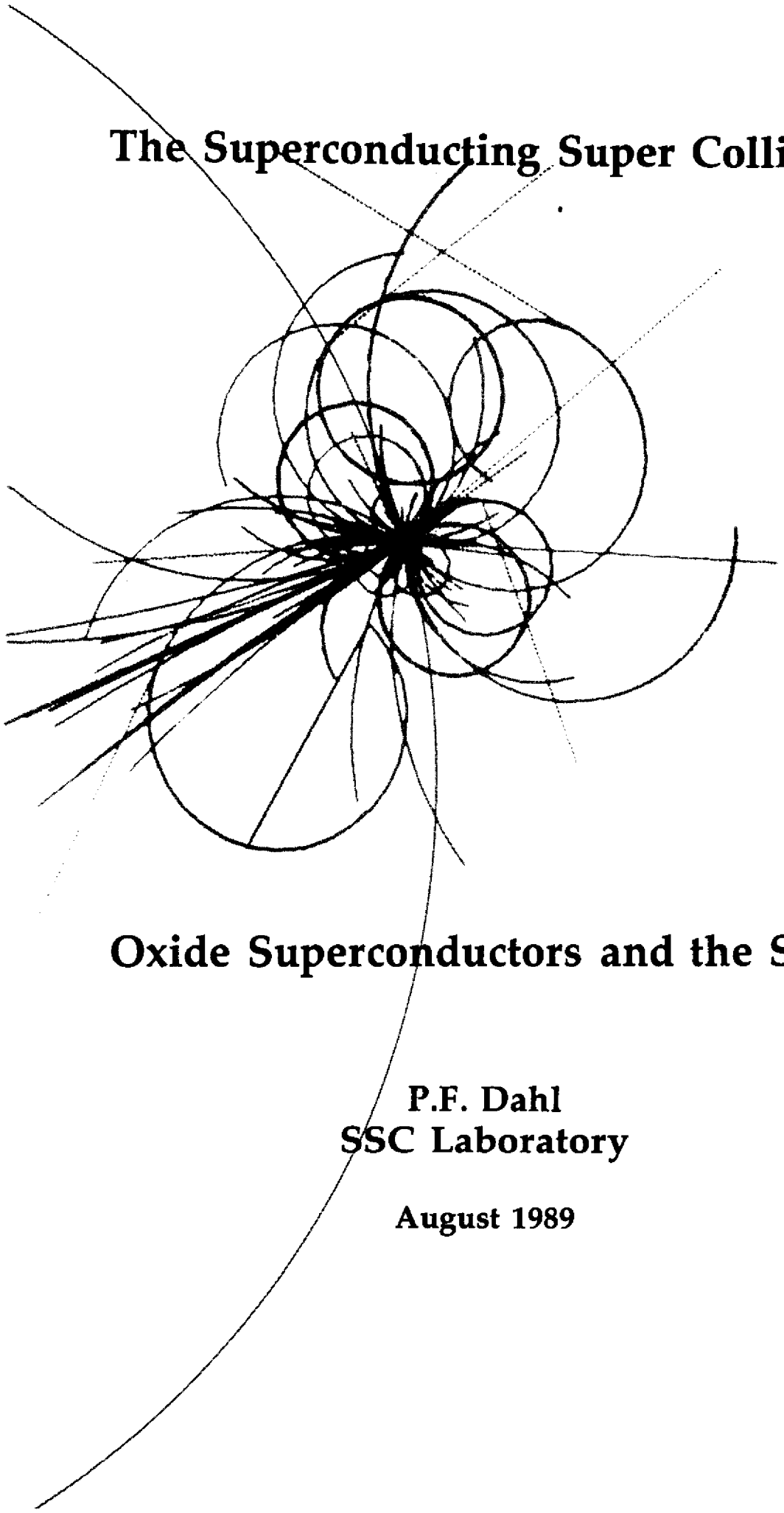
SSC-223

The Superconducting Super Collider



Oxide Superconductors and the SSC

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SSC Laboratory

August 1989

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† Operated by the Universities Research Association for the U.S. Department of Energy

Preface

In the spring of 1987, a CDG task force was formed to study the potential impact that the new high-T_c oxide superconductors might have on the SSC. The charge to the task force was to investigate the cost and operational impact of introducing a conductor having a range of transition temperatures and upper critical fields well above those of today's niobium-titanium. The task force members included A. Chao, T. Elioff, J. D. Jackson, P. Limon, R. Meuser, J. Sanford, C. Taylor, and M. Tigner, Chairman, as well as J. Lawson, CDG visitor from Rutherford Laboratory, UK. In carrying out its investigation, the task force frequently consulted with key individuals in this developing field, among them scientists from Bellcore, Westinghouse, Brookhaven National Laboratory's Materials Science Division, and the Applied Superconductivity Center at the University of Wisconsin. The task force issued preliminary reports addressing the cost of operating the collider at liquid nitrogen temperature and issues concerning operation at magnetic field levels well in excess of that currently specified for the SSC design. In addition, the task force members strove to stay well informed of both basic and applied superconductivity developments worldwide via the burgeoning technical literature.

The present report summarizes the principal findings of the task force, no longer active, to address the paramount issues within the purview of its original charge in light of the tentative state of knowledge of oxide superconductivity then available, and to readdress the findings from the vantage of 1989.

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1. Introduction

1.1 Cost Implications of Oxide Superconductors

The advent of a heretofore unsuspected class of nonmetallic superconductors with a transition temperature above the boiling point of liquid nitrogen, and capable of maintaining the superconducting state in magnetic fields well above those possible with today's metallic superconductors, has prompted close scrutiny by CDG staff and consultants of the potential application of these materials in the design of the Superconducting Super Collider. In particular, two operational regimes have—at first sight—the potential for allowing significant cost reductions in the construction and operation of the SSC. The first, operation at liquid nitrogen temperatures, is attractive in light of the simplified refrigeration at 77 K. Second, operation at higher field than the 6.6 T presently contemplated would imply significant reduction in the cost of civil construction, due to the concomitant reduction in SSC ring size for a given field. These potential savings must, however, be judiciously weighed against unforeseen adverse cost or operational implications dictated by the very replacement itself. Moreover, they are obviously predicated on the technical feasibility of a direct substitution of an oxide superconductor developed from a brittle ceramic shard to the stage of meeting the demanding mechanical and electrical specification of accelerator magnets. One purpose of the present report is to summarize under a single rubric conclusions to date from several studies of the economics of high-T_c superconductivity for the SSC. Another is to briefly review certain developments in the field of high-T_c superconductivity since these studies were made.

1.2 Technical Aspects of High-Temperature and High-Field Operation

In addition to cost-effectiveness issues raised by hypothesizing superconducting accelerator magnets operating at elevated temperatures or fields, there are technical issues at stake. Some of them concern particular aspects of the superconducting performance of conductors, whether metallic or not, under these elevated conditions. Others concern the manufacturability of the perovskite materials in forms suitable for superconducting accelerator magnets—forms dictated by accelerator physics considerations alone. We address these issues in the context of the known properties of the ceramic materials.

1.3 Special-Purpose Applications of Oxide Superconductors

Conventional metallic superconductors have been successfully exploited in diverse applications not limited to the generation of high magnetic fields, yet highly relevant to experimental particle physics. It may well be precisely these areas —e.g., electronic applications based on thin films and RF superconductivity—that will be the first to benefit from high-T_c superconductivity. Most of these applications receive only cursory notice, if any, in this report.

2. Oxide Superconductors

2.1 Discovery of High-T_c Superconductivity

The momentous developments in the field of superconductivity during 1986–87 have a parallel in John Gavaler's discovery in 1973 of the compound Nb_3Ge with a T_c of 23.2 K; his discovery[1] broke the extant critical temperature record of 18.1 K for Nb_3Sn, dating from 1961. In fact, niobium-germanium had been investigated as a potential superconductor since 1954 and was known to be one for about a decade—albeit in the beta-tungsten crystal phase Nb_5Ge_3, which has a transition temperature of only 6 K. Moreover, superconductors were first brought out of the liquid-helium range in the unlikely year of 1941, when G. Ascherman and colleagues in wartime Germany found that niobium nitride is superconducting at about 15 K.

The perovskite-type compounds had been under study for superconductivity since 1964, when the first superconducting metallic oxide, $SrTiO_3$, was discovered.[2] To be sure, T_c was only 0.3 K, eventually raised to a paltry 0.7 K. Indeed, J. G. Bednorz and K. A. Müller were guided by previous French work on the perovskites—work that emphasized the importance of the copper-oxide plane. Thus, in a 1981 paper, the French group wrote as follows: "The presence of copper in these compounds, simultaneously with two oxidation states, Cu(II) and Cu(III), suggests interesting electrical properties, which will be investigated as a function of oxygen amounts."[3]

The follow-up investigation was performed by a different team at the IBM laboratory in Zürich. In their attempt to reproduce the French mixed oxide, IBM's Bednorz and Müller focused in early 1986 on the resistivity of the perovskite variant $LaBaCu_5O_4$ and found strong evidence for the onset of superconductivity at approximately 30 K. Their first sample was fabricated in January of 1986, but, curiously, their publication did not appear until the following September. Moreover, they hedged their announcement with the cautious title, "Possible High T_c Superconductivity in the Ba-La-Cu-O System," since they were not equipped to perform the definitive test for the Meissner effect via magnetic susceptibility measurements. But once the news broke, their tentative finding was quickly confirmed by several other groups in close pursuit of oxide superconductors. By happenstance, this was a hot topic, since long before (1975) BaPbBiO had been found to be a superconductor with $T_c \sim 13$ K. Leading contenders in the race were S. Tanaka at Tokyo University, P. Chu at the University of Houston, and B. Bartlogg and coworkers at AT&T. Late in 1986, the critical temperature was raised from 30 K to 40 K by replacing barium with strontium, a rare earth component of the very first perovskite superconductor (Table 2-1).

Pressing ahead early in 1987, Chu's team, working in collaboration with a group under K. K. Wu at the University of Alabama in Huntsville, found reproducible superconductivity near 95 K in a mixed-phase sample of yttrium-barium-copper-oxygen; the discovery was made independently by Z. X. Zhao and coworkers at the Institute of Physics in Beijing. The widely hailed landmark discovery, bringing superconductivity within reach of liquid nitrogen, was rapidly confirmed in laboratories worldwide and the material identified as the "1-2-3 compound," $YBa_2Cu_3O_7$. A year later, in January of 1988, another milestone was reached with the announcement by H. Maeda at the National Institute of Metals in Tsukuba, Japan, of superconductivity near 110 K in bismuth-strontium-calcium-copper-oxygen.

Within a month there followed a second "triple-digit" superconductor, this time thallium-based, announced by A. Hermann of the University of Arkansas. Soon the transition point of TlBaCaCuO was raised from 110 K to 125 K at the IBM Almaden Research Center.

TABLE 2-1. Superconducting Oxides

Perovskite	T_c	Year
$SrTiO_3$	0.7 K	1964
BaPbBiO	13 K	1975
$LaBaCuO_4$	30–35 K	1986
$LaSrCuO_4$	40 K	1986
YBa_2Cu_3O	90–95 K	1987
BiCaSrCuO	110 K	1988
TlCaBaCuO	110–125 K	1988

2.2 Critical Current Density

Type I superconductors, i. e., elemental superconductors, are characterized by three critical parameters, the critical temperature T_c, critical field H_c, and critical current density J_c. All three parameters are related and form a critical surface below which the material in question is in the superconducting state and above it is resistive. In magnets wound from such conductors, the critical current density is reached when the sum of the applied field and self-field of the transport current exceeds the critical field, H_c. Since H_c of type I materials rarely exceeds a few hundred gauss, J_c is correspondingly low. In contrast, in type II superconductors exhibiting incomplete Meissner effect (mainly alloys and compounds) the critical current density is reached when the Lorentz force between the current and the lattice fluxoids exceeds the maximum pinning force holding the fluxoids in place. (Strictly speaking, for type II superconductors there are two critical fields involved, the lower critical field H_{c1} and the upper critical field H_{c2}. In applied fields less than H_{c1}, the superconductor completely excludes the field, i. e., exhibits complete Meissner effect, as do type I superconductors below H_c. At fields just above H_{c1}, flux starts to penetrate the superconductor, and at H_{c2} it is normal with the field fully penetrated.) A typical low-field critical current density for metallic type II materials is 10^4 A/mm^2 (Figure 2-1), or an order of magnitude lower than the BCS electron depairing critical current density.[4] By contrast, although the superconducting oxides exhibit most of the characteristics of type II superconductivity, they differ in one important respect: critical current densities achieved to date are vastly lower, typically ~10 A/mm^2 for bulk polycrystalline materials, as indicated in Table 2-2 and Figure 2-2, or not much better than copper. They also exhibit greater fall in J_c with increasing field, falling by as much as an order of magnitude in fields as low as 0.1 T. For the newer triple-digit materials, not much more is known than that they appear able to carry at least as much current as the yttrium compound, or more at a corresponding stage of

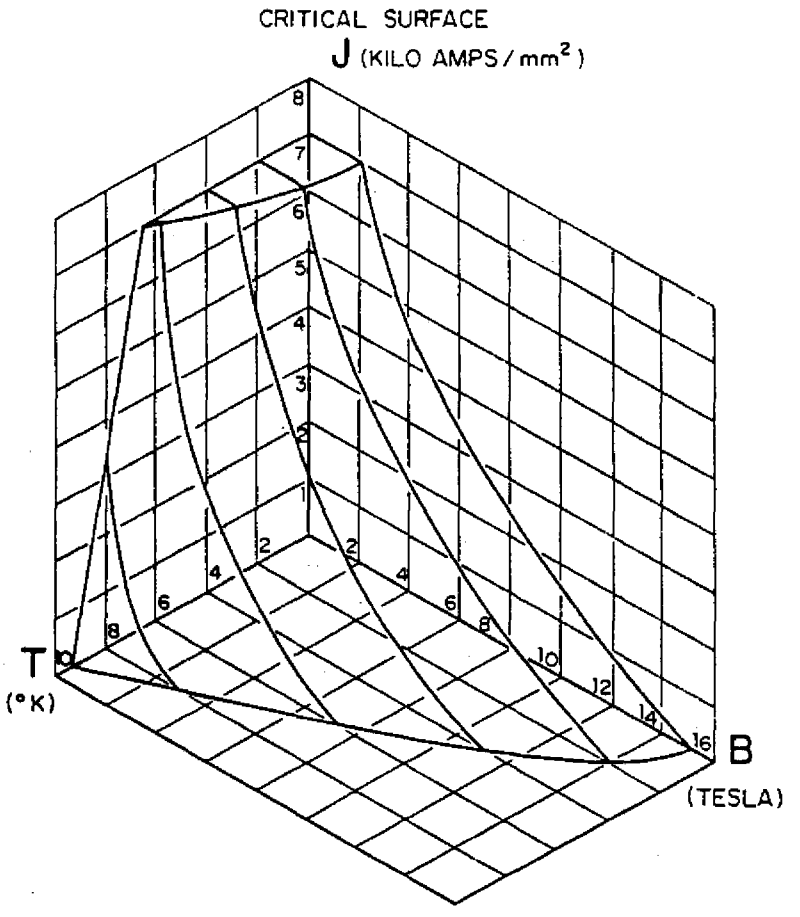

Figure 2-1. Critical surface for NbTi.

development.[5] On the other hand, J_c, unlike T_c and H_c of superconductors generally, is not an intrinsic but an extrinsic property of the material—at least for metallic type II materials—depending mainly on the details of the metallurgical treatment employed in fabricating the conductor sample. If this proves the case once more, there may ultimately be room for improvement. We return to this question in Section 6.

Of most serious concern is the fact that the oxides are highly anisotropic, as is evident from Table 2-2. Not only is J_c in unoriented bulk samples an order of magnitude lower than for oriented films and single crystals, but the ratio $J_c(||)/J_c(\perp)$, where the comparison is with respect to the CuO plane of the crystal structure, ranges between one and two orders of magnitude. A clue to the anisotropy is provided by the observation that the (upper) critical field, H_{c2}, exhibits similar behavior. This anisotropy and the low absolute magnitudes of J_c are believed to stem partly from the anisotropy and smallness of the coherence length, which is related to H_{c2}. Thus, according to Geballe and Hulm[6]:

$$\xi(T = 0, ||)/\xi(T = 0, \perp) \sim 7.$$

The short absolute coherence lengths estimated from H_{c2} measurements, 5–20 Å compared to 10^3–10^4 Å in metallic superconductors, mean that there are few electron pairs within a coherence volume and cast doubt on the meaning of coherence and depairing limits in oxide superconductors. In addition to anisotropy, the low J_cs are associated with the grain structure. There is consensus that *intragranular* J_cs are quite large, but *intergranular* current densities are impeded by "weak links" (decoupling or depletion of oxygen in CuO plane, second phases, impurities). Maley[7] summarizes the evidence for weak links thusly:

- J_c values derived from magnetization loops » J_c obtained from direct transport current measurements;
- Bulk J_c values drop with field as e^{-H/H_0}, which suggests tunneling between isolated superconducting grains;
- Magnetization loops for bulk samples do not change much when the samples are powdered, indicating the shielding is mainly performed by the grains.

Maley concludes that the development of high-current HTS conductors will be very challenging, particularly if weak links prove to be intrinsic.

2.3 Processing Techniques

Technological exploitation of the ceramics will require as much progress in synthesis and processing as will be necessary to achieve useful current densities. To quote Murphy, Johnson and Howard, "The eventual use of the new superconductors may require new processing techniques as innovative as the discovery of the materials themselves."[8] Processing of the oxide materials generally consists of shaping an assemblage of fine particles and then densifying them into a solid by sintering at high temperature (900°C-975°C), followed by a final annealing step. Variants on this basic technique have been used to fabricate primitive wire strands or single-filament composite wires. One example is the drawing of a nonreactive silver tube packed with pulverized YBaCuO, winding this composite over a mandrel, then sintering and annealing.[9] In another approach,

TABLE 2-2. Critical Current Densities of $YBa_2Cu_3O_7$

Sample Type	J_c, A/mm^2	T, K	Orientation	Lab
I.[a]	1.1×10^1	77	Unoriented	Bell
II.[b]	3.2×10^2	77	∥ CuO	Sumitomo
	2.0×10^3	60	∥ CuO	Sumitomo
III.[c]	1.6×10^4	77	∥ CuO	Nippon T&T
	10^2	77	⊥ CuO	Nippon T&T
	7.0×10^3	77	∥ CuO	Stanford & Varian
	5.0×10^5	4.2	∥ CuO	Stanford & Varian
	$> 10^3$	77	∥ CuO	IBM
	2.0×10^1	77	⊥ CuO	IBM
	2.0×10^4	4.2	∥ CuO	IBM
	4.0×10^2	4.2	⊥ CuO	IBM

Source: M. Rabinowitz, EPRI Workshop on High-Temperature Superconductivity EL/ER-5894 P-SR, April 1988 (EPRI, Palo Alto, CA, 1988)

[a] Unoriented polycrystalline bulk

[b] Oriented polycrystalline film ~1 μ thick

[c] Single crystal film ~1 μ thick

a composite wire with BaYCuO enveloping a normal metal core is obtained by coating the normal wire with an oxide slurry, followed by sintering.[10] The former approach offers the by-product of environmental protection, the latter better control of oxygen stoichiometry. Invariably, however, the final product exhibits J_c values below 10 A/mm^2 in zero field and values dropping rapidly at high fields (attributed to weak links). In contrast, thin films (produced by evaporation, sputtering, or other means) are much more promising in this regard, as we have seen. More recently, however, a new processing technique termed melt-textured-growth (MTG) appears to hold some promise for alleviating the weak link problem plaguing the bulk material in wire form.[11] Unlike conventional sintering, it employs melting of BaYCuO followed by controlled recrystallization, thereby transforming the granular, random microstructure to a dense structure consisting of long, needle-like grains aligned predominantly parallel to the high-J_c basal plane. Nevertheless, while MTG-processed samples have shown dramatic improvements in J_c (1.7×10^2A/mm^2 at 77 K and H = 0, 4×10^1 at H = 1 T), the feasibility of the process on long lengths of bulk material has yet to be demonstrated.

The notorious brittleness of the A-15 compounds, which possess superconducting properties superior to those of the type II superconducting alloys (mainly NbTi), has to some extent been circumvented in the case of Nb_3Sn (and V3Ga) by reacting Nb(V) with a Cu-Sn bronze (Cu-Ga alloy) matrix, forming a thin film at the niobium-bronze (vanadium-alloy) interface between the materials. Even so, the sensitivity to strain (Nb3Sn starts to lose its current-carrying capacity with strain rates as low as 0.4 percent, depending on the state of precompression and whether the strain is tensile or compressive12) has hitherto blocked react-and-wind applications of Nb_3Sn to all but the simplest winding applications. The

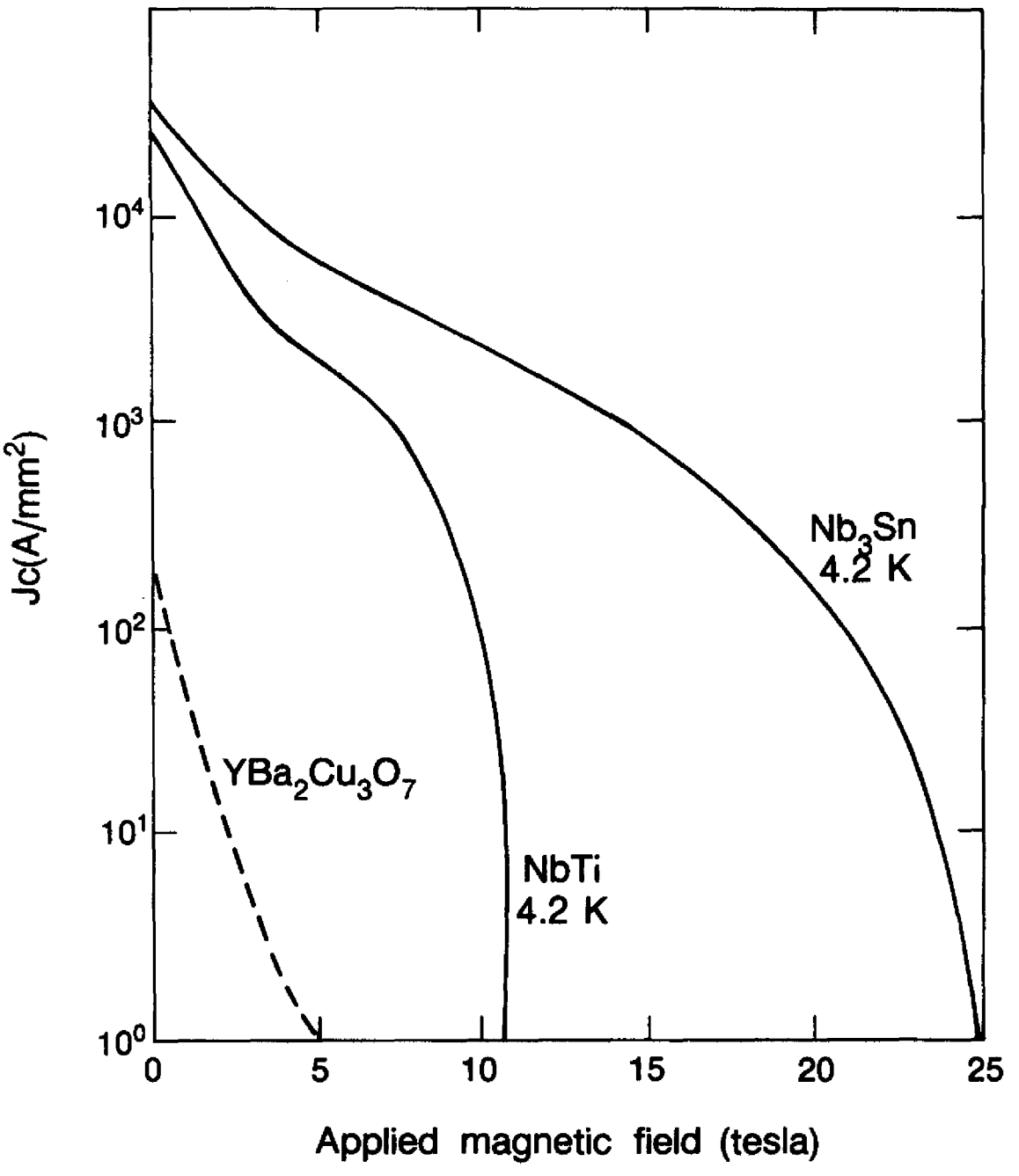

Figure 2-2. Variation of J_c with applied field of currently available NbTi and Nb_3Sn wire at 4.2 K and projected values for $YBa_2Cu_3O_7$.*

* Adapted from Fig. 2 of D. W. Murphy *et al.*, *Science*, 241, (1988), 922–930, on 923.

oxide materials can be expected to be even more sensitive to strain than the A-15 materials. Nor is the alternative, wind-and-react, particularly promising for the oxides because of their chemical reactivity: most candidate matrix materials (or substrates) are voracious getters for oxygen.

In conclusion, it may be appropriate to recall the case of the ceramic diesel engine—a highly touted prospect about a decade ago.

> Investigators intrigued by the promise of the new superconducting ceramics might do well to consider the painfully slow progress that engineers are making in developing another class of ceramics, one they hope will sharply improve the performance of diesel engines. . . An appropriate date of the "discovery" of ceramic cutting tools is 1960, but it is only within the past couple of years that these ceramics have truly achieved prominence.[13]

2.4 Desired Characteristics

The two dominant technical parameters of the SSC are operating field and machine aperture. The operating field determines the circumference of the ring and hence the cost of the tunnel. The field is consequently chosen to be as high as practicable, consistent with a judicious balance between sound magnet design principles and minimum unit magnet cost. Equivalently, the operating field represents the optimum balance between the cost of the technical collider systems, including magnets, and the cost of civil construction. At low fields the ring size increases and the cost of civil construction dominates. At high fields, the magnet costs rise more rapidly than the civil construction costs decrease, since the electromagnetic forces that must be contained increase as the square of the field. The minimum required physical size of the magnetic field volume—size of beam aperture—is dictated by basic accelerator physics alone. The required aperture and desired operating field dictate, within close limits, the current density that the superconductor must support to produce the desired field. The current density also governs the overall magnet size, and hence, its cost.

In the SSC Conceptual Design Report, these two parameters, field and aperture, have been specified as 6.6 T over a circular aperture (inner coil diameter) of 4.0 cm,[14] based on currently available NbTi superconductor with a critical current density of 2.75×10^3 A/mm^2 at 4.2 K and 5 T (and a resistivity of 10^{-14} Ω·m), and a critical current density at 8 T at the same temperature and effective resistivity of 1.1×10^3A/mm^2. This impressive performance, representing nearly 50 percent improvement in the current-carrying capacity over the last four years, is the result of a development program organized with the help of experts at the University of Wisconsin and the national laboratories and involving the principal industrial firms in the areas of superconductors and superconducting magnet technology; the objective of this collaboration has been the development of high-current-density, fine-filament material capable of meeting the detailed SSC specifications, including low magnetization effects. These specifications, which any potential replacement conductor must meet at equal or lower cost, are included in the following review of factors that affect the use of superconductors in accelerator magnets generally.

1. Critical current density: $J_c \geq 3 \times 10^3$ A/mm^2 at 5 T and the operating temperature. Conceptually, T_{op} may be taken as the boiling point of liquid helium (T_{op} = 4.35 K as specified for the SSC) or liquid nitrogen; see Section 3.
2. Filamentary form: Twisted filamentary composite, with filament diameter $d \leq 10$ μm, determined by field uniformity dictated by low-field magnetization effects, not stability criteria that are more tolerant but nevertheless demand filaments as well. (Item 5, below.)
3. Filament matrix: Filaments embedded in a matrix of normal material of high thermal conductivity and low electrical resistivity. The matrix materials will probably be copper or bronze, since the sintering temperature for synthesizing the high-T_c materials (900–975°C) exceeds the melting temperature of aluminum.
4. Ductility and sensitivity to strain: The superconductor and matrix material should be ductile with approximately the same hardness to allow them to be extruded and drawn together, and the superconducting properties impervious to strain up to, say, 1 percent. The composite should have a high ultimate breaking stress in tension, as well as a high elastic modulus.[15]
5. Stability considerations: The most conservative method of stabilizing a superconductor is by "cryogenic" stabilization, i.e., combining it with sufficient normal metal of high electrical conductivity to smother local hot spots and to ensure an alternative current path during periods of instability. The balance between ohmic heating and (nucleate boiling) heat transfer may be expressed as

$$J^2\rho(T) = \alpha h \Delta T S/A.$$

Here J and $\rho(T)$ are the current density and resistivity of the normal metal, h the heat-transfer coefficient, ΔT the liquid-composite temperature difference, and A and S the conductor cross section and surface area, respectively. The stability criterion is expressed in terms of the stability parameter α. The normal region will recover to the superconducting state if α is less than unity, that is, if the rate of Joule heating in the normal metal is less than the rate of heat dissipation into the helium bath. Solving for J,

$$J = \sqrt{\frac{\alpha \phi S}{\rho(T) A}}$$

where $\phi = h\Delta T$ is the nucleate boiling heat flux. Since ϕ increases by a factor of 10 in going from liquid helium to liquid nitrogen,[16] and $\rho(T)$ increases by the same factor, the normal metal current density should be about the same in the two cooling regimes; this implies no particular advantage of cryogenic stabilization for high-T_c superconductors.

Full or cryogenic stabilization is only practical in very large devices, such as the formerly ubiquitous bubble chamber magnets and more recent solenoids for the new generation of collider detectors, but their high copper-to-superconductor ratio and concomitant low overall current density makes them quite unsuitable for use in more compact high-field magnets where current density is a major consideration. Adiabatic or enthalpy stabilization depends on the empirical fact that a critical

parameter influencing "flux jumping" is the size of the superconductor. At low temperatures the specific heat of metals, including superconductors, is very low. However, by subdividing the superconductor into many filaments of small cross section, the energy dissipated during an adiabatic flux jump can be absorbed by the material itself with a negligible rise in temperature. The criterion for adiabatic stability requires that the filament diameter d be limited to

$$d < \frac{1}{J_c}\sqrt{\frac{3C_s(T)\Delta T_{op}}{\mu_0}}$$

where J_c is the critical current density, $C_s(T)$ the heat capacity of the superconductor, and $\Delta T_{op} = T_c - T_0$ is the operating temperature range. Since the heat capacity of the superconductor is 10^3 times higher at 77 K than at 4 K[17] (Table 2-3) and ΔT_{op} increases by a factor of ten over the same temperature interval, and furthermore, assuming J_c of the ceramics is of the same order as that of NbTi, the adiabatic stability criterion for the high-T_c superconductors is relaxed by at least a factor of 100. However, the implied gain in permissible filament size is probably not realizable because of strain (and magnetization) considerations (Section 2.3).

6. Normal zone propagation: The longitudinal quench propagation velocity is given by an expression of the form:

$$V_L \sim \frac{J}{C(T)}\sqrt{\frac{k\rho(T)}{\Delta T_{op}}}\,.$$

Here k is the thermal conductivity of the matrix material, $\rho(T)$ and $C(T)$ its electrical resistivity and specific heat per unit volume respectively, J the current density in the normal metal, and $\Delta T_{op} = T_c - T_o$ is again the operating temperature range. Since k is approximately constant between 4 K and 77 K and $\rho(T)$ increases by the same amount as does ΔT_{op} (from ~1 K to ~10 K), $V_L \sim 1/C \sim 1/2000$. Thus, the propagation velocity is reduced by many orders of magnitude. Invariably, a very stable superconductor (item 5 above) is a very slow normal front propagator.

Coupled with specification 7, below, the reduced quench propagation velocity has serious consequences with regard to quench protection, as noted under the next specification.

7. Quench protection: The figure of merit quantity $F(T_{op}, T_f)$ should be maximized, where

$$F(T_{op}, T_f) = \int_{T_{op}}^{T_f} \alpha\frac{C(T)}{\rho(T)}dT = \int_0^{\infty} J^2(t)dt\,,$$

$$\text{or } F(T_{op}, T_f) \geq J^2\tau/2\,.$$

TABLE 2-3. Characteristic Properties of Various Conductors

	T = 4 K	T = 77 K
Copper		
ρ (Ωm)	1×10^{-10}	2.3×10^{-9}
C ($Jm^{-3}K^{-1}$)	1.6×10^{3}	1.7×10^{6}
k ($Wm^{-1}K^{-1}$)	7×10^{2}	5.5×10^{2}
NbTi		
ρ (Ωm)	1.5×10^{-10}	1.5×10^{-9}
C ($Jm^{-3}K^{-1}$)	3.5×10^{3}	6.0×10^{6}
k ($Wm^{-1}K^{-1}$)	0.1	~0.1
YBaCuO		
ρ (Ωm)	1.0×10^{-7}+	2.0×10^{-6}*
C ($Jm^{-3}K^{-1}$)	0.5×10^{3}*	1.0×10^{6}*
k ($Wm^{-1}K^{-1}$)	5.0×10^{-2}	1.0

* H. L. Laquer, *et al.*, *IEEE Trans. on Magnetics*, *25* (1989), 1516-1519.
\+ Y. Iwasa, *IEEE Trans. on Magnetics*, *24* (1988), 1211-1214.

T_{op} is the operating temperature, T_f the maximum allowable hot-spot temperature following the initiation of a normal zone by a quench, τ the decay time needed to dump the current before T_f is reached, C(T) and ρ(T) are defined as before, and J(t) the current density in the normal metal. The utility of F lies in the fact that it is a function of material properties only. Since ρ of copper is an order of magnitude higher at 77 K, $F(T_{op} = 77\text{ K}, T_f)$ is correspondingly reduced and with it the operating margin. This implies a higher matrix:SC ratio, with a further erosion in the effective J_c.

These two factors, (a) drastically reduced quench front propagation and (b) smaller margin to burnout, cast serious doubts on the feasibility of a passive quench-protection system for accelerator magnet systems based on high-T_c superconductors. Indeed, it would appear that, at least for accelerator magnet applications, the quench protection problem will have to be reevaluated from first principles.

8. Energy needed to initiate a quench: Intuitively, since the specific heat of the conductor is much higher at 77 K than at 4 K, one expects the energy needed to initiate a quench to be higher for high-T_c conductors. Closer examination confirms that this is the case.[18] The energy needed to initiate a quench is given by the product of the enthalpy change needed to initiate a quench and the volume of the so-called minimum propagating zone, MPZ (smallest normal region necessary for thermal runaway to be initiated). The MPZ should be about the same at 77 K and 4 K, since it is proportional to

$$\sqrt{\frac{k\Delta T_{op}}{\rho J^2}}$$

and ΔT_{op} increases with T as ρ while there is no reason to expect a variation of J with temperature. However, the enthalpy change is proportional to

$$\int_{T_{op}}^{T_q} C(T)dT ,$$

where again C(T) is the volumetric specific heat of the matrix material and T_q the quench initiation temperature. For conventional superconductors, the quench initiation energy is typically 10^3–10^4 Jm^{-3}, highly sensitive to the proximity of liquid helium due to its high heat of vaporization. Little is gained by the close proximity of the liquid cryogen in the case of high-T_c conductors at liquid nitrogen temperatures; however, increasing T_c as well as T_{op} contributes to increasing the energy per unit volume needed to initiate a quench (by a factor ranging between 10^2 and 10^5, depending on detailed assumptions about the method of stabilization).

3. High-Temperature Operation

3.1 Introduction

Two scenarios have been suggested in which the new materials might, in principle, be exploited for the economic benefit of the SSC. One possibility explored by M. S. McAshan and P. VanderArend is that of replacing the SSC helium refrigeration system with one based on liquid nitrogen. A second more speculative possibility examined in a preliminary way by R. Meuser and colleagues takes advantage of the superior high-field superconducting properties in magnets of significantly greater bending power than possible with today's alloy conductors, thereby shrinking proportionally the overall size of the facility and hence, goes the conventional argument, its cost. Both scenarios assume that the new materials can be obtained at the same cost per pound as the alloy conductors and in a form that can be incorporated directly in the present magnet design. In this section the salient conclusions of the first study on liquid-nitrogen operation are reviewed, and in the next section the consequences of the high-field alternative (assuming liquid-helium operation) are discussed.

3.2 Specific Assumptions

The economic incentive for replacing the present NbTi alloy superconductor with one of the high-T_c ceramics with $T_c \geq 90$ K, allowing collider operation at the temperature of liquid nitrogen (77 K), would be reduction in capital cost of the simplified refrigeration system and cryogenic plant and lifetime operating cost of the facility. In their cost analysis of this possibility, McAshan and VanderArend[19] make the further heady and *ad hoc* assumptions that (a) the dipole cold mass design remains largely unaffected by the substitution with respect to size, weight, field, field quality, quench protection, and cost; and (b) the cryostat is appropriately simplified compared to that of the 4-K design, principally in the elimination of the inner (20-K) heat shield, simplification of the support structure (simpler posts and elimination of longitudinal struts), and elimination of all cryostat helium piping. Concerning assumptions (a), McAshan and VanderArend soon concluded that the beam-line high-vacuum system would have to be drastically modified and with it the magnet aperture. In addition, the general assumption of retaining the basic design is clearly questionable at best; however, in the two years elapsed since that study our knowledge of the properties to be expected of industrially refined versions of the new materials has not improved to the point where alternative assumptions are admissible. If anything, expectations for their near-term deployment in applications as technically demanding as the SSC have been considerably diminished.

Before presenting the conclusions of the economic study, we review briefly the aforesaid consequences of liquid-nitrogen operation with respect to the collider vacuum system and reiterate earlier remarks on two technical aspects of the oxide materials that are likely to have significant impact on their contemplated use in high-field accelerator applications: their brittle nature and electrical properties *vis a vis* quench protection considerations.

3.3 Vacuum System

In addition to maintaining the ambient coil temperature below the critical T_c, a second vital function of the liquid-helium system for the SSC is that of providing the necessary high vacuum along the beam pipe by distributed cryopumping—freezing the residual gas molecules onto the inner surface of the cold bore tube. Cryopumping will limit the residual partial pressure for hydrogen to 10^{-8} Torr, thereby ensuring adequate luminosity lifetime for the stored beams as well as limiting the cryogenic heat load and radiation from gas scattering. At 77 K, however, cryopumping would not be effective for hydrogen, the most important residual gas (also photodesorbed by the synchrotron radiation), nor for CO. An alternative scheme for distributed vacuum pumping in the beam tube would be necessary. In electron-positron storage rings the vacuum is maintained in the presence of copious synchrotron radiation loads with the aid of integrated, continuously operating sputter-ion pumps relying on the dipole fields of the bending magnets. This solution would not be feasible in the SSC. Instead, one based on nonevaporable gettering has been proposed,[20] similar to one chosen for LEP (the large electron-positron collider under construction at CERN) because of the low magnetic field in the LEP dipoles. While such a system would probably work for hydrogen, it would be marginal for CO. Moreover, such a system with its double-walled beam tube and getter strips and heaters[21] will necessitate an increase in the SSC beam tube and hence dipole magnet cross section. The increase in magnet aperture, with the attendant new vacuum system and necessary R&D, will severely compromise the cost benefits reaped from the simpler cryogenic system.

3.4 Nb_3Sn Experience

It seems quite likely that the brittleness problem will remain a basic feature of the new ceramic materials as discussed earlier in section 2.3; on the other hand, 30 years of experience with the intermetallic compound superconductors Nb_3Sn and V_3Ga can be brought to bear on the problem of accommodating the brittleness in magnet fabrication. Unconventional procedures have been developed for depositing the compounds on a substrate directly by vapor deposition or reacting constituent elements by diffusion; several diffusion methods are also used to form multifilamentary conductors. While prereacted Nb_3Sn conductors have found fairly widespread commercial application in solenoids and other laboratory and industrial coils of simple geometry, their use in the more demanding accelerator magnets (dipoles and quadrupoles) has been limited to prototype modeling using either of the two basic approaches: react and wind, and wind and react. Fairly recent examples of the former approach are 4.5-m–long Nb_3Sn dipole coils produced early in the SSC R&D program. They were wound from prereacted cable, incorporating "dog-bone" (flared) coil ends to minimize sensitivity to strain by maximizing the winding radius; however, they were not deployed in finished dipoles.[22] An example of a dipole of the same vintage constructed by the wind and react technique is one constructed at LBL.[23] A quite recent example of wind and react Nb_3Sn dipoles is a 1-m model for the Large Hadron Collider (LHC) project at CERN, constructed under a collaboration between CERN and the Austrian firm ELIN; this dipole reached the nominal design field of 10 T at 4.28 K.[24] Nevertheless, the feasibility of utilizing Nb_3Sn successfully in accelerator magnets on a

production basis cannot yet be said to have been convincingly demonstrated after all this time, and there are grounds for believing that the brittleness problem will be even more acute for the ceramic superconductors due to their high chemical reactivity (Section 2.3).

3.5 Quench Protection

Perhaps the most serious consequence of the hypothetical high-temperature operation concerns quench protection. As already noted in Section 2.4, the high operating temperature T_{op} has two consequences: first, it reduces the function $F(T_{op}, T_{max})$, hence the time τ needed to dump the current before the temperature exceeds the maximum allowable value T_{max}.

Thus
$$\frac{F(T_0 = 77, T_{max} = 300)}{F(T_0 = 4, T_{max} = 300)} \sim 1/2 \ .$$

Reducing T_{max} exacerbates the problem:
$$\frac{F(T_0 = 77, T_{max} = 100)}{F(T_0 = 4, T_{max} = 100)} \sim 1/10 \ .$$

Second, the propagation velocity of the normal zone is reduced by several orders of magnitude, essentially in proportion to the increase in specific heat capacity. These facts conspire to eliminate the possibility of relying on a "passive" quench-protection system, such as is currently proposed for the SSC. More than that, they render the feasibility of a workable quench-protection scheme for accelerator magnets an open question at this time.

3.6 Economic Analysis

In their first pass at an analysis of the high-temperature SSC scenario, McAshan and VanderArend concluded there would be a savings on the initial capital cost of the collider facility (technical components and conventional facilities totalling $2000 M in the Conceptual Design Report of 1986) of approximately $213 M: $187 M in savings on technical components, including magnets and cryogenics; $16 M for conventional facilities; $10 M for system re-optimization. This savings is, however, partly negated by the cost of replacing the present high-vacuum system and particularly by the concomitant increase in ring-magnet aperture dictated by this replacement. These cost differentials have been estimated as follows[25]: $125 M for increasing the magnet aperture from 4 cm to 5 cm (also taking into account certain cost benefits accruing from a larger aperture); $26 M for the new double-walled beam tube and NEG pumps plus sundry support equipment; $5 M for R&D. Thus, the net price for providing distributed pumping is $156 M, making the net overall capital savings associated with the nitrogen temperature SSC $57 M, or about 3 percent of the total estimated cost of the collider technical and conventional facilities.

A further savings can be expected in operating costs, particularly in electric power. Assuming a base power cost of $50 per Megawatt-hour and supposing the helium plant operates 6000 hours per year with the ring at nitrogen temperature for the balance of the time, a savings of $11.1 M per year could be expected, compared to the liquid nitrogen scenario where the magnets are at operating temperature all the time. (In fact, projected SSC power costs in the Dallas-Fort Worth area are substantially lower than McAshan and VanderArend's assumed base cost, but the order of magnitude savings estimate is not

appreciably affected.) Additionally, savings of roughly the same amount, $10.3 M per year, might accrue from savings on staff, materials, and services (estimated simply as 10 percent of the cost of these items in the CDR). Finally, savings of $6.1 M per year were estimated on maintenance and higher expected physics output due to the higher reliability of the simpler 77-K cryogenic system, bringing the total savings on operating costs up to $27.5 M per year, or approximately 10 percent of the projected annual operating cost of the SSC.

Thus, the savings to be expected from a liquid-nitrogen supercollider are barely significant, considering the uncertainties in the original cost estimate for the SSC and the specific assumptions constituting the high-temperature scenario. This is not particularly surprising, since the cost of the collider is driven by the capital cost of the superconducting magnets, not by the cryogenics and associated power costs. The cost of the helium refrigeration system equals roughly 10 percent of the cost of the technical systems, while the magnet system represents nearly 60 percent of the facility cost—and of that, fully 30 percent is associated with the basic NbTi alloy. Ergo, for a replacement scenario to have significant economic impact on the SSC, it must reflect the higher H_{c2} of the oxides and invoke improvements in critical current and other material parameters, not the transition temperature alone—in short, the replacement must be predicated on higher field (or much lower cost of material), not temperature.

4. High-Field Operation

4.1 Introduction

We turn, therefore, to an alternative replacement scenario, namely that of Meuser *et al.*,[26] predicated on high-T_c materials capable of operation at higher bending fields than the value B_0 = 6.6 T presently specified in the CDR. The attendant reduction in ring size might be assumed to lead to reduction in overall cost. Alas, this too proves doubtful even under the fundamental supposition—optimistic at best—that the critical current density remains ~2.75 x 10^3 A/mm^2 at 4.2 K *independent of field strength* and at the presently quoted unit cost of NbTi.

4.2 Economic Analysis

In their analysis, Meuser *et al.* categorize the various collider systems according to whether their costs scale with field or are independent of field. The basic CDR dipole design (and its cost) is taken as the starting point, and the current density is held constant while the magnet cross section (coil, collar, iron yoke) is scaled with field from 6.6 T to 14.2 T; that is, the collar is scaled with total Lorentz force such as to maintain adequate circumferential prestress to prevent azimuthal separation of coil from collar at the pole, and the (infinite μ) yoke I.D. is scaled to maintain constant flux density on the yoke midplane. The CDR component costs were scaled first with the various changes in dimensions using plausible scaling factors (e.g., coil cost proportional to volume of superconductor, beam tube cost independent of field), and then field-dependent technical systems and conventional facilities were scaled inversely with field as the 20-TeV collider ring shrinks in circumference. The results are summarized in Figure 4-1, where the costs of the various field-dependent systems are plotted against field strength (items in Table V, Part I in Ref. 26). As can be seen, the cost of the magnet system rises faster with field than does the savings in conventional facilities, owing to the rapidly rising cost of supporting the Lorentz forces (which go as B^2) and of containing the return flux.

4.3 Forces in Dipole

As noted, the high-field scenario of Section 3 was predicated on maintaining constant current density (the CDR value) as the radial thickness of the coil grows to accommodate the increasing current; the forces are transmitted to the collars which, in turn, are scaled in thickness with total Lorentz force to ensure that the azimuthal prestress in the coil dominates over the azimuthal Lorentz force component. It is implicitly assumed in all of this that the superconductor composite maintains adequate breaking stress (Section 2.4); Green recommends[27] an ultimate breaking stress in tension in excess of 3×10^8 Nm^{-2}. For comparison, at the highest field in the analysis by Meuser *et al.*, 13.7 T (not necessarily advocated by them as a practical maximum operating field), the magnetic pressure, $B^2/2\mu_0$, is 7.8×10^7 Nm^{-2} or twice the yield strength of annealed copper.

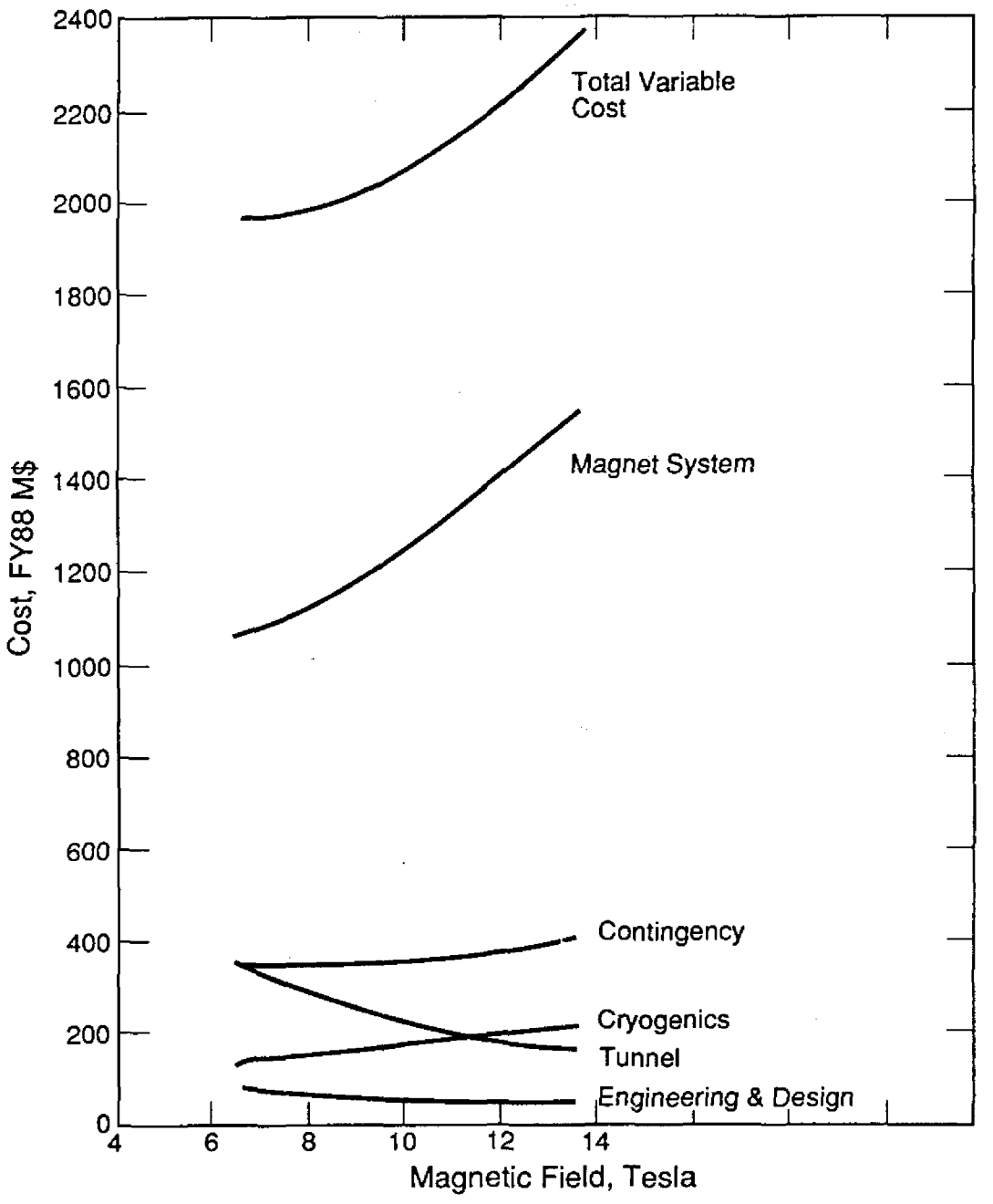

Figure 4-1. Field-dependant system costs versus dipole bending field. To obtain total fixed and variable costs, add 1235 M$ at each field value.

It may be noted that the maximum operating field level contemplated for the Large Hadron Collider under study at CERN is in the range 8–10 T,[28] to be achieved either with NbTi at superfluid temperatures or Nb_3Sn at 4.5 K (the alloy and compound exhibit comparable J_c values at 10 T).

4.4 Vacuum and Refrigeration Considerations

In contrast to the high-temperature scenario, the high-field scenario discussed here avoids the vacuum problem associated with liquid-nitrogen operation, since the liquid-helium refrigeration system is retained. However, the synchrotron radiation heat load is already significant at 6.6 T and since the energy loss scales linearly with field, the demands on the refrigeration system rise correspondingly, as reflected in Figure 4-1.

4.5 Additional Remarks

The cost and technical implications of the two scenarios treated here, high-temperature operation at "low" (6.6 T) fields and high-field operation at low (liquid-helium) temperatures, render another untreated scenario moot, namely high-field operation at high (liquid-nitrogen) temperatures. (Room-temperature operation is ignored as a high-T_c operational scenario in this report.) Note also the strong reduction in J_c with increasing temperature between 4.2 K and 77 K (Table 2-2). In addition J_c, as noted earlier, is strongly dependent on field strength—far from constant as optimistically assumed here. But perhaps the greatest flaw in all treatments to date is that of assuming a direct conductor replacement scenario in magnets whose design is predicated on today's NbTi or Nb_3Sn. It would seem more reasasonable to assume that dipole designs based on oxide superconductors will be very different from the usual constant current density or cosine theta configurations presently dominating superconducting accelerator magnets; perhaps better prototypes are the so-called superferric magnets or similar dipole designs incorporating simpler coil configurations.

5. Special-Purpose Applications

5.1 Large-Scale and Laboratory-Scale Applications

The bottom line of the foregoing must be the doubtful feasibility of harnessing the ceramic oxides for accelerator dipoles and quadrupoles in the foreseeable future, on account of their unacceptable current density and quench protection properties, with poor prospects for significant improvements after several years of worldwide effort, coupled with their inherently brittle nature, which well-nigh dictates wind-and-react with its own problematic effects. For the same reasons, the ceramics appear unpromising for very-high-field magnets generally, including large solenoids, D-coils for Tokamaks, and the like. However, their eventual application in various low current density laboratory solenoids, in small systems where the refrigeration costs constitute a large fraction of the total system cost, cannot be precluded—indeed, is sure to come. Crude prototypes already exist in the form of simple ceramic coils constructed from rings or spirals of $YBa_2Cu_3O_7$ material, energized by induction or D.C. current.[29] Coils have also been wound from "wire" produced by co-drawing $YBa_2Cu_3O_7$ powder in a normal metal tube with a diffusion barrier; the coil is subsequently heat-treated.[30]

One area of potential magnet application relevant to the SSC is in the cryogenic current leads for conventional, helium-cooled superconducting magnets generally, and for the superconducting bus between magnets in a string of accelerator magnets such as in the SSC lattice.[31]

Another area receiving recent attention is the application of the high-T_c materials in superconducting permanent magnets—an old idea involving trapped fields in superconducting shells, cylinders, or short-circuited coils. Hitherto, the low value of the first flux jump field[32] for conventional type II superconductors (0.5–1 T) has thwarted their utilization for this purpose. However, the fact that the flux jump fields for the oxide superconductors should be substantially higher (4–9 T) at 77 K warrants reconsideration of this interesting option.[33] One potential application in high-energy physics might be for permanent magnet-focusing quadrupoles for drift-tube linear accelerators.

5.2 Microwave Cavities

In recent years radiofrequency (RF) superconductivity has progressed to a state of maturity where low-loss niobium RF cavities can be utilized in the design and construction of linear accelerators with substantially higher accelerating gradients (in CW or long-pulse operation) than hitherto possible with room-temperature cavities. The possibility of replacing niobium by one of the ceramic materials will depend on whether adequate low-loss performance (surface superconducting properties at microwave frequencies) can be obtained with them. Concomitant improvement in linac performance could be of great significance for future injectors—e.g., for the SSC—for recirculating linear accelerators for nuclear physics, and for the expected next generation of linear colliders.

Until recently, the relevant RF properties of the oxides have been largely unknown, except for some weak evidence that their surface will have to be greatly improved to make this application possible.[34] However, the RF behavior of $YBa_2Cu_3O_7$ is presently under study at Cornell, among other places, with the focus on single crystals and thin films at

1.5 GHz and 6 GHz.[35] The most promising results have been obtained for the single crystals, which show a residual resistance at 6 GHz and 77 K substantially below the resistance of copper at that temperature, and the sharpness of the drop in resistance at the superconducting transition comparable to that of niobium. It is believed that the crystals are still far from ideal, and their properties appear to deteriorate with time.

6. R&D Issues

6.1 Conductor

From the point of view of large-scale, high-field technological application, the two pressing issues concerning the high-T_c materials are their poor critical current densities and their brittle nature. Both issues are being intensely pursued in ongoing worldwide research on high-T_c superconductivity. With regard to the first issue, the starting point is the classical type II superconductor, whose high-J_c values are made possible by deliberately introduced (by cold working and heat treatment) pinning centers—inhomogeneities or defects in the crystal lattice that provide a pinning force that counteracts the $J \times B$ Lorentz force arising from the simultaneous presence of current and field in this class of superconductor. The relevant and apparently inadequate defects for $YBa_2Cu_3O_7$ and the newer triple-digit materials have until recently been poorly understood, but there is ground for optimism that the pinning behavior can be improved with the introduction of artificial defects.[36] The short coherence length suggests that even defects on the scale of single atoms may be important.[37] One structural defect on this scale is "twinning" (stacking defects) between the copper-oxygen planes. Moreover, the possibility exists of counteracting the anisotropy by orienting the crystal grain structure. One possibility, melt-textured growth with its improvement in J_c, was noted earlier. Another is alignment by magnetic means, taking advantage of the magnetic anisotropy of the material in the normal state.

New developments during the past year may also throw new light on the critical current question. Experiments on single crystals (magnetization and resistivity measurements, as well as direct "magnetic decoration" experiments) suggest that the behavior of the oxide superconductors in a magnetic field may in fact be fundamentally different from that of conventional type II superconductors.[38] In conventional type II materials, resistivity due to flux creep (flux motion from thermal activation when the pinning force exceeds the Lorentz force exerted by the current on the flux lines) is very small due to the strong pinning. By contrast, in the superconducting oxides, the flux creep appears larger by an order of magnitude; high flux creep may be an intrinsic property of these materials, and a consequence both of their high critical temperature and small coherence length.[39] Furthermore, since the high flux creep arises from thermal activation, it should increase with temperature.

Indeed, it has become customary to speak of the "melting" of the flux lattice. For conventional type II superconductors, the lattice melting temperature is comfortably above the critical temperature. However, the lattice of YBaCuO melts slightly below the temperature of LN_2, and the bismuth and thallium-based materials have lattice melting temperatures around 30 K—far below their T_c.[40]

These developments may provide a fresh explanation of the low critical current densities encountered in high-T_c superconductors exposed to a magnetic field: degradation of J_c by thermal dislodgement of the flux lines (vortices) from their pinning centers due to inherently low pinning barriers. At the same time, they may point to new pinning mechanisms or suggest that additional pinning centers are needed to improve the presently bleak critical current performance—at least for certain applications (thin films in particular). In some circles there is nervous optimism for the superconductor to arrange itself

into a "vortex glass state" of pinning largely devoid of flux creep. Perhaps the thin films border on such a state.

Despite much progress, the brittleness problem remains a pervasive and extremely challenging issue. Fortunately, guidance is provided by the materials technology evolved with the conventional A-15 compounds, augmenting the extensive available ceramic technology. The principal issues with respect to accelerator magnets, as in the case of Nb_3Sn, will be whether "react and wind" proves viable, and the feasibility of processing the new materials in fine filamentary form. Other areas of concern for this particular application include the sensitivity of the new materials to neutron damage[41] and their reactivity and chemical and thermodynamic stability in general.

6.2 Magnets

The outstanding issue here remains that of quench protection. Another issue pertinent to large-scale systems operation and particularly relevant in the case of $YBa_2Cu_3O_7$ is that of the temperature margin for operation in liquid nitrogen where $T_0/T_c \sim 77$ K/95 K = 0.81. Here the triple-digit materials offer promise, with T_c in the range 110–125 K. Alternatively, the limited temperature margin for the 1-2-3 compound at 77 K suggests examining the possibility of operating at substantially lower temperatures. Thus, at 20 K, $T/T_c = 0.21$—the equivalent of NbTi or Nb_3Sn at 4.2 K ($T/T_c = 0.45$ and 0.23, respectively). At this temperature thin films of $YBa_2Cu_3O_7$ are projected to carry significantly more current density than Nb_3Sn at 4.2 K.[42] Unfortunately, liquid hydrogen, though possessing excellent cryogenic properties, is highly flammable. Its nearest competitor, liquid neon (boiling point ~27 K), is both expensive and a poorer cryogen.

7. Conclusions

We conclude, on the basis of the current state of development of the oxide superconductors, that their utilization in what amounts to replacement scenarios in today's class of accelerator magnets—constant current density dipoles, cosine theta magnets, or saddle coils generally—does not appear promising for the foreseeable future. To be sure, progress is being made in the two areas of greatest technical concern for high-field utilization. New innovative processing techniques could well alleviate, if not obviate, the acute brittleness problem, and progress in understanding pinning mechanisms is likely to throw fresh light on the bulk critical current problem. Even so, several pervasive factors will most likely conspire to negate high-field applications on a large scale. Quench protection will remain problematic at elevated (liquid-nitrogen and higher) temperatures, in the absence of viable alternative design concepts, as will structural and other factors at high ($\geq$ 6.5 T) magnetic fields. Furthermore, wind and react, the only viable magnet fabrication approach, is incompatible with the precision requirements of accelerator magnets and particularly so with the superconducting oxides. In this regard, we acknowledge the CERN/ELIN Nb_3Sn magnet[43] and the fact that wind and react Nb_3Sn remains the basis for one of several magnet technologies still under consideration for the LHC (Section 4.3).

The oxides may well find eventual application in solenoids and other laboratory magnets of low current density, simple geometry, and under conditions in which the refrigeration system occupies a significant fraction of the system cost. In our opinion, however, the most promising route to applied high-T_c superconductivity is by exploiting thin films where the superconducting and materials properties attain optimum values or are most amenable to manipulation.

In the longer run, in view of the formidable resources and materials effort being brought to bear on the ceramic materials in this country and abroad, new and novel applications cannot be discounted—not even high-field applications. Nor, for that matter, can we assume that the impact of high-T_c superconductivity in elementary particle physics needs necessarily to be restricted to potential applications to the technology of particle accelerators. Progress in particle physics over the past twenty-five years has to a remarkable extent benefitted from appropriating concepts of condensed matter physics, including Ginzburg-Landau as well as BCS theory,[44] and the theoretical interpretation of high-T_c superconductivity remains as vexing as the material properties involved. If events of the past several years are a guide, we can be confident of wondrous developments in applied *and basic* superconductivity in years to come, and, as was true for metallic type II superconductivity, particle science will both contribute to and benefit from these developments.

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