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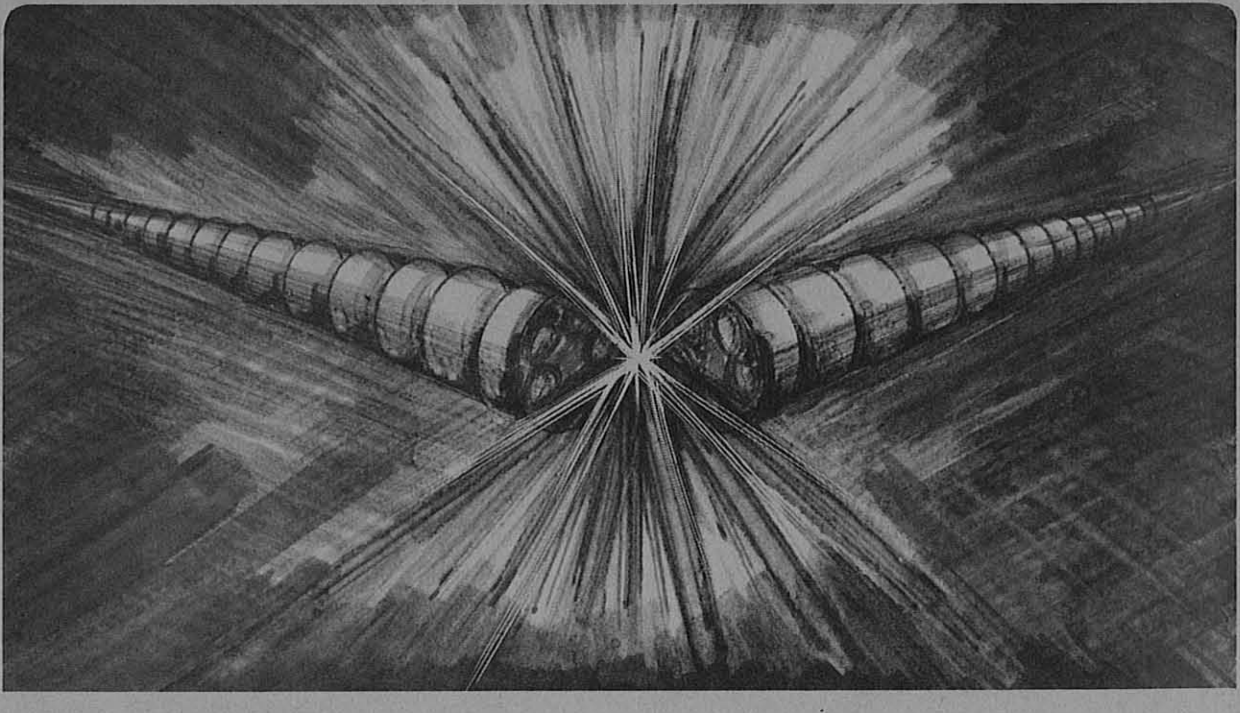

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INTRODUCTION

In this paper we survey the high field superconductors which could possibly be used in accelerator dipole magnets, and then we rank these candidates with respect to ease of fabrication and cost as well as superconducting properties. We will present only a summary of results; references will be listed for those who wish more detail. The superconducting properties[1] which are important for applications involving electromagnets are transition temperature, T_c, upper critical field, H_{c2}, and critical current density, J_c. The first two are often referred to as "intrinsic" properties because they are determined by the chemical composition and are not strongly dependent on the microstructure, as is the case for J_c. However, in addition to these properties, the superconductor must have a high J_c and also be capable of manufacture at a reasonable cost.

A major difference between NbTi and the other potentially useful superconductors is its ease of fabrication. NbTi is a ductile alloy which can be processed from cm-size rods to micron-size filaments by standard extrusion and cold drawing techniques. On the other hand, the other high-field superconductors are intermetallic compounds which can be deformed only about 0.2% in tension before they fracture and become useless in superconducting wires. In order to utilize these materials in the form of continuous multifilamentary superconductors, a number of special fabrication techniques have been developed.[1,2] Within the group of intermetallic compound superconductors, fabrication technology is most advanced for Nb_3Sn. We now evaluate Nb_3Sn and NbTi with respect to their near-term use in dipole magnets.

Nb_3Sn AND NbTi CONDUCTOR FABRICATION

Several processes have been developed which allow Nb filaments to be fabricated and then converted to Nb_3Sn after mechanical deformation is complete. In the first, called the "bronze process", Nb filaments are processed in a bronze (Cu-13 wt % Sn) matrix and then reacted typically at 650-750°C for 10-100 hrs. to form the Nb_3Sn superconductor. This process is well established in industry and has been used to fabricate about 10 tons of superconductor compound, primarily for fusion research magnets.[3-5] Note, however, that this amount is still small in comparison with the quantity necessary for an accelerator the size of the SSC, i.e., between 250 and 500 tons of Nb_3Sn compound, depending on operating fields (see Table 1). Two major limitations of this process are (1) the limited ductility of bronze requires many costly intermediate anneals during wire drawing, and (2) the need to co-process with bronze means that the overall current density is reduced.[2] Alternate processes are under development, and the most advanced is the "internal tin process" in which pure or low-alloy Sn is co-processed with Cu and Nb. Problems associated with bronze processing, such as limits on Sn content, limited ductility, and the risk of Nb_3Sn formation during bronze annealing,[6] are avoided. Approximately 1 ton of material has been processed using this technique and several fabrication problems have been identified. [Ref. 7, paper by M. Suenaga, these proceedings.] Another fabrication approach [8] which is under development utilizies Nb tubes filled with $NbSn_2$ powder or alloyed Sn; the material is processed to wire and the powder or Sn reacted with the Nb tube wall to produce Nb_3Sn. Although laboratory processing has produced approximately 100 lbs. of material with very good J_c values, many production problems remain, such as quality control on the powder and limits on filament diameters achievable using a tube approach.

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Table 1. Production Status of Superconductors

	Fabricability	Quanitites of Alloy or Superconductor Compounds Produced	Present Cost
NbTi	Excellent (ductile alloy, compatible with Cu)	Present rate 35 tons/yr NMR HERA requirement 50 tons	\$60 - \$80/lb.
NbTiTa	Good, but not as ductile as NbTi	< 1 ton	\$150/lb.
Nb_3Sn	Special fabrication techniques are necessary to avoid brittle phase	4 tons MFTF, HFTF, 5 tons LCP	\$250 - \$600/lb.
V_3Ga	Special fabrication techniques are necessary to avoid brittle phase	Approximately 100 kgm	\$1000/lb.
Nb_3Al	Special fabrication techniques are necessary to avoid brittle phase	Approximately 20 kgm	?

NOTE: SSC requirements for 6.6 T magnets are ~ 2000 tons of NbTi wire or ~ 800 tons of NbTi alloy.

The time scale for the evolution of these processes for fabrication of multifilamentary Nb_3Sn has been quite long; the bronze process was initially proposed about 1970,[9,10] the Nb tube-$NbSn_2$ powder process in 1975, and the internal-tin process in 1974.[11] The long development time is due in part to the rather complex and lengthly processing required for Nb_3Sn and in part to the lack of a strong demand for this type of conductor. As a result, the industrial base does not appear adequate for producing the 250-500 tons of Nb_3Sn compound (1000-2000 tons of wire) which would be required to begin construction of the SSC in 1988.

On the other hand, the industrial fabrication of NbTi is well developed with about 35 tons/yr being produced, largely for NMR tomography applications. In addition, recent results from the SSC related R&D program[13-15] show that significant improvements in NbTi are possible. These improvements will now be described.

In the first phase of the SSC-related conductor R and D program, the effort was focussed on improving the $J_c(5T)$ from a value of about 1800 A/mm^2, as specified for the Tevatron and CBA strands, to a value of greater than 2400 A/mm^2, chosen as the target specification in the May 1984 Reference Design Study. This goal was achieved for strands with filament sizes in the range 15-22μm by a combination of improved NbTi alloy and an alternate heat treatment schedule developed by Larbalestier and co-workers.[13] The reproducibility of these results was demonstrated by the fabrication of 14 production-size billets between July 1984 and September 1986 as shown in Fig. 1.

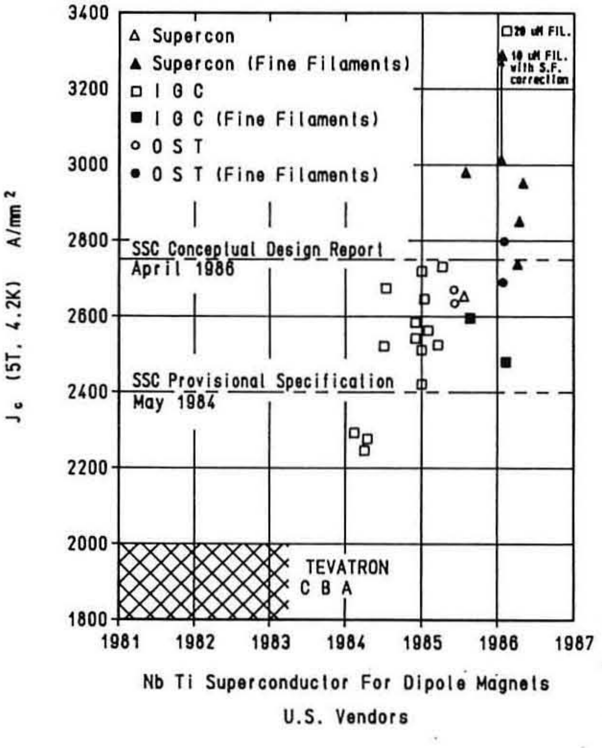

Fig. 1. Summary of the improvements in NbTi J_c as a result of the SSC-related R&D efforts described in the text.

The next phase of this R and D effort was focussed on the process changes necessary to achieve high current densities at fine filament sizes, e.g., less than 10μm. A number of approaches were evaluated; these are discussed in more detail in Ref. 14-16 and two other papers in these proceedings.[17, 18] The goals of this work are to (1) maintain filament quality at fine diameters by eliminating the formation of intermetallic compounds at the Cu-NbTi interfaces, and (2) develop reliable and cost effective methods for obtaining large numbers of filaments in a single strand. As indicated in Fig. 1, several different approaches have been evaluated and were found to produce fine filament material with high J_c values.

IGC[18] used a double stack approach whereby a 19 element billet was extruded and cold drawn to produce stacking elements for a second billet. This approach yielded wire with $J_c(5T)$ values in the range of 2450-2550 A/mm^2, and with n values in the range 20-25. These values are to be contrasted with $J_c(5T)$ values of 3300-3400 A/mm^2 and an n value of approximately 70 for the 19 element first extrusion material which was processed to a fine wire size without being reextruded. Further analysis showed a tendency for the outer layer of filaments in the 19 element subassembly to exhibit sausaging when the double extrusion material was processed to a fine filament size.

An alternate approach, developed at Supercon on an LBL-funded R and D contract, consists of improving conventional billet stacking technology so that 20,000 - 40,000 filaments can be stacked in a single billet (in contrast to 55 - 2,000 elements previously stacked in single billets). This approach has proven to be very promising, both in terms of the J_c and n values achieved and in terms of cost-effective fabrication. The $J_c(5T, 4.2K)$ and n values range from 2700 A/mm^2 and n = 57 for billet LBL-2 to $J_c(5T, 4.2K) = 3450$ A/mm^2 and n = 57 for billet LBL-1 (see Ref. 17 for more details). The results of this R and D program provide the experimental justification for the choice of the SSC design parameters $J_c(5T, 4.2K) > 2750$ A/mm^2, $J_c(8T, 4.2K) > 1100$ A/mm^2, and a filament size of 5 μm. Additional production-size billets are being fabricated in order to establish reproducibility of these results and to determine the most cost-effective approach for fabrication of fine filament conductors by this large single stack method.

EXISTING NbTi AND Nb_3Sn MAGNETS FOR FUSION AND FOR ACCELERATORS

NbTi is the "workhorse" of the superconducting materials industry and accounts for over 90% of the conductor that has been produced. Several thousand magnets of various shapes and sizes are currently in use, and no attempt will be made to describe these in detail. Three cases that are most relevant for evaluating the suitability of NbTi for the SSC magnets will be mentioned; these are the Tevatron accelerator, the HERA Project and the results of the SSC R&D program. About 1000 magnets were built and are operating in the Tevatron at Fermilab. An additional about 800 magnets will be constructed over the next several years for the HERA Project at DESY. During the last 18 months, 12 dipole magnets 1 m in length (LBL) and 8 dipole magnets 4.5 m long (BNL) have been built and tested as part of the SSC R&D program.[19] All these magnets performed as expected and indicate, with the improved NbTi superconductor now being delivered, that the SSC design goals can be met with an adequate safety margin.[21] Currently, Nb_3Sn is being used where the magnetic field requirements are beyond the capability of NbTi. These applications are mainly laboratory R&D solenoids and magnets for fusion experiments. In the fusion area, Nb_3Sn coils using a reacted Nb_3Sn conductor were built for the High Field Test Facility (HFTF)[22] (11.5 T) and Mirror Fusion Test Facility (MFTF)[23] (12.0 T) at Lawrence Livermore National Laboratory, and for the Large Coil Program (LCP)[24] (8.0 T) at Oak Ridge National Laboratory. The large diameters of these coils and the rugged design of the conductor permitted the use of a reacted Nb_3Sn superconductor. Most accelerator dipole designs require that the conductor be bent around a relatively small diameter at the ends and that the conductor be somewhat less robust than the conductors used in the fusion coils (to achieve a higher overall current density). This has led to R&D efforts aimed at building accelerator coils by two different methods, react-after-winding and wind-after-reacting. React-after-winding dipoles have been built at Saclay[25] and LBL;[26] a quadrupole using this approach was built at CERN.[27] Wind-after-reacting dipoles were built at BNL in 1978 and more recently in the early stages of the SSC R&D program. The results of these projects can be summarized as showing progress, but requiring more R&D before success is assured. Long models using the react-after-winding approach are necessary to demonstrate that the differential thermal expansion and void-free epoxy impregnation problems can be solved. Additional work employing the wind-after-reacting approach is necessary to demonstrate that coil fabrication can be accomplished without seriously degrading the Nb_3Sn superconductor.

COMPARISON OF PERFORMANCE OF Nb_3Sn WITH NbTi FOR SSC DESIGN D MAGNETS

Of primary interest in the evaluation of different superconductor materials is to investigate the performance in an SSC magnet design. Figure 2 (based on data provided by C. Taylor for the SSC Conceptual Design Report) attempts to provide such an evaluation. Here we have shown the critical current performance for NbTi based on a wire current density of 2750 A/mm^2 at 4.2 K, 5 T. These data have been plotted at fields from 3 to 8 Tesla using a field enhancement factor in the magnet of 1.045 x B_0, and have been adjusted for the magnet operating temperature of 4.35 K.

The Nb_3Sn critical current line has been plotted using the same field enhancement and temperature corrections; it has been normalized to J_c = 865 A/mm^2 at 4.2 K, 10 T. This J_c[7] is the value measured for strand fabricated using the internal tin process with filament spacing designed to reduce magnetization to acceptable levels. The 10T current density intercepts for Nb_3Sn conductors produced by alternate methods are indicated on the right side of Fig. 2.

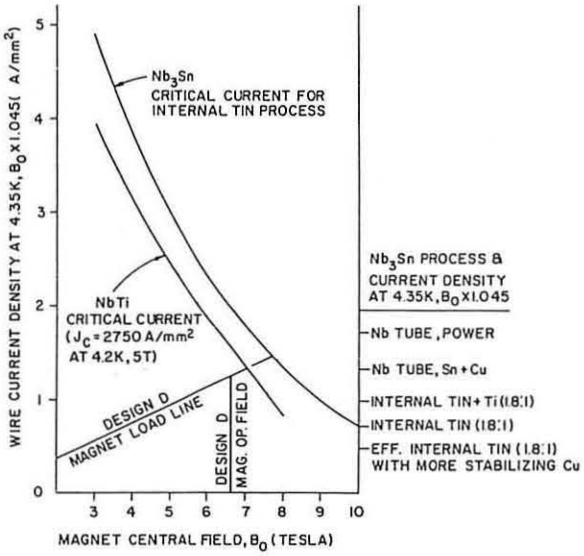

Fig. 2. Predicted performance of an SSC Design D magnet constructed of NbTi and Nb_3Sn. The critical current lines for NbTi and Nb_3Sn are for wire production methods currently well developed. Additional stabilizing copper would be required for Nb_3Sn effectively lowering the curve to the value indicated on the right.

However, those processes are not yet fully developed and are not in large-scale production. An important question that still remains is the amount of stabilizing copper required for Nb_3Sn magnets. The critical current line for Nb_3Sn in Fig. 2. is for wire with a copper-to-superconductor ratio of 1:1. This ratio is most likely too low for a 17 m long SSC dipole. The ratio is 1.3:1 for inner layer Design D magnet coils and 1.8:1 for outer layer coils; these values are found to be adequate for NbTi. Although there is considerable debate over the amount of stabilizing copper required for Nb_3Sn, a ratio of 1.5:1 is probably a reasonable requirement. This adjustment in the copper would effectively lower all points on the Nb_3Sn critical current line in Fig. 2. by a factor of 0.67. As a consequence, the SSC magnets would not be expected to perform significantly better with Nb_3Sn made by the present internal tin process than if they were constructed with currently available NbTi. Of course, improvements to the Nb_3Sn fabrication process, as indicated in Fig. 2, could eventually change the situation.

CONCLUSIONS

Among the available superconducting materials, NbTi and Nb_3Sn are the only ones which are available for large-scale production of accelerator magnets for SSC. For dipole magnets designed to operate in the 6 to 7 Tesla field range,the currently available Nb_3Sn produced by the internal tin process holds no advantages over the latest generation NbTi superconducting wire. The situation regarding choice of superconducting wires has changed significantly in the past year due to a large improvement in the current density of NbTi wires accompanied by reductions in filament size. There appear to be methods for improving Nb_3Sn further, possibly through addition of Ti. However, these improvements will require further R&D and 3 to 5 years of production scale-up depending on the level of the effort. For accelerator dipole magnets to operate in the 8 to 10 Tesla range, Nb_3Sn would hold the advantage over NbTi because of its higher critical field. However, the mechanical design and construction for such high field magnets present totally new challenges and would require significant additional magnet R&D. A final consideration is that magnets built with Nb_3Sn could operate at higher temperatures thereby leading to a reduction in operating costs for the SSC. There is optimism about perfecting the techniques for constructing accelerator magnets with Nb_3Sn using either the react-after-wind or wind-after-react methods. It would appear prudent to continue to pursue these development activities at a low level within the overall SSC R&D program to learn how to use brittle superconducting compounds in magnet construction. In fact, there might be a role for Nb_3Sn in SSC if it is necessary to construct a few special magnets with very high dipole fields or especially large quadrupole gradients. However, for perhaps the next few years there appears to be no practical alternative to the choice of NbTi for the magnets of the main lattice of the SSC.

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