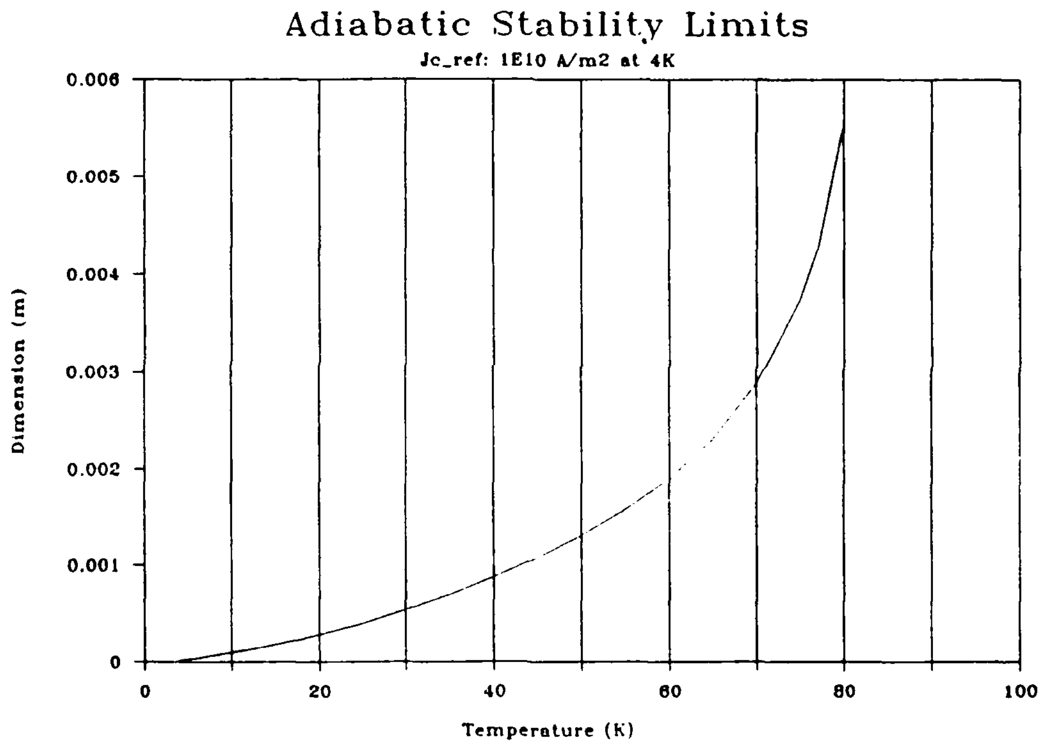

Fig. 2a *Adiabatic stability limits for generic HTSC with a linear decrease in J_c and a T_c of 85 K.*

Figure 2a and 2b are linear and semi-log plots, respectively, of this limiting stable dimension for a reference critical current density of 10^{10} A/m^2 at 4 K and an effective T_C (or Γ^*) of 85 K. With the assumed linear slope, J_C at 75 K becomes 1200 A/mm^2, or $1.2 \cdot 10^9$ A/m^2. The increase in the critical dimension on going from low to high temperatures is a dramatic two orders of magnitude, mainly due to the strong increase in specific heat with temperature. For a fixed critical temperature, the stability dimension scales as $1/J_C$, *i.e.* a material a with lower current density can be thicker, but there has to be more of it.

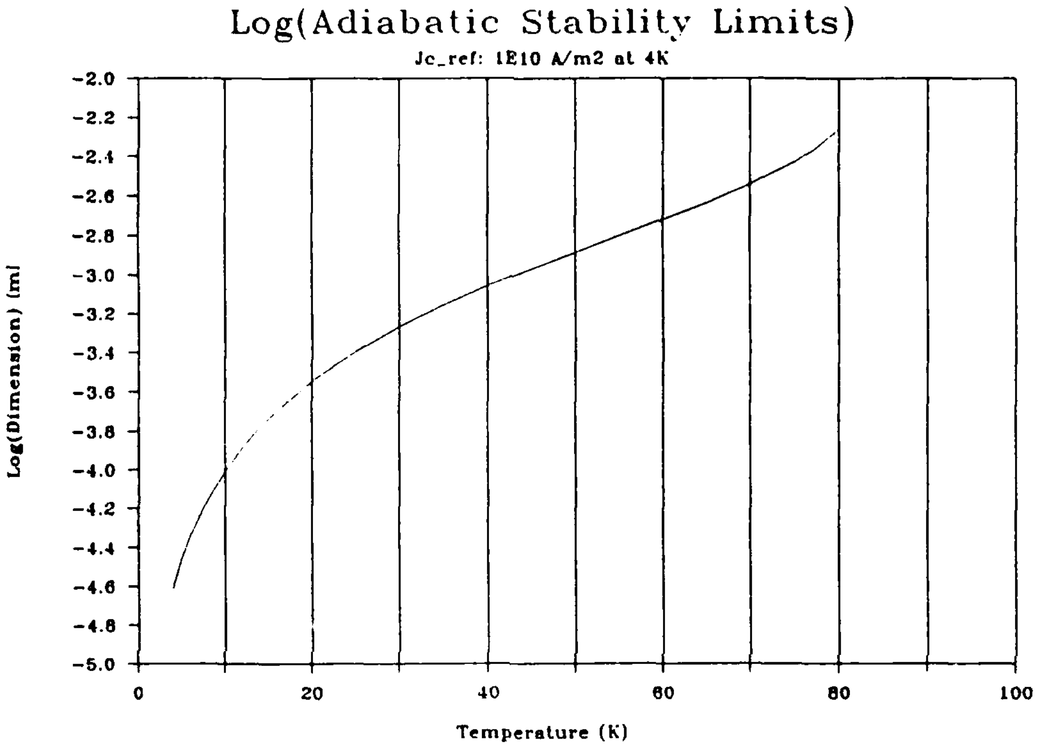

Fig. 2b *Semi-log Plot of Fig. 2a.*

For conventional superconductors the critical dimensions are well below a millimeter and can best be obtained by incorporating the superconductor in a matrix of normal metal. The manufacture of such multifilamentary conductors involves many complex steps between the ingot and the final wire or cable.

For high temperature superconductors, used near T_c, it should be possible to satisfy the adiabatic stability criterion without incurring the cost and complexity of manufacturing ultra-fine filamentary composites. Maximum filament diameters will only be dictated by permissible AC losses and by the desired flexibility of the wire or cable; and tapes may, at long last, become a viable conductor option.

3.1.3. Minimum Propagating Zone

Up to this point we have described the behavior of a thermally isolated superconductor. In most real situations there will be some heat transfer between each element of conductor and its surroundings, which include other parts of the winding and, ultimately, a cooling reservoir. We next discuss to what extent heat transfer can be relied upon to keep a superconducting structure at its proper operating temperature in the presence of various heat inputs.

Full cryostabilization is not discussed in the present note because the associated heat transfer differs for each cryogen, which, moreover, can only be used over a narrow temperature range. However, heat transfer from superconductors to various cryogenic liquids needs to be evaluated in future work, particularly since liquid nitrogen is almost 10 times as effective a cooling medium as liquid helium.

For the simplest case we look at a current carrying superconducting wire with an accidentally created hot spot at a temperature above T_C. The hot spot will, of course, produce ohmic heating and some of that heat will be conducted away along the wire. If the hot spot is very short, heat conduction will exceed heat generation, the spot will contract and the wire will recover superconductivity. On the other hand, if the hot spot exceeds a certain length, it will grow. The term Minimum Propagating Zone (MPZ) for the boundary between expansion and contraction was coined by Wipf [13] in his original analysis of the problem.

Equation (4) gives the expression for the radius, R, of the MPZ in terms of the mean current density, J_m, thermal conductivity, k, and normal state resistivity, ρ, in the material, as well as the thermal safety margin, ΔT, at the operating conditions. For typical superconductors k is low, ρ is high and the change in ρ with temperature is small.

However, if the superconductor is closely connected over its entire length to a good normal conductor, such as copper or aluminum, the **effective** normal state thermal and electrical conductivities of the composite are greatly improved. The MPZ of the composite is controlled by the transfer of some current from the superconductor into the normal conductor, whenever the transport current density exceeds the critical current density, J_C (for the prevailing field and temperature). There will then be a voltage drop and energy dissipation (or generation) in both the superconductor and the parallel normal conductor. The temperature where current transfer begins to take place is called the "generating" temperature, T_g.

The designer of a system has to select the thermal safety margin, *i.e.* the permissible increase in temperature at the operating field and current density. That choice is, clearly, an engineering and cost compromise. Superconducting magnets operating at liquid helium temperatures typically are designed with a margin of 0.2 to 0.5 K, or about 5 to 10% of the bath or refrigerant temperature, T_0. In the following we, therefore, assume that high temperature superconducting systems can also be operated with a ΔT of 10 percent of T_0.

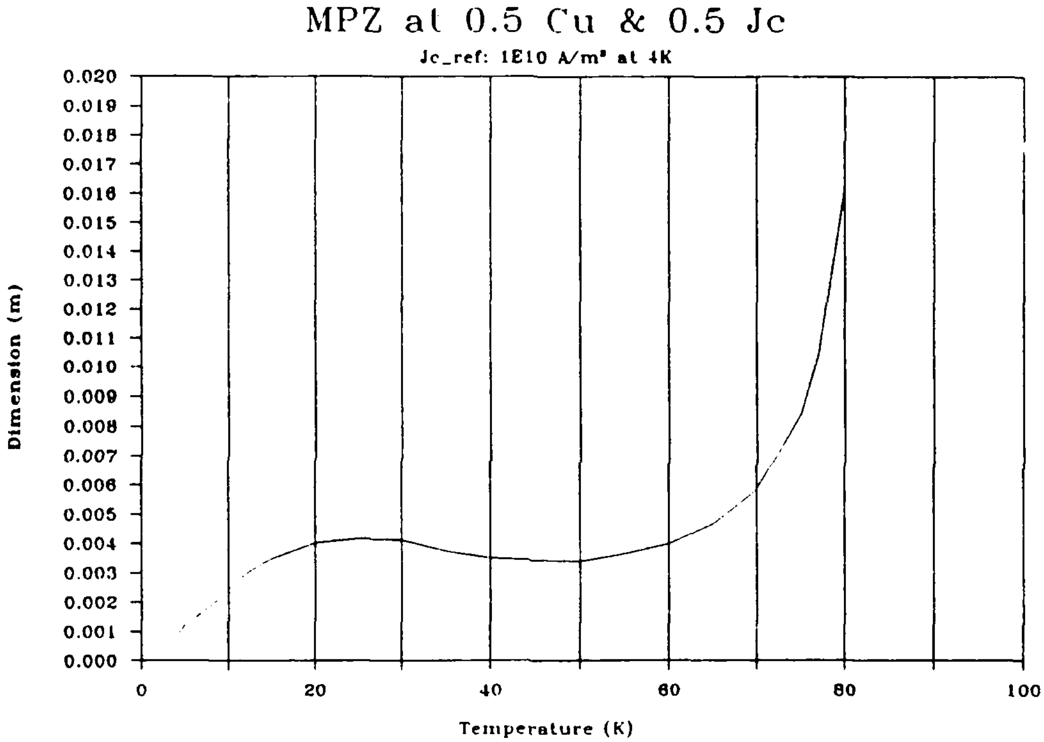

Fig. 3 *Dimension of Minimum Propagating Zone for HTSC Stabilized with 50 % Copper.*

Figure 3 plots the radius, R, of the MPZ obtained from equation (4), assuming a composition with 50% copper, an operating current density J_m in the superconductor equal to 50% of J_C, and neglecting thermal and normal-state electrical conduction in the superconductor proper, since they are orders of magnitude smaller than in the copper. With actual materials, the thermal margin, $\Delta T = T_g - T_0$, is related to J_m through the critical current density curve, so that the choice of parameters will be somewhat limited.

The MPZ varies less than an order of magnitude over most of the range, but, as discussed in the next section, the detailed geometry of the MPZ and the energy necessary to create it are strongly dependent on many design choices.

3.1.4. Triggering Energy

The minimum energy necessary to trigger the growth of a normal zone measures the sensitivity of the structure to thermal disturbances. Conceptually, it is the product of the volume of the MPZ times the enthalpy change for the available temperature difference ΔT. The only difficulty is to correctly define the volume.

A cylindrical model is appropriate for the extreme anisotropy of a free-standing wire, because there can be no radial heat flow beyond the circumference of the wire and because current can bypass a spherical zone smaller than the diameter of the wire. On the other hand, in most coil configurations the MPZ will be an ellipsoid, with transverse thermal conduction, perpendicular to the current flow, less than longitudinal conduction along the cable.

These boundary conditions have to be kept in mind when interpreting the generic results presented in Figure 4 and in Table I. We note that over the temperature range from 4 to 70 K, the *linear dimension* of the minimum propagating zone increases by a factor of 3 to 5, but because of the rise in specific heats, triggering energies increase by many orders of magnitude.

The Table lists the average physical properties of pure and composite, conventional and high temperature superconductors at their respective operating temperatures. It also gives the size of the MPZ and the energy required to trigger its formation for both spherical and cylindrical models, with the latter based on a 0.25 mm diameter wire. The thermal margin is determined by the difference between the operating temperature, T_0, and the "generating" temperature, T_g, where energy dissipation first appears.

We can see that at the low current density of 10 A/mm^2, unstabilized high temperature superconductors could take as large a disturbance as present accelerator dipole windings at their much higher current densities (and with a 1:1 copper matrix) and far more than unstabilized *NbTi*. More importantly, even if current densities can be increased by two orders of magnitude, the addition of merely 25 % of a material with the properties of copper, will improve the energy tolerance of the high temperature materials at liquid nitrogen temperatures by a factor of 20 over *NbTi* accelerator wire.

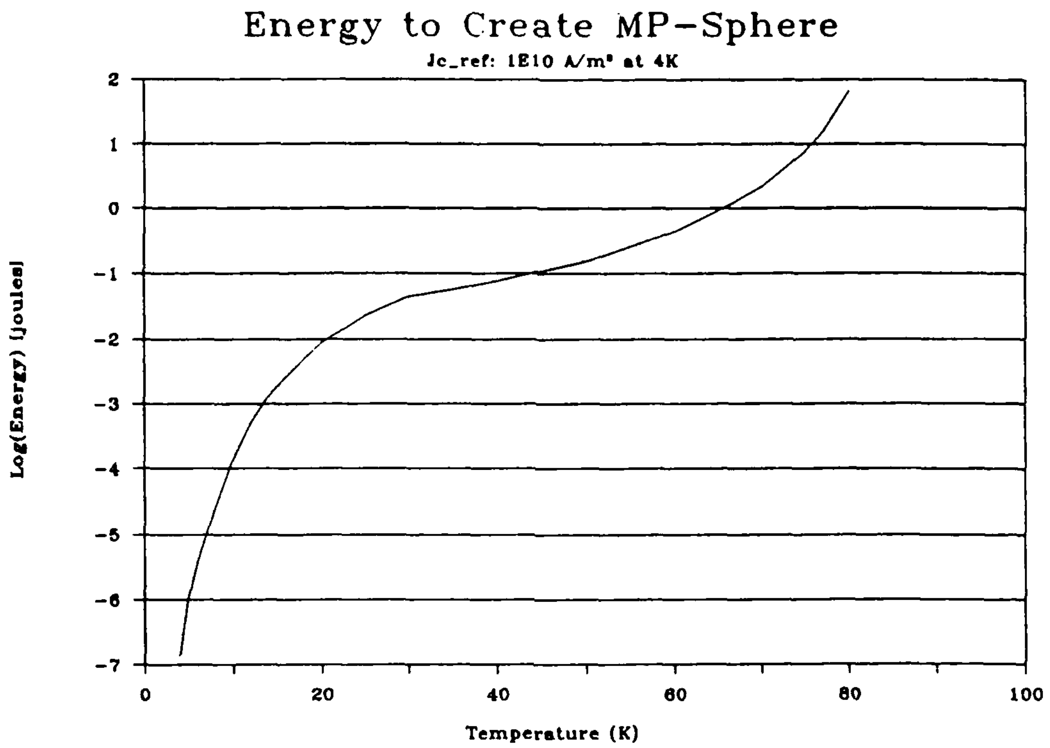

Fig. 4 *Triggering Energy for Spherical Propagating Zone in Stabilized HTSC (Dimensions from Fig. 3).*

The effect of the fractional amount of stabilizer on the energy tolerance of high temperature superconductors at 75 K is shown in more detail in Fig.5. It is obvious that stabilization against external thermal disturbances will be much easier for the new materials, no matter what their current densities turn out to be.

Table I

Minimum Propagating Zones and Triggering Energies

Material Stabilizer	Units	NbTi None	NbTi 50% Cu	123 Lo None	123 Med None	123 Hi None	123 Hi 25% "Cu"
J_m	A/mm^2	2000	1000	10	100	1000	750
T_g	K	6.5	6.5	82	82	82	82
T_o	K	4.2	4.2	75	75	75	75
k_m	$W/m \cdot K$	0.1	450	0.5	0.5	0.5	125
ρ_m	$\Omega \cdot m$	$6.5 \cdot 10^{-7}$	$7.2 \cdot 10^{-10}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$1.2 \cdot 10^{-8}$
R-MPZ	mm	$5 \cdot 10^{-4}$	2.1	0.23	0.02	0.002	0.6
V-Sph	m^3	$6 \cdot 10^{-19}$	$4 \cdot 10^{-8}$	$5 \cdot 10^{-11}$	$5 \cdot 10^{-14}$	$5 \cdot 10^{-17}$	$1 \cdot 10^{-9}$
V-Cyl	m^3	$5 \cdot 10^{-14}$	$2 \cdot 10^{-10}$	$2 \cdot 10^{-11}$	$2 \cdot 10^{-12}$	$2 \cdot 10^{-13}$	$6 \cdot 10^{-11}$
Heat-Cap	$J/m^3 \cdot K$	$1 \cdot 10^4$	$5.5 \cdot 10^3$	$1 \cdot 10^6$	$1 \cdot 10^6$	$1 \cdot 10^6$	$1.3 \cdot 10^6$
TRG-Sph	μJ	$1.3 \cdot 10^{-8}$	475	350	0.35	$3.5 \cdot 10^{-4}$	9000
TRG-Cyl	μJ	$1.2 \cdot 10^{-3}$	2.6	160	16	1.6	540

Where:

X_m = Mean value averaged over cross section of conductor
T_g = Temperature where heat generation starts
T_o = Operating temperature
V-Sph = Volume of spherical MPZ of radius R-MPZ
V-Cyl = Volume of cylindrical MPZ in 0.25 mm dia wire
TRG-Sph = Triggering energy to form spherical MPZ at T_o
TRG-Cyl = Triggering energy to form cylindrical MPZ at T_o
Heat-Cap = Volumetric heat capacity -- average between T_o and T_g

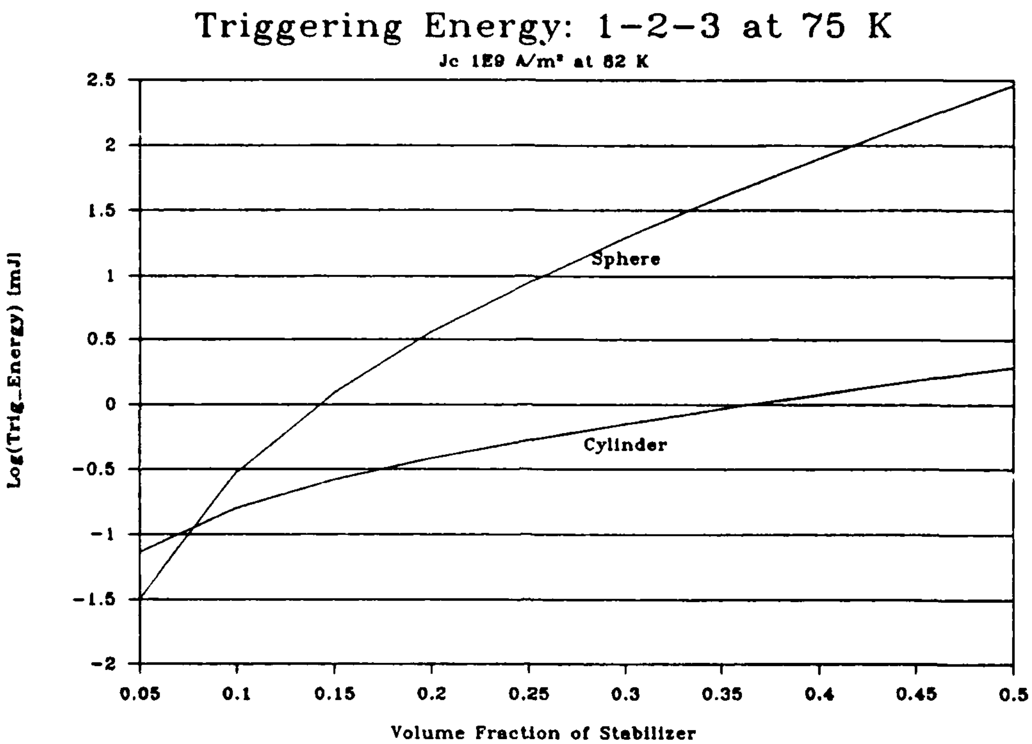

Fig. 5 *Logarithm of Triggering Energies at 75 K for Spherical and Cylindrical Propagating Zones in HTSC as a Function of the Amount of Stabilizer.*

3.1.5. Quench Propagation Velocity

The velocity at which a normal zone grows is called the quench propagation velocity, V, and, if large enough, can be used to safely shut down a magnet after an accidental thermal disturbance. In many presently operating high current density superconducting magnets, fast quench propagation from a number of strategically located heaters is used to command a quick and fairly uniform shut-down.

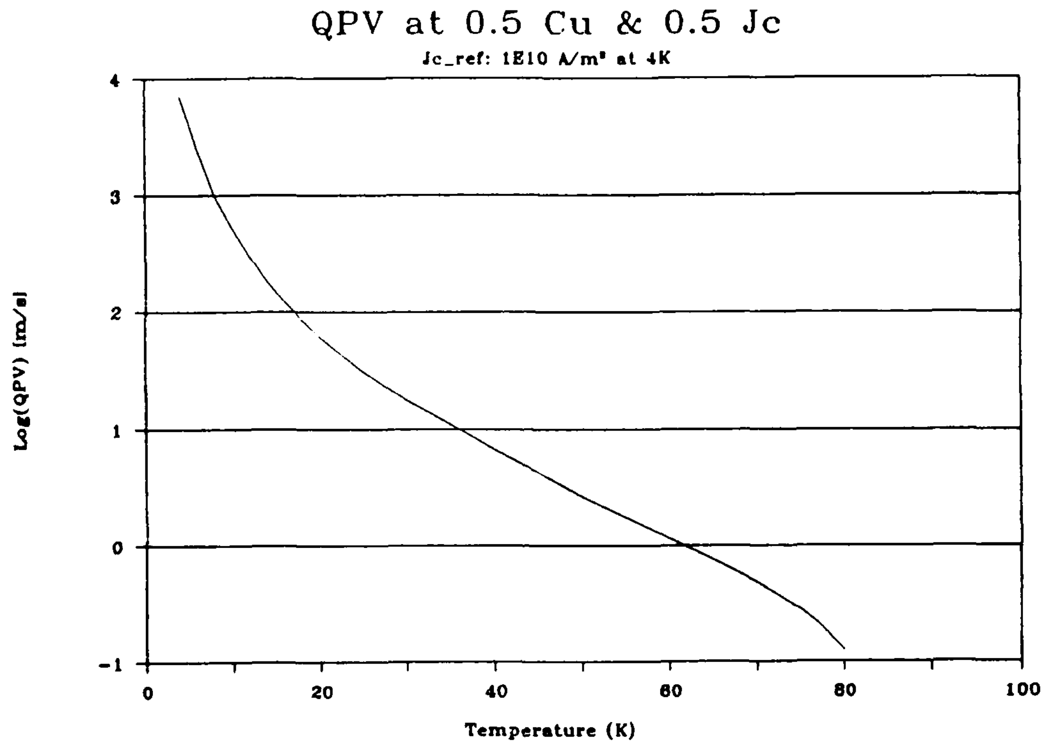

Fig. 6 *Quench Propagation Velocity in Stabilized HTSC.*

Unfortunately, as shown in Figure 6, quench propagation velocity drops by 4 or 5 orders of magnitude. Propagation will be exceedingly slow at the elevated temperatures, primarily due to the increased specific heat. Clearly, new methods of coil protection will have to be developed that are different from what is now used for high current density superconducting accelerator dipoles.

Actually, with the inherently increased stability of high temperature superconductors, the whole protection scenario has to be re-thought. Dumping all the energy quickly and uniformly into a magnet system has, so far, only been practiced by the high energy physics community, and will need to be re-thought for other magnet systems.

4. Conclusions

We conclude that high temperature superconducting materials will, on the whole, have much higher stability than the classical Type II superconductors. The main reasons for this are to be found in the greatly increased specific heats at the higher operating temperatures, and in the greater temperature margins between operating and effective critical temperatures that now become economically feasible.

The surprisingly high flux jump fields remove or simplify the need for expensive multifilamentary conductors, and improve the outlook for an easier-to-develop tape conductor.

The energy needed to create a minimum propagating zone also increases significantly with temperature. Unfortunately, if a, now-less-likely, quench should occur, the growth of the quenched zone would be so slow as to almost guarantee a burn-out. Present methods of coil protection will not work. New engineering ideas and approaches will have to be developed for protecting coils made from high temperature superconductors, once they are able to carry useful current densities.

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