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SURVEY OF HIGH FIELD SUPERCONDUCTING MATERIALS FOR ACCELERATOR MAGNETS

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I. Survey of High Field Superconductors

In this section we present a survey of 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. The relationship between H_{c2} and T_c for many potentially useful high field superconductors is shown in Fig. I-1. However, in addition to these properties, the superconductor must have a high J_c (see Section III) and also be capable of manufacture at a reasonable cost.

A major difference between NbTi and the other superconductors shown in Fig. I-1 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 (Fig. I-2). On the other hand, the other materials in Fig. I-1 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. (See Table I-1.)

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" (Fig. I-3), 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 I-2.) 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. (See Section III.) Alternate processes are under development, and the most advanced is the "internal tin process" (Fig. I-4) 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. (See Section III.) Another fabrication approach[7] which is under development utilzies 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 (Section III), many production problems remain, such as quality control on the powder and limits on filament diameters achievable using a tube approach.

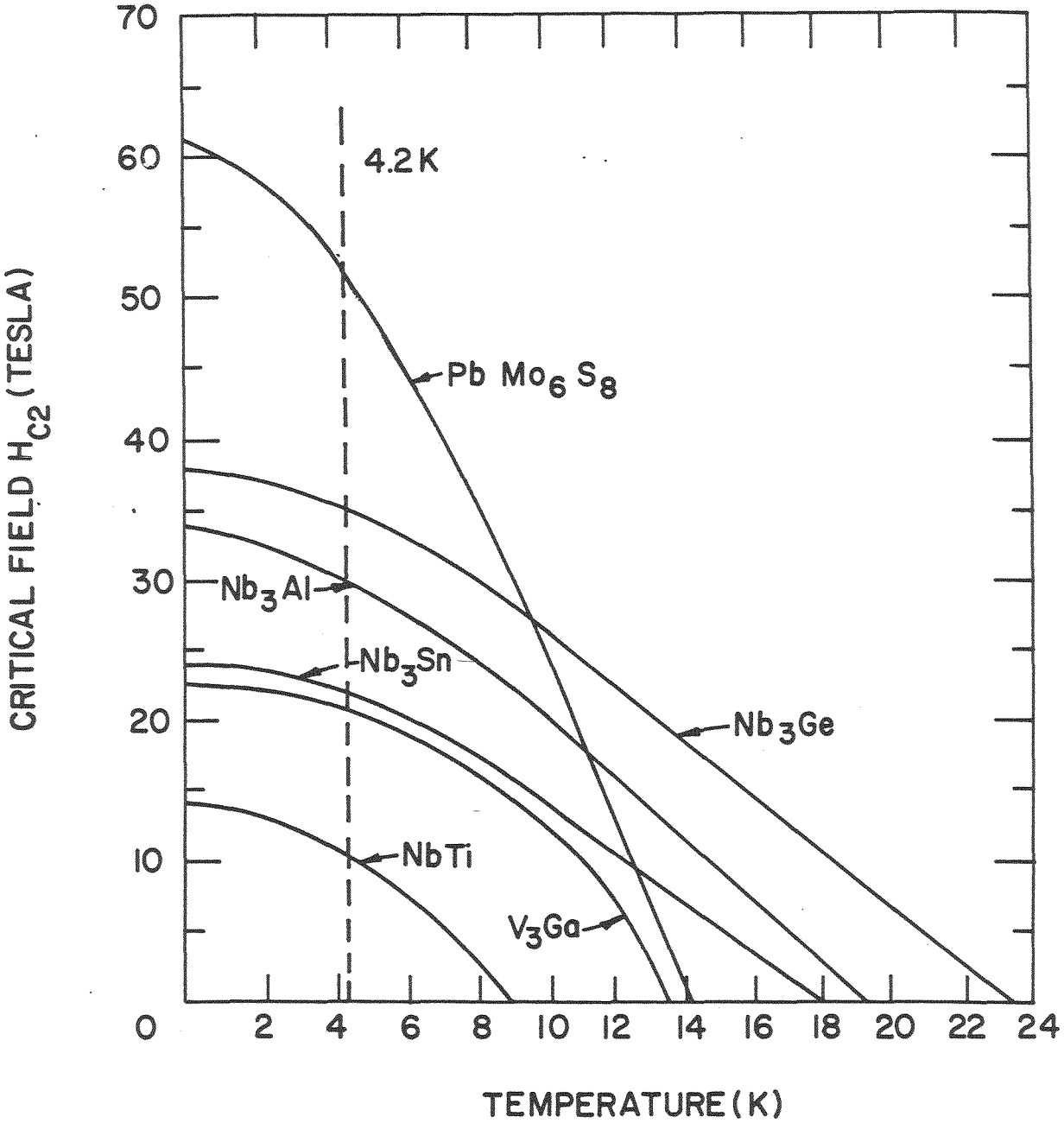

Fig. I-1. Critical Field Versus Temperature for Various High Field Superconducting Materials.

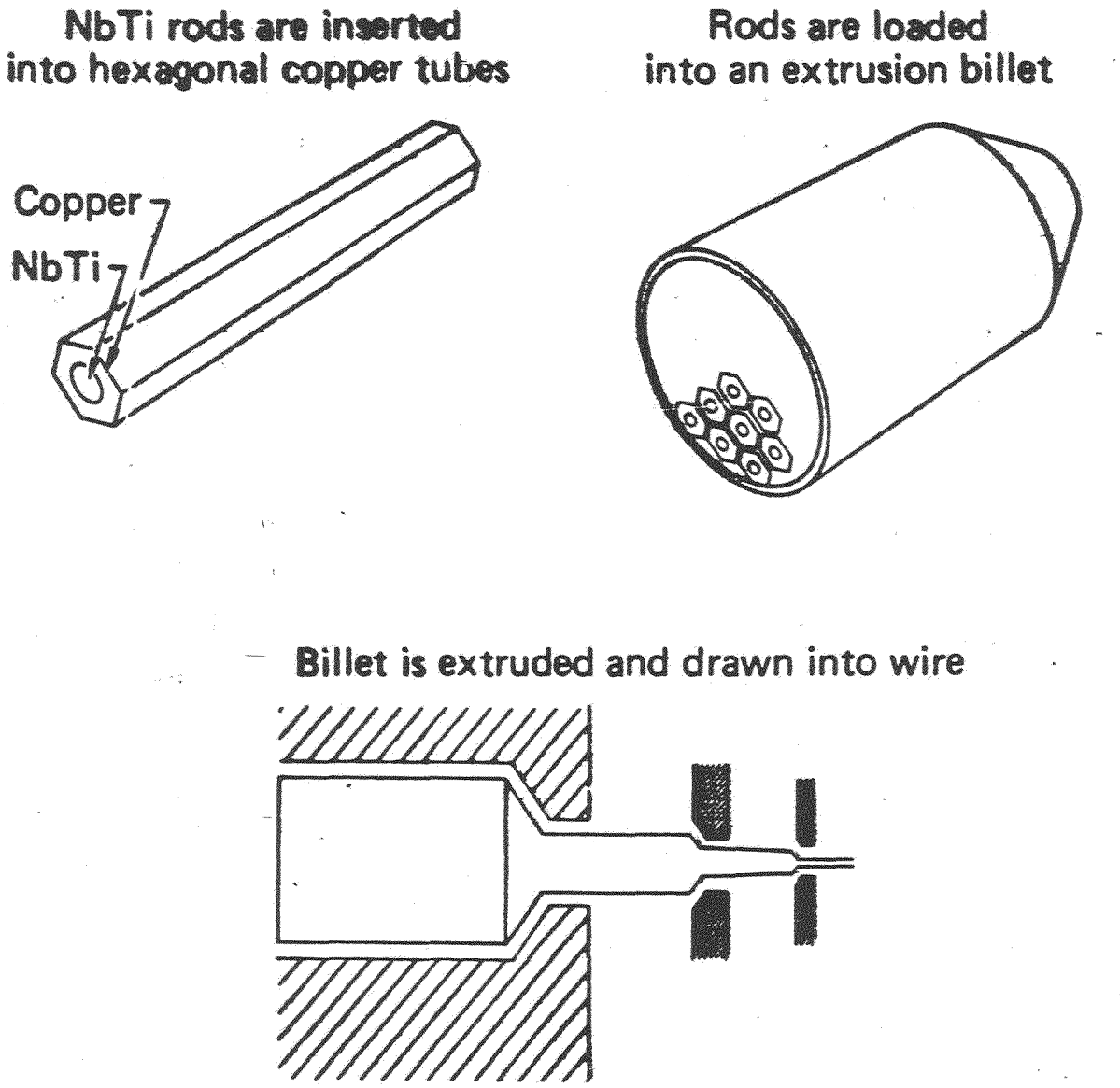

Fig. I-2. Schematic Diagram of the NbTi Wire Fabrication Methods.

Table I-1. Fine Multifilament Superconductor Fabrication Techniques

Material	Mechanical Properties	Fabrication Process	Remarks
NbTi	Very ductile	Conventional hot extrusion or hydrostatic extrusion followed by cold drawing	Versatile, cost effective processing.
Nb_3Sn	0.2% tensile strain limit before fracture	"Bronze" process	Many intermediate anneals are necessary.
		"Internal Tin" process	Redistribution of tin is necessary before conversion into Nb_3Sn.
V_3Ga	0.2% tensile strain limit before fracture	"Bronze" process	Best properties are with V-Ga alloy rods.
Nb_3Al	0.2% tensile strain	Nb, Al powder process	Lab scale demonstration only. High purity powders, good quality control required. Filaments may be electrically coupled.
$PbMo_6S_8$	0.2% tensile strain	Mo, MoS_2, PbS powders	Lab scale demonstration only. High purity powders, good quality control required. Filaments may be electrically coupled.

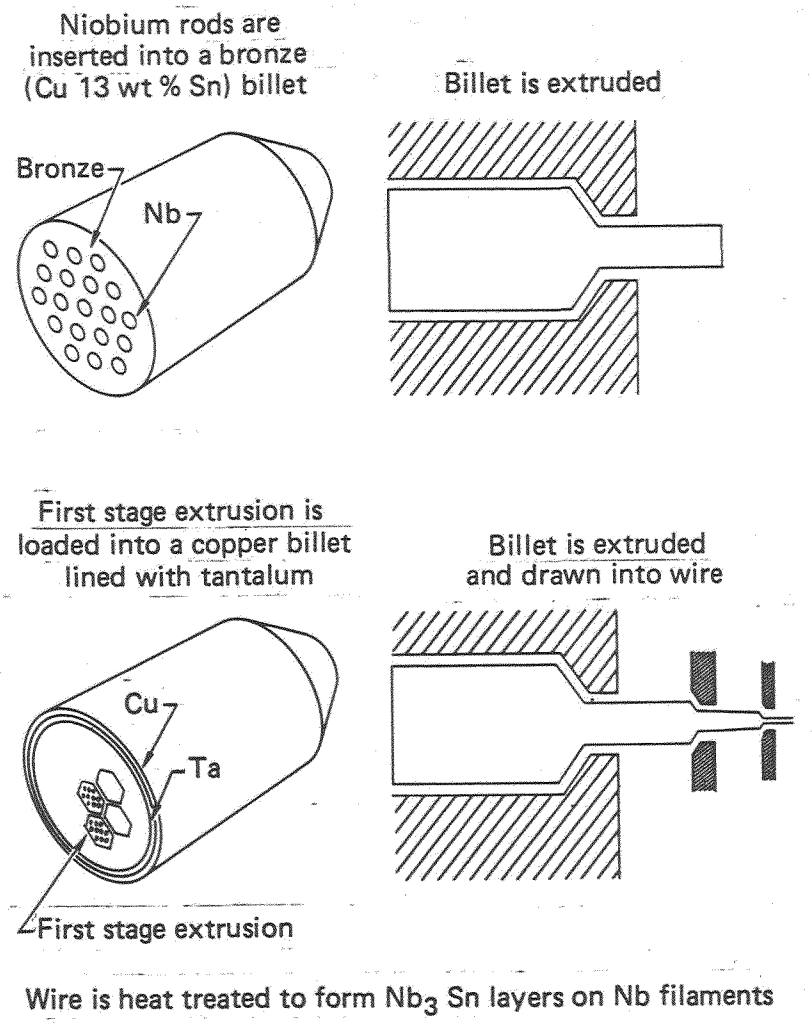

Fig. I-3. Schematic Diagram of the Nb_3Sn "Bronze Process" Wire Fabrication Methods.

"INTERNAL TIN" PROCESS

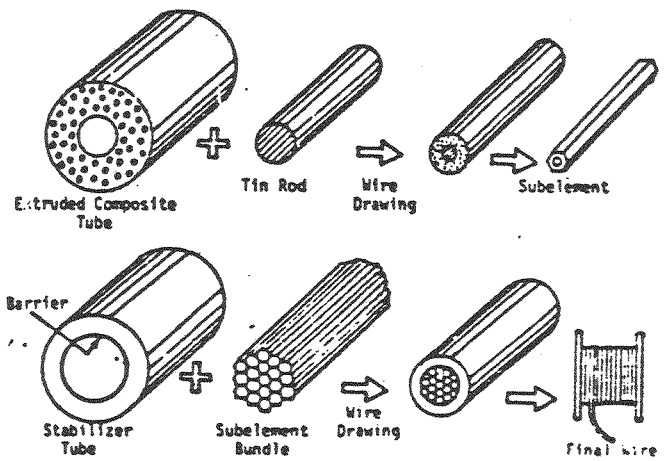

Fig. 1 A schematic diagram of the internal tin process.

Fig. I-4. Schematic Diagram of the Nb_3Sn "Internal Tin Process" Wire Fabrication Methods.

Table I-2. 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,[8,9] the Nb tube-$NbSn_2$ powder process in 1975,[7] and the internal-tin process in 1974.[10] 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[11] being produced, largely for NMR tomography applications. In addition, recent results from the SSC related R&D program[12-14] show that significant improvements in NbTi are possible. As shown in Fig. I-5, the critical current density J_c (5.0 T, 4.2 K) achievable in production-size billets has been increased from about 1800-2000 A/mm^2 (typical for the Tevatron and CBA conductor procurements), to 2400-2750 A/mm^2 for SSC R&D procurements. More recent results[15] with an R&D billet indicate that values as high as 3000 A/mm^2 are possible.

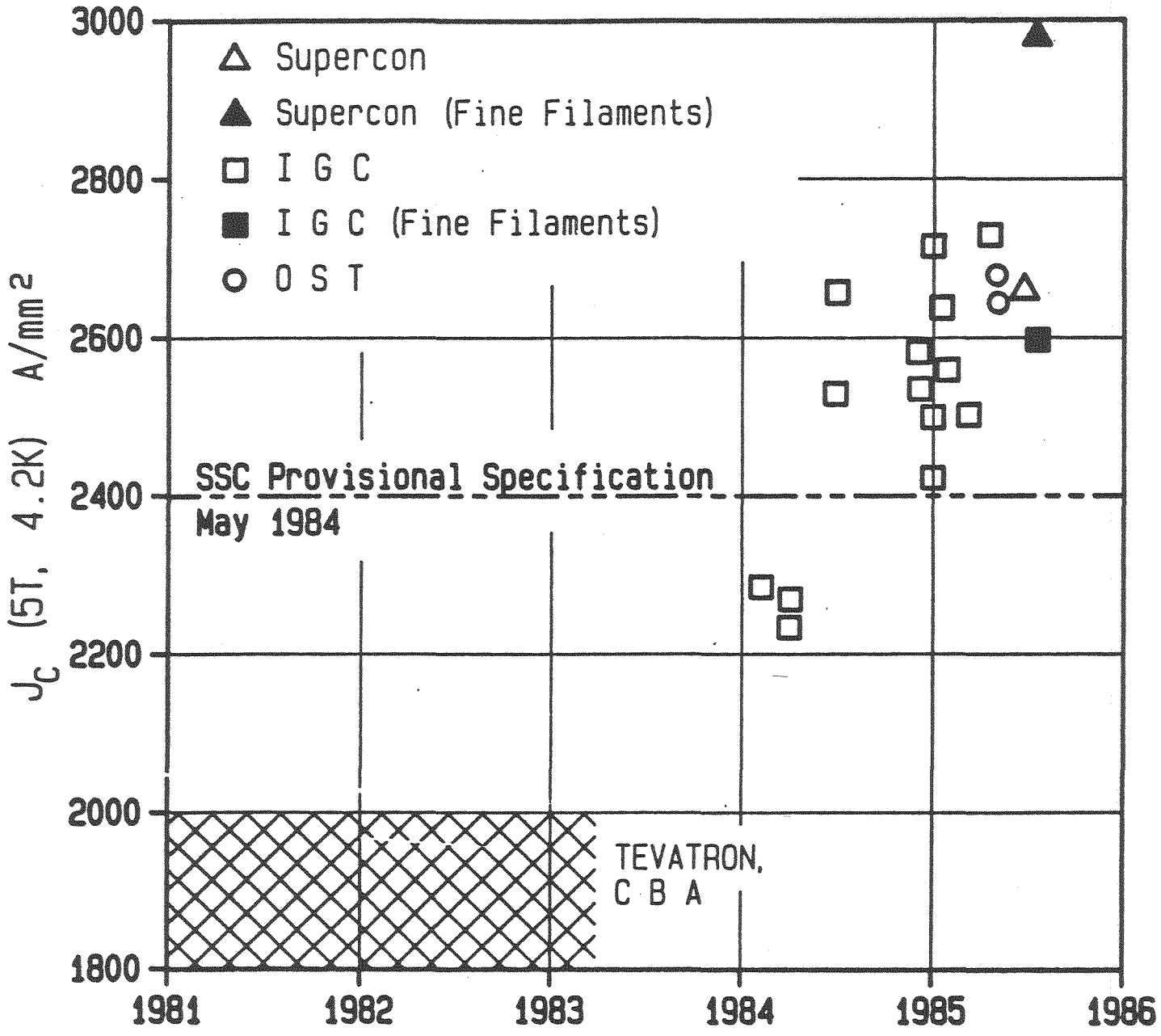

Fig. I-5. Improvement in the Current Density of NbTi Superconducting Wire Developed for the SSC R&D Program by U.S. Vendors.

II. Existing NbTi and Nb_3Sn Magnets

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, 8 dipole magnets 1 m in length (LBL) and 8 dipole magnets 4 m long (BNL) have been built and tested as part of the SSC R&D program.[16,17] 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.[18]

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)[19] (11.5 T) and Mirror Fusion Test Facility (MFTF)[20] (12.0 T) at Lawrence Livermore National Laboratory, and for the Large Coil Program (LCP)[21] (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[22] and LBL;[23] a quadrupole using this approach was built at CERN.[24] Wind-after-reacting dipoles were built at BNL in 1978 and more recently in the early stages of the SSC R&D program. (See Section IV.) 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. (See Section IV.)

III. Evaluation of Nb_3Sn Wires and Cables

A. Current Density of Nb_3Sn Wires Produced by Various Methods

Primary requirements for superconducting wires for construction of accelerator magnets are high current density, J_c, and small diameter filaments for low residual magnetic fields at injection. For Nb_3Sn wires in dipole magnets operating at $\sim$10 T, these requirements translate to $J_c \geq 1200$ A/mm^2 (preferably ≥ 1400 A/mm^2) and filaments of $\sim$ 2 μm in diameter. Available data on Nb_3Sn wires are discussed below in reference to these primary requirements.

As discussed in Section I, there are a number of existing methods for fabricating multifilamentary Nb_3Sn wires. Evaluation of superconducting

properties as well as metallurgical characterization of all these wires are continuously made at BNL. However, critical current densities for the wires which are made by three particular processes ((1) the bronze, (2) the internal tin, and (3) the Nb tube processes), will be discussed here. These are singled out since they represent the processes which have significant industrial production experience, may result in a significant cost reduction, or have shown possibilities of achieving the highest current densities among these Nb_3Sn wires. The results of critical current measurements as well as other pertinent physical parameters are given in Table III-1.

As shown in the table, it is encouraging to note that values of critical current density (for the area excluding stabilizing copper) of 1200 A/mm^2 or higher at 10 T are achievable in the wires which are produced by all of these processing methods. However, each process has some disadvantages in fabrication of wire suitable for accelerator magnets. (1) In spite of its relatively extensive production experience, the bronze process may result in more expensive wires, particularly in fabricating wires with Nb filaments as small as $\sim$2 μm. (2) In contrast to the bronze process, the fact that the internal tin process does not require intermediate annealing steps suggests the wires fabricated by this process could be made at a significantly lower cost than by the bronze process. However, it is not certain that coalescence of the Nb_3Sn filaments (thus increasing the effective size of the filaments) can be avoided without an unacceptable decrease in the value of J_c. (3) Although the value of J_c of the wires fabricated by Nb tube method are the highest ever achieved in any Nb_3Sn wires, the size of the filaments in the present wires is unacceptably large. If this aspect of the fabrication process is solved, this process can produce very interesting wires for accelerator magnets.

As described below, the shortcomings in the last two processes are being investigated at BNL.

B. R&D to Reduce of Effective Filament Size

The internal tin and the Nb tube processes have important advantages in relative ease of fabrication or of high current density. However, both of these processes produce large Nb_3Sn filaments which are undesirable for accelerator magnets. Thus, two R&D programs were carried out to improve upon this aspect of the fabrication methods. Following are summaries of the results of the investigations.

1. Internal Tin Process:

In order to study the possibility of reducing the effective size of the Nb_3Sn filaments in the internal tin process a set of Nb_3Sn wires was fabricated by Intermagnetics General Corporation (IGC) where the size of Nb filaments (4.2-2.2 μm), the interfilamentary spacing (2.4-1.2 μm) and the total Sn content were varied. The variation in the filament spacing was achieved by changing the local ratio of Nb to the Cu matrix.

A number of magnetization measurements of a representative set of the wires for the various spacings indicates that the effective size of the filaments can be reduced by increasing the interfilament spacing (increases in the local Cu-to-Nb ratio).[32] For example, the effective size of the filaments was reduced to $\sim$4-6 μm for the wire with the local ratio of 1.8:1(23% Nb) from

Table III-1. Available Critical Current Densities in Multifilamentary Nb_3Sn Wires at 10 T, 4.2 K

	Process Method	Filament Size[a] μm	Amount of Nb[b] %	H.T. Temperature (°C)	J_c[c] (A/mm^2)	Ref.
(1)	Bronze Process					
	Pure Nb_3Sn	∽ 1	24	650	1200	(25)
	Nb_3Sn + Ti	∽ 1	21	600	1440	(26)
(2)	Internal Tin					
	Pure Nb_3Sn	∽ 2	28 (1.27:1)[d] 23 (1.8:1)	700	1050 865	(27) (28)
	Nb_3Sn + Ti	∽ 1.3	28 (1.27:1) 23 (1.8:1)	625	1480 1200[e]	(29)
(3)	Nb Tube Process $NbSn_2$ Powder	∽30	--	675	2100	(30)
	Sn + Cu	∽15	--	675	1600	(31)

NOTES:

(a) before reaction
(b) inside difussion barrier
(c) excluding stabilizing copper
(d) local Nb to Cu ratio
(e) an extrapolated value

$\sim$20-30 μm for the wire with the local ratio of 1.27:1(28%Nb). However, measurements of J_c for these wires has also shown that the values of J_c approximately scale with the amount of Nb in the wire. Thus, when the local ratio was increased to reduce the effective filament size, J_c of the wire became unattractively low (from 1050 to 865 A/mm^2 at 10 T). In order to improve upon this difficulty, the Sn core was alloyed with a small amount of Ti and this resulted in a significantly increased value of J_c (1480 A/mm^2) for the sample containing 28% Nb. Thus, it is expected that a wire with small effective filaments and a high value of J_c, $\sim$1200 A/mm^2 (using the scaling which is based on the amount of Nb), can be produced if a further development is carried out for the internal tin processed wires using the Ti alloyed Sn core.

Thus, it appears that Nb_3Sn wires suitable for accelerator magnets will be available in production quantities in the near future (3-5 years) if the above findings are incorporated in the manufacturing process of Nb_3Sn wires.

2. The Nb Tube Methods:

This processing method, which produces a Nb_3Sn wire with the highest critical current density, involves the use of $NbSn_2$ powder in Nb tubes. The size of the powder particles inherently limits the size of the smallest filaments to $\sim$25 μm. It was also shown that it is possible to make a similar wire by replacing the $NbSn_2$ powder with Sn-Cu alloys, thus removing the limitation on the filament size from the powder.

Attempts to produce finer filaments of Nb_3Sn by the latter method by IGC have resulted in fabrication of short lengths of the wire with the filaments as small as $\sim$15 μm. The critical current density for this wire is also shown in Table III-1 and is encouraging. However, a further reduction of the size to $\sim$2 μm appears to be very difficult at present.

C. Some Cost Projections for Nb_3Sn

The component materials used to fabricate Nb_3Sn wire have about the same value or slightly less than materials needed to manufacture wire of NbTi. Furthermore, the fabrication methods if the internal tin process were to be used would be essentially the same for Nb_3Sn and NbTi. Some additional cost would be required for reacting the Nb_3Sn conductor. Table III-2 gives a cost comparison of the two types of superconducting materials if used in SSC magnets. A few clarifying comments are necessary.

The estimated costs are given in 1984 U.S. dollars per pound of superconductor. The total cost of $65/lb. (or $3.75/ft.) of NbTi is the estimate used in the Reference Designs Study for the Design A magnet. (The costs for the Design D magnet would be the same.) When the Magnet Division at BNL was purchasing Nb_3Sn wire for model magnets in 1984 the costs were approximately $260/lb. At that time there were several rounds of discussions between BNL and the management at IGC of the future costs of the same wire but in large-scale production. The estimated future costs as given in Table III-2 are those after reconciliation of differences between independent BNL and IGC estimates.

Table III-2. Cost Comparisons of NbTi and Nb_3Sn Superconductor for SSC Magnets. The Actual Costs are Given for 1984 Purchases and Estimates are Provided for Large-Scale Future Manufacturing.

	NbTi SSC Est.	Nb_3Sn 1984 Purchases	Nb_3Sn Est. Future
1. Billet materials	$32	$ 30	$20-25
2. Billet ass'y., extrusion and drawing	21	210	30-35
3. Cabling and reacting (latter for Nb_3Sn only)	12	20	15-20
TOTALS -	$65/lb.	$260/lb.	$65-80/lb.

It is understood that considerable work in manufacturing development would be necessary before the estimated future costs of Nb_3Sn would be possible. IGC management estimated that the reduced costs at their facility would come about following manufacture of about 100,000 lb. of wire for about 150-200 full length magnets. Probably about $6M of purchases would be required to meet this level of production. In addition, the competitive production by other manufacturers would have to be faced. Therefore, a total investment of perhaps $10M would be necessary before a competitive market could be realized at an optimum cost for the SSC.

D. 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 III-1 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_o, 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 is the value measured for strand fabricated using the internal tin process with filament spacing designed to reduce magnetization to acceptable levels (1.8:1 local ratio - see Table III-1). Other likely cost-effective processes for producing Nb_3Sn would have critical current lines which would have current densities at 10 Tesla at the values indicated on the right side of Fig. III-1. However, those processes are not yet fully developed. The bronze process is not indicated here because it is felt that it would not be cost effective 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. III-1 is for wire with a copper-to-superconductor ratio of 1:1.

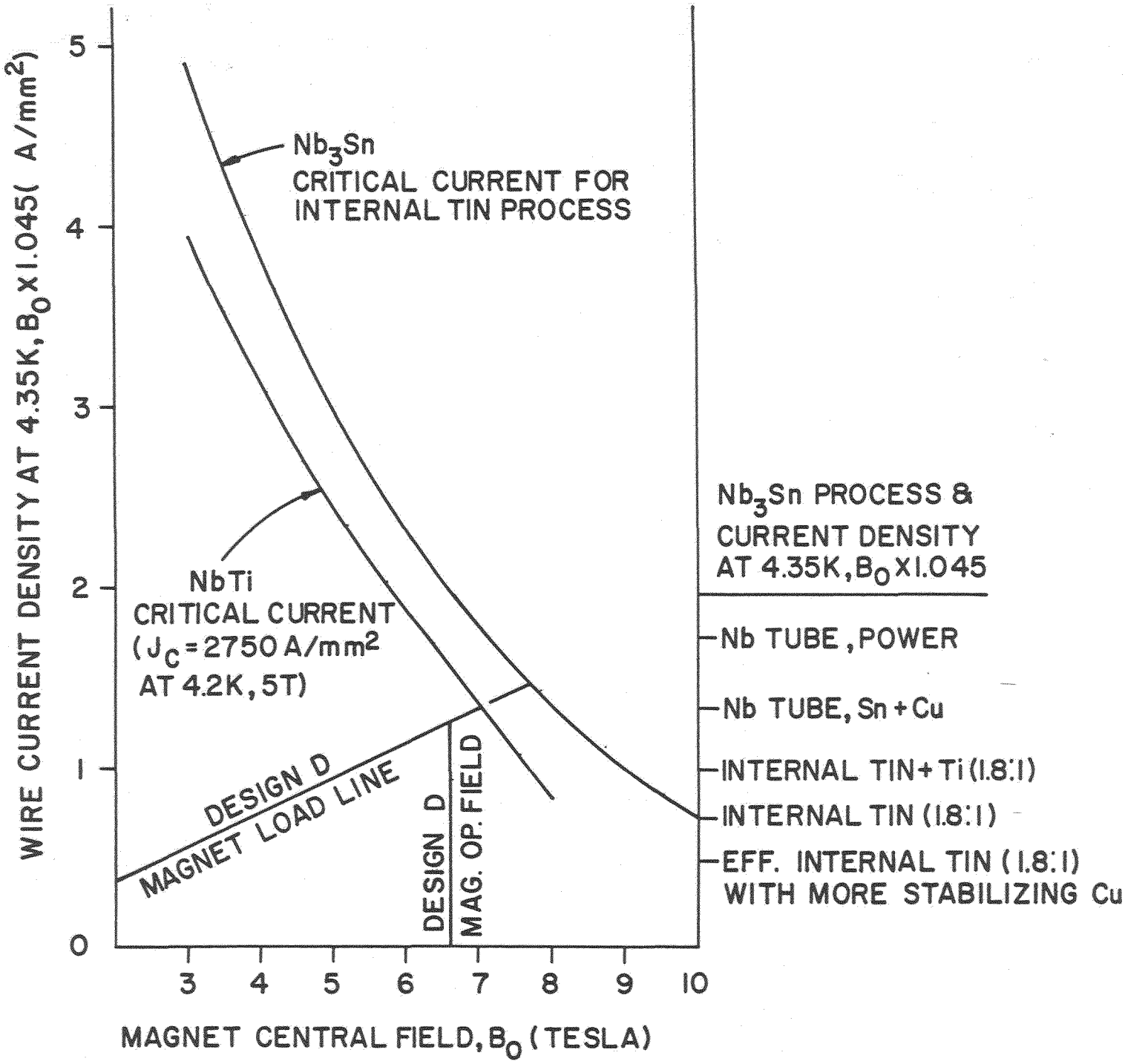

Fig. III-1. Attempt to compare performance of an SSC Design D magnet constructed of NbTi and Nb_3Sn. The critical current lines for NbTi and Nb_3Sn are for wire production methods currently well developed. Most likely additional stabilizing copper would be required for Nb_3Sn effectively lowering the curve as indicated.

This ratio is most likely too low. 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. III-1 by a factor of 0.67. As a consequence, the Design D magnets would not be expected to perform significantly better with Nb_3Sn 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 Table III-1 and Fig. III-1 could eventually change the arguments.

E. Nb_3Sn Conductor R&D for SSC

At the time when BNL initiated the study of Nb_3Sn conductor for use in accelerator magnets there were several technical problems which deserved a concentration of R&D efforts. Some of these problems appeared shortly after initial samples of candidate superconductor were evaluated. These are summarized briefly here.

1. Optimization of filament spacing to reduce effective magnetization. As described in Section III-B, the Nb_3Sn filaments by the internal tin process were found to grow together during reaction. This required a study of the optimum spacing of filaments.

2. Development of diffusion barriers to replace the use of niobium. During reaction the tin reacted with the niobium used for a diffusion barrier and formed a thin superconducting tube surrounding the filaments. This increased the effective magnetization of the conductor significantly.

3. Alternate methods for fabricating Nb_3Sn. Ideas were encouraged which would lead to more efficient fabrication methods and lower costs. Also, some methods might lead to higher current densities.

4. Competitive sources for Nb_3Sn manufacturing. In order to have a successful magnet design using Nb_3Sn there must be industrial suppliers ready to compete for orders. Manufacturing development funds would prepare these competitive suppliers.

Table III-3 provides a summary of the various Nb_3Sn R&D projects either funded through BNL or by various superconductor manufacturers using their own internal funds. All of these projects were generated as a result of the magnet development for the SSC. Three of the four technical problems stated above were addressed. Several proposals for competitive sources were submitted for consideration but were not funded.

Table III-3. Nb_3Sn Conductor R&D for SSC

Work Done By & Contract Amount	Project Description	Status
IGC $69K	Internal tin optimization study - 18 samples	Samples completed and evaluated
IGC Company-Sponsored	Barrier development for internal tin process using Ta/Nb	Solutions found but not yet used in production
IGC $22K	Nb tube process for Nb_3Sn wire	Samples completed and evaluated; now funded by DOE-SBIR contract
Supercon $50K	Internal tin process using "jelly roll" method and Nb wire mesh	In progress
Teledyne Wah Chang $17K	Internal tin process using "jelly roll" method and expanded Nb foil	In progress
Teledyne Wah Chang Company-Sponsored	Barrier development using vanadium	Solutions found but not yet used in production

IV. Development of a Manufacturing Process for Use of Nb_3Sn in Accelerator Magnets

A. Limitations of Strain Degradation

In the early SSC magnet development at BNL it was decided to employ Nb_3Sn in a way that would facilitate manufacturing of coils with this conductor. A decision was made to use the wind-after-react approach to manufacture the coils rather than react-after-wind. The advantages of this approach are listed below.

1. The Kapton/B-stage glass insulation scheme that had worked so well for previous $\cos\theta$ magnets at Fermilab and BNL could still be used.

2. The methods developed at BNL for producing coils of uniform size and field quality during a large production run could still be used. These methods rely on curing, measuring and recuring the B-stage glass insulation and, obviously, rely on use of the previously developed insulation.

3. For the most part, existing tooling and facilities could be used. The only addition was a furnace for heat treatment of the Nb_3Sn cable.

The first and most fundamental part of the BNL R&D program was to find a method to wind previously reacted cable around the ends of the small diameter coils. Normally this would require a severe strain to be applied to the cable around very small bend radii. To avoid this and the resulting certain damage to the Nb_3Sn, "dog bones" were added to the coil ends enabling instead large bend radii and reduced magnetic field. Experiments were done to discover the minimum bend radius which could be accomodated in such a "dog-bone" design. Figure IV-1 summarizes an experiment done to discover the minimum radius for previously reacted Rutherford-style cable to be used for magnet construction. Although the results do not compare directly, the observed strain degradation is similar to that measured in single reacted Nb_3Sn wires.[33] Based on these results and the practical features of designing tooling for "dog bone" ends, a minimum coil bend radius of 1.4-inches was chosen. Using calculations of the peak fields in the bend regions it was estimated that the critical currents of the strained cable would be 20-50% above the required operating current. Figure IV-2 shows an end developed for the inner coils at BNL. After the actual coil tooling was constructed, cable was wound onto a mandrel with "dog bones" following actual production techniques. The cable in the ends was marked and carefully removed again. Subsequent short sample tests of cable sections from the ends showed no degradation compared with sections unwound from the coil straight sections.

B. Creation of a Manufacturing Process

Accompanying the wind-after-react approach undertaken to produce SSC accelerator magnets at BNL there were numerous detailed problems that were solved and techniques developed. These are best described in simplified form in Table IV-1.

C. Status of the Nb_3Sn Magnet Program at BNL

The most intense activity occurred at BNL during Calendar Year 1984; conductor was procured, tooling was fabricated and Nb_3Sn coils were constructed. The summary below gives the status of this program.

1. Sufficient Nb_3Sn wire was obtained to assemble four two-in-one dipole magnets. The wire was purchased from IGC where the internal tin method was used.

2. Three test coils were constructed using wire from small quantities available early from IGC. Numerous tests were done on these coils during and after fabrication. Finally, the coils were cut into sections for testing of individual turns as short samples of superconducting cable.

3. Six inner and six outer coils were fabricated. (Sufficient cable remains to construct a like number of additional coils.) Problems were discovered among the coils first produced whereby the incoming leads and initial turns of cable were either broken or severely degraded. Coils are being assembled in pairs and are being cryogenically tested to check whether they are acceptable for assembly into a magnet. In most cases repairs are being made to the conductor. The cable was damaged during the coil molding operations and there are numerous suggestions for changes to those steps.

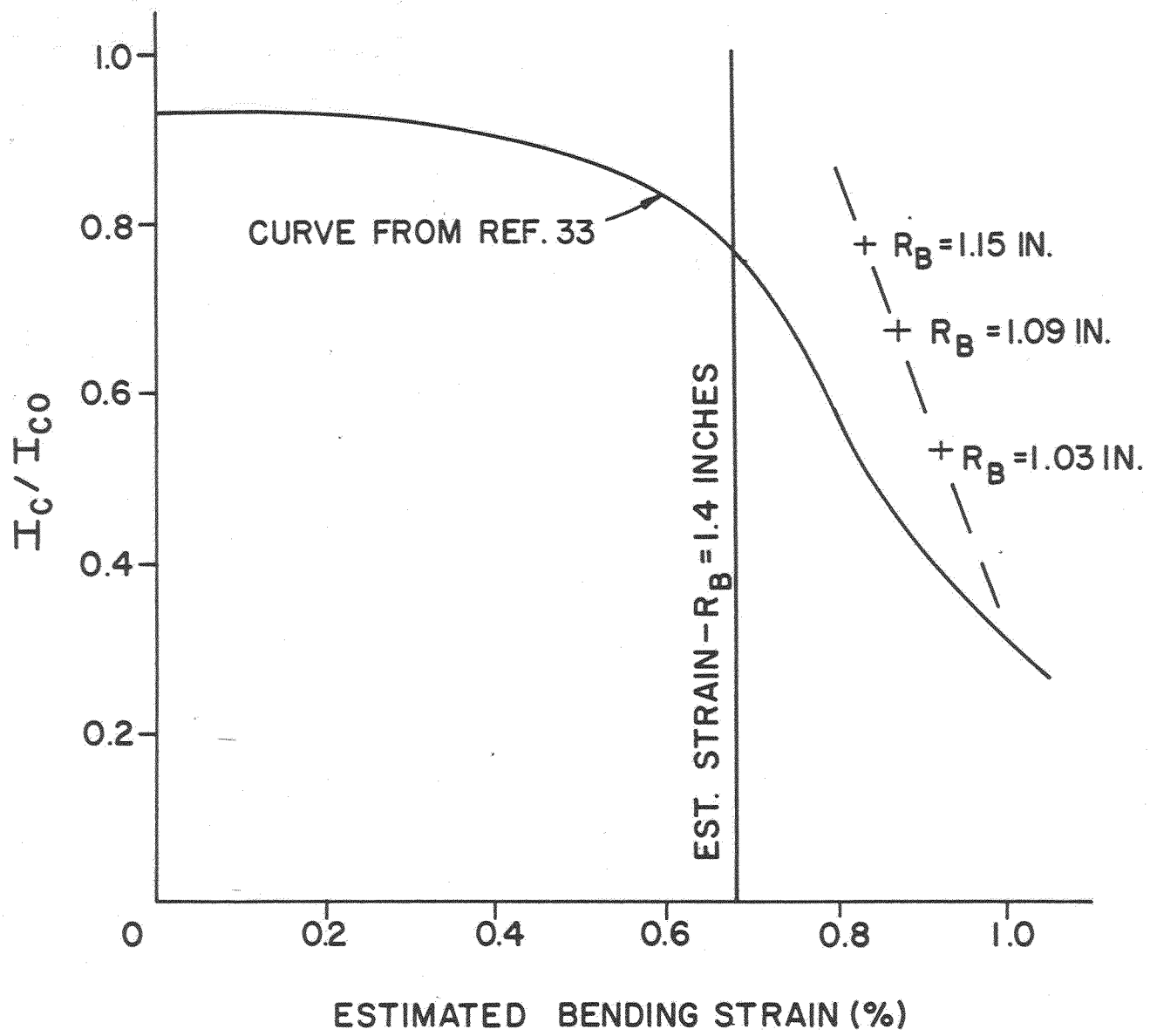

Fig. IV-1. Effect of bending strain on critical current of Nb_3Sn conductor. Measurements were made of the critical current, I_c, at 6 T of three samples of cable bent around radii, R_B, of 1.03, 1.09 and 1.15 inches and compared with an unbent sample measured as I_{co}. These measurements provided the basis for the choice at BNL of a minimum "dog bone" bend radius of 1.4 inches. The solid curve from Ref. 33 indicates the general features for Nb_3Sn, but would not be expected to reproduce the results for the BNL cable.

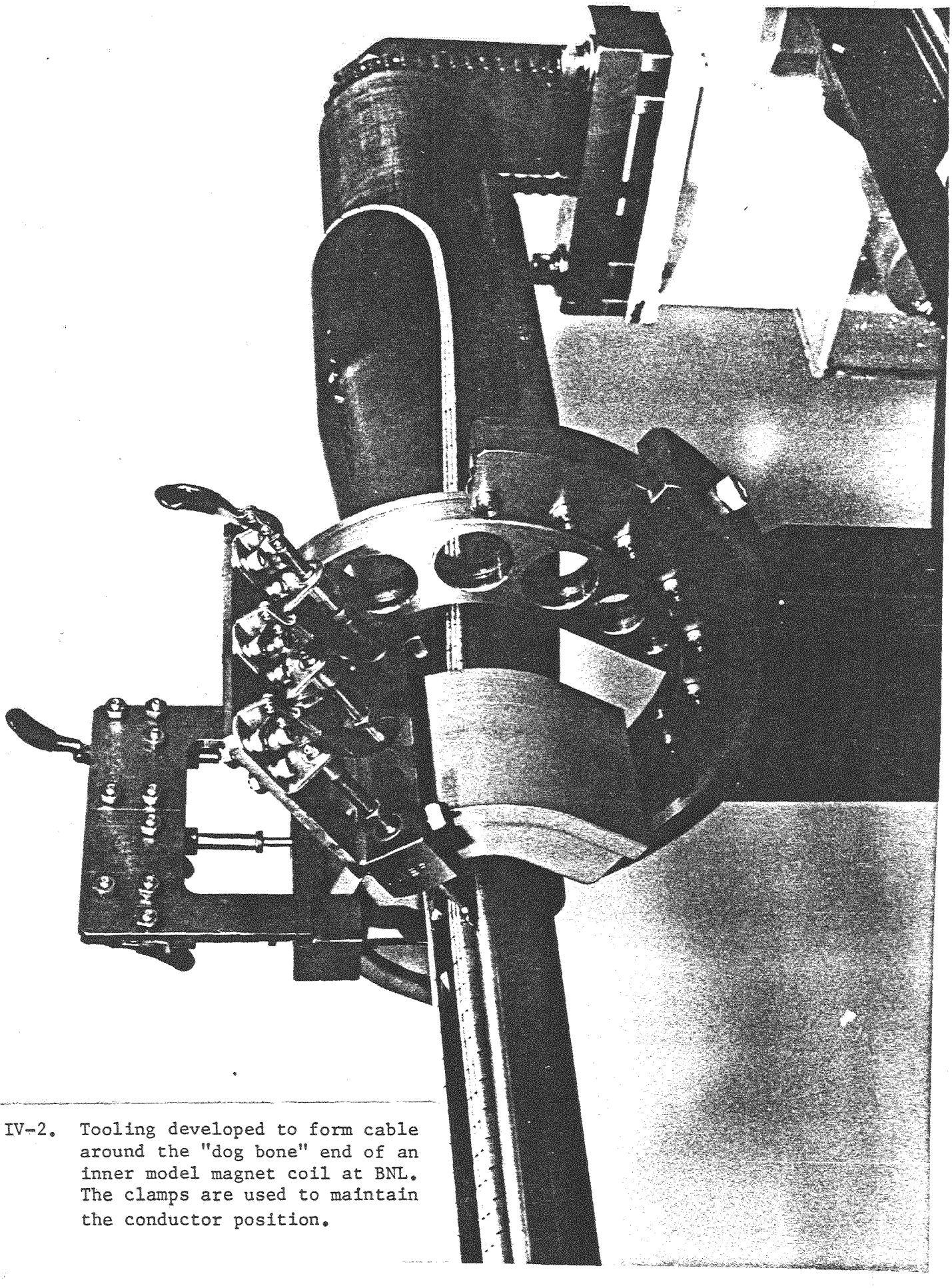

Fig. IV-2. Tooling developed to form cable around the "dog bone" end of an inner model magnet coil at BNL. The clamps are used to maintain the conductor position.

Table IV-1. Manufacturing Problems Solved at BNL Involving Nb_3Sn and a Wind-After-React Method

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1. Cabling

   Problem: It was not possible with Nb_3Sn to use "cold welding" methods as previously used to splice NbTi wires during cabling.

   Solution: A satisfactory "hot welding" technique was developed.

   Comments: Techniques were found to enable production cabling of unreacted Nb_3Sn wire so that the differences in properties between it and NbTi could not be discerned.

2. Reacting Large Quantities of Nb_3Sn Cable

   Problem: During reacting there was sintering of the copper strands in the cable resulting in a cable that was difficult to bend.

   Solution: Mobil 1 lubricant used during the cabling operation was left on the cable during reaction and argon gas was introduced into the reaction furnace. A very thin layer of carbon developed between strands in the cable and sintering was eliminated.

   Problem: Graphite paper used between cable layers during the reaction process adhered to the cable surface and was very difficult to remove.

   Solution: A cost-effective method was developed where alumina paper was used and subsequently any small residue was brushed and vacuumed off.

   Comments: A large reaction furnace and accompanying equipment were installed. The reaction process was completed for large quantities of cable using methods which could easily be employed in large-scale production.

3. Winding of Coils with Prereacted Nb_3Sn Cable

   Comments: Tooling and methods were developed which made possible routine procedures for winding coils of prereacted Nb_3Sn cable. No strain degradation of the cable was observed as a result of the coil winding operations. Production techniques were developed which eliminated cable handling by operators; these mostly relied on computer operation of the coil winding equipment.

Table IV. (Cont.)

4. Molding of Coils with Prereacted Nb_3Sn Cable

Comments: Of the tasks remaining to be done before completing the steps in routine production, coil molding requires the most development. So far most coils fabricated have shown some damage in the end regions due to molding. However, no fundamental problems have been encountered that remove the optimism about successful completion of this task.

5. Assembly of Coils

Comments: As described in the text, the specific problems of magnet assembly have not yet been encountered. However, magnets have been successfully built and tested with NbTi conductor using methods that were developed for Nb_3Sn.

At the end of 1984 the BNL efforts were shifted to the fabrication and testing of SSC Design D magnets using NbTi superconductor in collaboration with LBL and Fermilab. Because of the high priority given to the Design D R&D the Nb_3Sn work has continued at a slow pace. It is still hoped with the existing materials and tooling that one or more magnets with prereacted Nb_3Sn coils can eventually be tested.

V. 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 when there has been 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 additional development depending on the level of the R&D 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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