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TO SUPERCONDUCTING MATERIALS

FINAL REPORT

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ABSTRACT

Three processes for the production of low-loss superconducting tapes of Nb₃Sn were investigated. They are the rolled-bronze process, the electron-beam (EB) bronze deposition process, and the high-rate sputtering process. Shortly after the start of the investigation, effort on the last two processes was suspended because the process-development time that would be needed to arrive at a suitable transmission-line tape appeared most likely to be the shortest with the rolled-bronze process.

Long lengths of Nb₃Sn tapes were prepared by the rolled-bronze process from extruded and rolled bronze-clad niobium billets. Fine-grained Nb₃Sn layers with a maximum thickness of 5 μm were formed by heat treating at 700-750°C for several hours. Layer thickness was increased up to 15 μm by plating the bronze with tin before heat treatment. On slit tapes without bronze on the edges, a continuous Nb₃Sn layer was developed on the edges when the tapes were plated with both tin and copper before heat treatment. Tapes were stabilized by removing the bronze layer after reaction and then coating the exposed Nb₃Sn with high-purity copper by EB evaporation.

Several meters of high quality Nb₃Sn tapes were produced by the rolled-bronze process. Even when the tapes were stabilized with copper, the losses were as low as 1.8 $\mu\text{W}/\text{cm}^2$ at 4.2 K and a surface current density of 500 rms A/cm. The maximum resistivity ratio ($\rho_{273\text{K}}/\rho_{20\text{K}}$) that was attained in a stabilizing copper layer was 220.

Despite early curtailment of the effort on the EB bronze-deposition process, short samples of Nb₃Sn tapes

were produced. Bronze was deposited on a niobium substrate, and both niobium and bronze were deposited on copper and Hastelloy B substrates.

The rolled-bronze process can be scaled up easily to produce larger quantities of the basic unstabilized Nb_3Sn tape. The EB coating of this tape with high-purity copper cannot be done with the same degree of ease because it will require the design and construction of equipment that is specifically tailored for this application.

EB deposition of bronze and niobium and/or high-rate sputtering of Nb_3Sn should be investigated further. These processes might be economically attractive for assymetrical reinforced tape configurations in which high-strength substrates, such as Hastelloy B or molybdenum, are coated with both Nb_3Sn and copper in the same deposition apparatus.

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1. INTRODUCTION

The initial objective of this work was to determine which of three manufacturing processes was the best one for the production of Nb_3Sn tapes with thick reaction layers and low losses. The Nb_3Sn reaction layer would be roughly 12 to 20 μm thick in order to be able to carry the fault current. When carrying the normal operating current, the Nb_3Sn would have a loss of 10 $\mu\text{W}/\text{cm}^2$ or less at about 7K and a surface current density of 500 rms A/cm. The tape would be stabilized with about 25 μm of copper on each side. The three manufacturing processes that were investigated are the following:

- 1) The rolled-bronze process
- 2) The electron-beam (EB) bronze-deposition process
- 3) The high-rate sputtering process

In the rolled-bronze process, a single-strand billet of niobium and bronze is fabricated and extruded. The extruded material is drawn, rolled into tape and then heat treated to convert the Nb to Nb_3Sn .

The EB bronze-deposition process is similar to the rolled-bronze process in that bronze is used as the medium to supply tin for the conversion of Nb to Nb_3Sn . In this process, bronze is EB deposited on a conventionally produced niobium substrate or on a niobium layer that has been deposited on a copper or stainless steel substrate. The composite tape is subsequently heat treated to form Nb_3Sn .

The high-rate sputtering process deposits Nb_3Sn from a cathode directly onto a substrate such as Hastelloy B at 10 to 20 times the rate of conventional sputtering.

The tapes produced by these processes have to be clad with copper. Several cladding methods were evaluated for this step; they are solder bonding, electrodeposition and EB deposition.

Periodic meetings were held with staff members of Brookhaven National Laboratory. At one of these meetings, shortly after the start of the development program, Brookhaven and Airco personnel agreed to suspend effort on the EB bronze-deposition and high-rate sputtering processes and to concentrate on the rolled-bronze process. The latter seemed most likely to produce quickly the required low-loss tape that is needed in the transmission-line program.

Because of the urgent nature of the development program, the potential methods of copper cladding could not be evaluated as thoroughly as they might otherwise have been. On the basis of the limited amount of work that could be done, EB copper deposition appeared to have advantages over the other processes, and therefore, it was selected for cladding of the test samples.

2. THE ROLLED-BRONZE PROCESS

2.1 Billet Design

Billets of several different configurations and bronze compositions were fabricated and processed. These were made in order to determine the effect of configuration and composition on the processing parameters of a billet and on the properties of the final tapes.

The experimental billets were 50.8 mm in diameter and 101.6 mm long. Table 1 and Fig. 1-3 describe the various configurations. Billets A, C, G and H had solid niobium cores. The niobium core size varied from 19.1 mm to 38.1 mm. In billet B, a solid copper core was inserted into a niobium shell of 38.1-mm OD and 19.05-mm-ID. The niobium-to-bronze ratio varied from 6.11 to 1 for billets G and H to 1.04 to 1 for billet C. The weight percent of tin in the bronze varied from 11.7 to 15.

2.2 Billet Fabrication

The bronze-billet stock of OFHC copper and pure tin was vacuum induction melted in the furnace that is shown in Fig. 4, and the molten bronze was cast into a graphite mold. The bronze casting was extruded to 51-mm-diameter rod in order to obtain nonporous material for the fabrication of extrusion cans. The extruded bronze rod was machined into extrusion cans and cleaned. A billet for extrusion was formed by inserting a niobium rod into a bronze can and then TIG welding a lid onto the can. The billet was evacuated to 1.33 mPa or better through a pig-tail tube. While still under vacuum, the billet was heated to 250°C

TABLE 1

BILLET DESIGN FOR THE ROLLED-BRONZE PROCESS

<u>Configuration Designation</u>	<u>Outside Diameter of Billets, mm</u>	<u>Diameter of Niobium, mm</u>	<u>Diameter of Copper, mm</u>	<u>Tin in Bronze, wt. %</u>	<u>Ratio of Bronze to Niobium*</u>	<u>Figure Number of Configuration</u>
A	49.5	25.4	----	11.7	2.8	Fig. 1
B	49.5	38.1 OD 19.05 ID	19.05	11.7	0.92	Fig. 2
C	49.5	38.1	----	11.7	0.69	Fig. 2
G	49.5	19.05	----	13	5.75	Fig. 3
H	49.5	19.05	----	15	5.75	Fig. 3

* Ratio of areas in billet cross-section

Figure 1. Configuration of Billet A

Figure 2. Configuration of Billet B
(Billet C Is Similar with a
38.1-mm Nb Core)

Figure 3. Design of Billets G and H

Figure 4 Vacuum Induction Melting Furnace

to bake out any residual water vapor, and the pig-tail tube was sealed. A 50.8-mm-dia. extrusion billet is shown in Fig. 5.

2.3 Mechanical Working

2.3.1 Extrusion

Evacuated and sealed billets were preheated in an electric furnace for 3 hr. The billet temperature and die temperature are listed in Table 2 for all the billets. A 15.9-mm extrusion die with 45° die angle was used for all extrusions. No difficulties were encountered in extrusion. The extruded rods were 15.9 mm in diameter and 914 mm in length. Lengths of approximately 152 mm were cut off from each end of the extruded rods to avoid the bad ends. Cross sections of the as-extruded billets are shown in Fig. 6-10. Billet A had a very smooth interface between the niobium and bronze. The interfaces of other billets were not so smooth.

2.3.2 Rolling

All rolling was done on 254-mm and 152-mm-dia. rolling mills with front and back tension control; they are shown in Fig. 11 and 12. The rolling, drawing and annealing schedule for various billet designs are shown in Table 3. A 10 to 20% reduction was taken for each roll pass. After each rolling schedule, the tape was cleaned and annealed at 550°C for 1/2 hr. All annealing was done in an argon atmosphere.

Billets G and H were more difficult to process than billets A, B, and C, possibly because of the higher tin content in the bronze. The bronze matrix was harder in

Figure 5 50.8-Diameter Extrusion Billet

TABLE 2

EXTRUSION TEMPERATURES FOR VARIOUS BILLETS

<u>Billet Identity</u>	<u>Billet Temp., °C</u>	<u>Die Temp., °C</u>
A	650	315
B	677	320
C	677	320
G	631	304
H	615	426

Figure 6 Cross Section at 4.5X of As-Extruded
Billet A

Figure 7 Cross Section at 5.4X of As-Extruded
Billet B

Figure 8 Cross Section at 5.4X of as-Extruded
 Billet C

Figure 9 Cross Section at 6X of As-Extruded
Billet G

Figure 10 Cross Section at 6X of As-Extruded
Billet H

Figure 11 254-mm-Diameter Rolling Mill

Figure 12 150-mm-Diameter Rolling Mill

TABLE 3

ROLLING, DRAWING AND ANNEALING SCHEDULE FOR VARIOUS BILLETS

<u>Billet Identity</u>	<u>Drawn Dia., mm</u>	<u>1st Rolled (a) Thk., mm</u>	<u>2nd Rolled Thk., mm</u>	<u>3rd Rolled Thk., mm</u>	<u>4th Rolled Thk., mm</u>	<u>5th Rolled Thk., mm</u>
A	11.7	1.52	0.33	0.08		
B	7.34	1.22	0.30	0.08		
C	7.34	1.42	0.20	0.08		
G	ND ^(b)	5.23	1.63	0.51	0.23	0.08
G	ND	7.46	1.80	0.53	0.25	0.08
H	ND	5.25	1.63	0.48	0.25	0.08
H	ND	10	2.69 ^(c)	0.41 ^(c)	0.08 ^(c)	

a) Thk. = Thickness b) = Not drawn

c) Cracks developed at the edge of the tape

Note: (1) Initial billet diameter was 15.9 mm

(2) Annealed at 550°C for 1/2 hr after drawing and between each rolling

(3) No anneal after final rolling

billets G and H than in the other three, and edge cracks developed more easily. To prevent cracking, more frequent anneals were required. Generally, billets A, B and C took 80-85% reduction in thickness without annealing, whereas, billets G and H had to be annealed after 60-65% reduction in thickness.

A sample was taken from an end of each billet after every other roll pass. A cross section of each sample was examined under the microscope. A series of cross sections of billets with configurations A and C are shown in Fig. 13 and 14. The niobium-bronze interface became considerably smoother as rolling proceeded. Improved interfaces can be obtained by modification of the extrusion conditions to insure a more uniform cross section. The modification will include changes in extrusion temperature and extrusion-die angle.

In billets of configuration G, some lack of bonding was observed at the niobium-bronze interfaces as shown in Fig. 15. This lack of bonding, however, was not observed when the tape was rolled to the final size. Repeated rolling and annealing could have healed these improperly bonded areas.

Fig. 16-20 show the cross sections of tapes A, B, C, G and H at their final sizes. The thickness ratios of bronze to niobium are 1.47, 0.54, 0.8, 2.36 and 2.36 to 1 for, respectively, tapes A, B, C, G and H. Configurations B and C have insufficient tin in the bronze to form a thick Nb_3Sn reaction layer. Tin plating the tape before final heat treatment could provide the extra tin content; however, this extra tin would bring up the tin concentration in the bronze to more than 30 wt %. With this higher concentration, the final reaction temperature would have to be limited in order to avoid melting of the bronze matrix. Tapes A, G and H were therefore selected for the development of the final heat-treatment processes.

Figure 13 Series of Cross Sections of Configuration-A Billets after Various Roll Passes

Figure 14 Series of Cross Sections of Configuration-C Billets after Various Roll Passes

Figure 15 Billet-G Interface at 100X between Nb and Bronze after Seventh Roll Pass

Figure 16 Cross Section at 400X of As-Rolled Tape A
at Final Size

Figure 17 Cross Section at 400X of As-Rolled Tape B
at Final Size

Figure 18 Cross Section at 400X of As-Rolled Tape C
at Final Size

Figure 19 Cross Section at 400X of As-Rolled Tape G
at Final Size

Figure 20 Cross Section at 400X of As-Rolled Tape H
 at Final Size

2.4 Preparation for the Reaction Heat Treatment

Tape A was slit to 12.7 mm and tapes G and H were slit to 6 mm after the final roll pass. A schematic diagram showing unslit and slit tapes is shown in Fig. 21. The slit tapes were cleaned with trichlorethylene, acetone and methanol. The cleaned tapes were coated with milk of magnesia and wound on a graphite spool for the final heat treatment or plated with tin and copper. The Sn-Cu plating will be fully discussed in a later section of this report.

2.5 The Reacted Tapes

2.5.1 As-Rolled Tapes

Tapes of configurations A, G and H have been heat-treated for various times at 650°C and 750°C in the as-rolled and slit conditions. Fig. 22 shows the cross section of tape A(1)* which was reacted at 650°C for 115 hr. The thickness of the Nb₃Sn reaction layer was about 0.66 μm . Tapes G and H with higher tin content in the bronze and thicker bronze layers had thicker Nb₃Sn reaction layers than tape A(1). Fig. 23 and 24 show, respectively, the cross sections of the Nb₃Sn reaction layer of tapes G(1) and H(1). The estimated reaction layer thickness on each side was 2.5 μm for tape G(1) and 3.2 μm for tape H(1).

Higher reaction temperature will produce thicker reaction layers as shown in Fig. 25 and 26. Tapes G and H were heat treated at 750°C for 111 hr. The estimated reaction-layer thickness on each side of the niobium layer for tape G(2) was 4.2 μm ; the thickness on each side of the niobium layer for tape H(2) was 5.3 μm .

* The numbers in parentheses are for sample identification purpose.

Fig. 21 Schematic Diagram Showing Cross Section of
(a) Unslit and (b) Slit Tapes.

Figure 22 Cross Section 1200X of the Nb_3Sn Reaction Layers of Tape A(1). Tape Contained 11.7% Sn Bronze and Was Heat Treated at 650°C for 115 Hr. Reaction Layer Thickness Is $0.66\text{ }\mu\text{m}$ on Each Side.

Figure 23 Cross Section at 600X of Tape G(1) with a $2.5\text{ }\mu\text{m}$ Nb_3Sn Reaction Layer on Each Side. Tape Contained 13% Sn Bronze; It Was Heat Treated at 650°C for 176 Hr.

Figure 24 Cross Section at 600X of Tape H(1) with a $3.2\text{ }\mu\text{m}$ Nb_3Sn Reaction Layer on Each Side. Tape Contained 15% Sn Bronze; It Was Heat Treated at 650°C for 176 Hr.

Figure 25 Cross Section at 600X of Tape G(2) with a 4.2 μm Nb_3Sn Reaction Layer on Each Side. Tape Contained 13% Sn Bronze; It Was Heat Treated at 750°C for 111 Hr.

Figure 26 Cross Section at 600X of Tape H(2) with a 5.3 μm Nb_3Sn Reaction Layer on Each Side. Tape Contained 15% Sn Bronze; It Was Heat Treated at 750°C for 111 Hr.

2.5.2 Tin Plating

In order to produce thick Nb_3Sn layers at lower reaction temperature and shorter reaction time, an increase in the tin content of the bronze by electroplating before final reaction treatment would be desirable. The tin-layer thickness that is required is a function of the bronze-layer thickness and the tin content of the bronze. The theoretical calculation of the amount of tin that is needed to fully react the niobium layer is shown in Fig. 27.

A continuous tinning bath with a standard stannous sulphate solution was set up. Fig. 28 is a schematic diagram of this bath; the solution composition is shown in Table 4. The maximum cathode current density that was used was 0.28 kA/m^2 to insure a smooth and uniform deposit.

2.5.3 Tin-Plated Tapes

The tin-plated tapes generally produced a thicker Nb_3Sn layer than the nonplated tapes. Fig. 29 shows the cross section of the Nb_3Sn reaction layer of tape A(3). The bronze was plated with $2.8 \text{ }\mu\text{m}$ of Sn on each side before heat treatment at 650°C for 115 hr. The Nb_3Sn reaction layers were $2.2 \text{ }\mu\text{m}$ thick on each side of the niobium layer. The reaction-layer thickness was increased by a factor of 3.3 when compared to the same tape without Sn plating (see Fig. 22).

A thicker Nb_3Sn reaction layer also can be obtained by heat treating the tin-plated tape at a higher reaction temperature. Tape A(4), plated with $2.8 \text{ }\mu\text{m}$ of tin on each side, was heat treated at 750°C for 66 hr. Fig. 30 shows the cross section of the reaction layer which is estimated to be $8 \text{ }\mu\text{m}$ on each side.

Fig. 27 Thickness of Tin Coating that is Required to React Fully a Bronze-Nb Tape with a 25- μm -Thick Nb Core.

Fig. 28 Schematic Diagram of Continuous Plating Bath.

TABLE 4

CHEMICAL COMPOSITION OF STANNOUS SULPHATE PLATING SOLUTION

Stannous sulphate	55 - 90 g/l
Sulphuric acid	22 - 38 ml/l
Phenolsulphonic acid	30 - 40 g/l
Gelatin	2 g/l
B-naphthol	1 g/l

Figure 29 Cross Section at 600X of Tape A(3) with a 2.2 μm Nb_3Sn Reaction Layer on Each Side. Tape Contained 11.7% Sn Bronze which was Plated with a 2.8 μm Layer of Sn on Each Side before Heat Treatment. Tape was Heat Treated at 650°C for 115 Hr.

Figure 30 Cross Section at 500X of Tape A(4) with an 8 μm Nb_3Sn Reaction Layer on Each Side. Tape Contained a 11.7% Sn Bronze which was Plated with 2.8 μm of Sn on Each Side before Heat Treatment. The Tape Was Heat Treated in Accordance with the Following Schedule: 240°C for 15 Hr; 420°C for 18 Hr, 660°C for 24 Hr and 750°C for 66 Hr

Fig. 31 and 32 show the Nb_3Sn surface texture after etching off the bronze layers. Grain size appears to be similar for both the 650°C and 750°C heat-treated samples. The 750°C heat-treated sample showed nonuniform Nb_3Sn grain size.

2.5.4 Copper Plating of Tapes

Since tin has a low melting point, any appreciable amount of tin that is plated on the bronze surface (2.5 - 3 μm maximum thickness) has a tendency to form balls of molten tin when a tape is heat treated. The molten tin tends to bind the adjacent layers of tape which have been wound up for heat treatment before the tin can diffuse into the bronze. If a significant amount of molten tin has agglomerated on the bronze surface during heat treatment, it will produce holes through the bronze and the niobium layer. The problem of hole formation became more acute when the bronze layers were thin and the thickness was not uniform. Because of these difficulties, the amount of tin that can be plated is limited, and long lengths of tin-plated specimens cannot be wound up for final heat treatment. A thin protective copper coating on top of the tin layer is proposed as a method of overcoming the adverse effect of the molten tin.

Several different baths were tried for the plating of copper on tin. Since tin has a higher electromotive force than copper, tin will tend to dissolve in any acid bath with copper ions. In a copper sulphate solution, a loose deposit of copper indicated that the tin was partially dissolved before the copper was deposited, and therefore, this solution cannot be used. A slightly basic pyrophosphate copper solution was satisfactory. The solution composition is shown in Table 5. The solution's pH value was controlled

Figure 31 Scanning Electron Micrograph at 4800X of Nb_3Sn Surface Texture after Bronze Removal by Etching. Same Specimen as in Fig. 29.

Figure 32 Scanning Electron Micrograph at 4800X of Nb_3Sn Surface Texture. Same Specimen as in Fig. 30.

TABLE 5

COMPOSITION OF PYROPHOSPHATE COPPER PLATING SOLUTION

Potassium Pyrophosphate	295 g/l
Copper Pyrophosphate	60 g/l
Sodium Oxalate	20 g/l
Ammonium Nitrate	8 g/l

at 8.5 by adding nitric acid. The operating current density was between 210 to 480 A/m² at bath temperature of 50-60°C. Fig. 33 is a scanning electron micrograph which shows a cross section of Sn-Cu plated tape before final heat treatment.

2.5.5 Optimizing the Formation of the Nb₃Sn Layer

It is clear from the preceding discussion on the rolled-bronze process that the rate of formation and the thickness of the Nb₃Sn reaction layers can be controlled by varying the amount of tin plating, the thickness and tin content of the bronze layers and the reaction temperature. These factors were therefore varied in making a series of tapes for the purpose of optimizing the formation of the Nb₃Sn reaction layer.

In an attempt to form Nb₃Sn throughout the entire thickness of the niobium layer, tape H(6) was slit to 6.35 mm, plated with 3.7 μm of tin per side and reacted at 750°C for 70 hr. Fig. 34 shows a cross section of the reacted tape. In some areas, the Nb₃Sn layer has grown through the whole thickness of the original niobium layer, but the layer thickness is not very uniform. One drawback of this thick-reaction-layer tape is that it is brittle and thus very difficult to handle. The minimum bending radius is 12.7 - 17.7 mm which is larger than the specified minimum bending radius of 7.6 - 10.7 mm. Nb₃Sn grew around the edge of this tape at all cross sections that were examined.

In order to obtain a tape which has a reasonably thick Nb₃Sn layer and good mechanical properties, tapes were plated with different amounts of tin and copper and reacted at 650°C, 700°C and 750°C for different lengths of time. Table 6

Figure 33 Scanning Electron Micrograph at 2650X
which Shows a Cross Section of Sn-Cu
Plated Tape Before Final Heat Treatment.

Figure 34 Cross Section at 200X of Tape H(6) which Shows the Nb_3Sn Reaction Layer. The Tape Contained 15% Sn Bronze, and Was Sn Plated to a Thickness of $3.7 \mu\text{m}$ on Each Side before Final Heat Treatment at 750°C for 70 Hr. Sections of the Nb Layer Are Completely Reacted.

TABLE 6

PROPERTIES OF Nb₃Sn TAPES

Tape	Amount of Plated Sn, μm	Amount of Plated Cu, μm	Total Sn in Bronze, wt %	Reaction Temp/Time, $^{\circ}\text{C/hr}$	Approx. Nb ₃ Sn Thickness, μm	Fig. No. Showing Cross Section	ac Loss at 500 rms A/cm and 4.2 K, $\mu\text{W/cm}^2$	T _c , K	J _c @ 4.2 K, 10^5 A/cm^2
A(1)*	0	0	11.7	650/115	0.66	Fig. 22	4.5**	16.96	9 at 5 T 7.1 at 6 T 5.6 at 7 T
A(2)	0	0	11.7	700/160	1.6		2 (bare Nb ₃ Sn)	17.3	8.8 at 7 T
A(3)	2.8	0	22	650/115	2.2	Fig. 29	7.2**		
A(4)	2.8	0	22	750/66	8	Fig. 30	8.6** 8.5 (bronze removed by molten tin)		
G(1)	0	0	13	650/176	2.5	Fig. 23	4.7**		
G(2)	0	0	13	750/111	4.2	Fig. 25	4.7**		
G(3)	1.65	1.32	16.8	750/60	7.5		3.4+ 1.8 (HF etched)	17.8	2.2 at 9 T 39 (self-field)
G(4)	3.2	1.77	19.5	750/67	8	Fig. 40	3.8 (bare Nb ₃ Sn) 9.8** 26 (Cu cladded)		
H(1)	0	0	15	650/176	3.2	Fig. 24	6.8**		
H(2)	0	0	15	750/111	5	Fig. 26			
H(3)	1.27	0.91	17.8	750/38	4	Fig. 42			
H(3)	1.27	0.91	17.8	750/67	8	Fig. 37	6.8***		
H(4)	1.93	0.91	19.5	750/50	8.5		5** 5.6 (bare Nb ₃ Sn)		2 at 9 T
H(5)	3.2	1.78	21	750/67	9	Fig. 35 Fig. 36			
H(6)	3.56	0.91	23.3	750/70	12	Fig. 34 & Fig. 39			
H(7)	1.88	2.13	18.7	700/86	7.5	Fig. 38			

* The numbers in parentheses are for sample identification purpose.

+ coated with EB copper

** Measurement taken with bronze left on the tape.

*** Measurement taken with bronze removed by etching and 28 μm of copper electrodeposited on the tape.

summarizes the variation in thickness of the Nb_3Sn reaction layer with thickness of Sn-Cu plating, reaction temperature and time. Also shown in Table 6 are the properties of these differently processed tapes. It was found that a tape with a 6-8 μm thick Nb_3Sn layer on each side would pass the minimum-radius bending test and would be reasonably easy to handle in further processing.

Fig. 35 and 36, show representative cross sections of tape H(5) which was heat treated at 750°C for 67 hr. The Nb_3Sn reaction layer thickness was not uniform under these processing conditions. At some areas, as shown in Fig. 36, a very thin reaction layer was found on one side of the tape with concomitant high-tin-content beta phase in the adjacent bronze layer. The Nb_3Sn layer grew slowly even though the tin content in the adjacent bronze layer was not exhausted. This is probably due to either insufficient bonding or a contaminated interface between the bronze and Nb_3Sn layers. The nonuniform thickness in the Nb_3Sn layer may not be a serious problem. Although the thickness of the Nb_3Sn layer varied, the total cross-sectional area of the Nb_3Sn layer was fairly constant along the length of the tape.

Fig. 37 shows a cross section of tape H(3) which was plated with 1.3 μm of tin on each side before it was heat treated at 750°C for 67 hr. The irregular growth rate of the Nb_3Sn layers is evident; it may be due to the relatively high activity of tin in a high-tin bronze at a high reaction temperature.

A very uniform Nb_3Sn layer thickness was obtained when a tape, H(7), was plated with a moderate amount of tin and reacted at 700°C for 86 hr. A cross section of the tape is shown in Fig. 38.

Figure 35 Cross Section at 600X of Tape H(5) which Shows a $9.0\text{ }\mu\text{m}$ Nb_3Sn Reaction Layer on Each Side. The Tape Contained 15% Sn Bronze, and Was Sn Plated to a Thickness of $3.2\text{ }\mu\text{m}$ on Each Side before Final Heat Treatment at 750°C for 67 Hr.

Figure 36 Tape H(5) at a Cross Section with a Reaction-Layer Thickness Different from that Shown in Fig. 35. Notice the High-Tin-Content Areas in the Top Bronze Layer.

Figure 37 Cross Section at 600X of Tape H(3) which Shows an 8 μm Nb_3Sn Reaction Layer on Each Side. Sn Was Plated on Each Side of the Tape to a Thickness of 1.3 μm before Final Heat Treatment at 750°C for 67 Hr.

Figure 38 Cross Section at 200X of Tape H(7) which Shows a Nb_3Sn Reaction Layer with a Very Uniform $5\text{ }\mu\text{m}$ Thickness on Each Side. Sn Was Plated on Each Side to a Thickness of $1.9\text{ }\mu\text{m}$ before Final Heat Treatment at 700°C for 86 Hr.

2.5.6 Formation of Nb_3Sn on a Slit-Tape Edge

Brookhaven National Laboratory stated that a superconducting tape with a Nb_3Sn layer completely around the niobium would have lower ac losses than one with niobium exposed at the edges by a slitting operation. Conversion of the exposed niobium to Nb_3Sn can be accomplished by plating a slit tape with tin and copper and then heat treating it. The tin for the reaction would be provided by the tin coated on the edge of the slit tape and by the bronze-layer tin which diffuses to the edge of the niobium through the electroplated tin and copper.

The bare niobium edge faces a bronze composition different from that faced by the rest of the niobium during the final treatment when the tin and copper react to form a bronze. The composition of the bronze at the edge is determined by the amounts of tin and copper coating.

The rate of Nb_3Sn formation at the edge is affected by the composition of the bronze at the edge of the tape and by the rate of tin diffusion from the bronze in place before plating. Once the electroplated tin is exhausted, any extra tin that is needed for the formation of Nb_3Sn must migrate from the top and bottom bronze layers to the tape edge. Because the length of the tin-diffusion path from the bronze layers on the sides to the niobium edges is longer than the path from these layers to the other surfaces of the niobium, the reaction rate at the edges with the tin that is provided by these side layers of bronze will be lower than elsewhere. This rate reduction could account for the thinner Nb_3Sn reaction layer observed at the edge of the tape as shown in Fig. 39.

Figure 39 Edge Cross Section at 600X of the Specimen Shown in Fig. 34. The Nb_3Sn Layer Extended Around the Edges.

2.6 Replacement of the Bronze Layer by Copper

2.6.1 Molten Tin Bath

Since the bronze layers have poor electrical and thermal conductivity, they must be removed after heat treatment, and the exposed Nb_3Sn must then be clad with high conductivity copper. Removal can be accomplished by passing the tape through a molten tin bath at a controlled rate. This treatment also leaves a thin layer of tin [or Stay-brite (Sn-5% Ag) if a molten Stay-brite bath is used] on the tape which serves as an aid in solder bonding the Nb_3Sn and copper.

A short sample was prepared by this method, and a 25- μm -thick copper strip was solder bonded manually to each side of the tape as shown in Fig. 40. The bonding between the copper and the Nb_3Sn was quite good. The solder layer was about 10 μm thick. The thickness of the solder layer could have been reduced if a uniform pressure had been exerted on the tape during the solidification of the Stay-brite solder.

2.6.2 Chemical Method

An alternative to the molten-tin-bath method is to dissolve the bronze layer either chemically or electro-chemically. The bronze was removed in about 120 seconds by dissolution in a solution of one part HNO_3 and one part H_2O .

The chemical method of bronze removal produces a bare Nb_3Sn that is difficult to solder. Either a thin copper layer must be flashplated onto the Nb_3Sn before it is copper clad by soldering or the Nb_3Sn must be electro-plated with copper to a thickness of 25 μm .

Figure 40 Cross Section of Copper-Clad Tape G(4)

Three copper plating techniques were investigated. These were electroplating, sputtering and electron-beam (EB) evaporation of copper. Of these techniques only EB evaporation provided a layer with a high resistivity ratio.

Baths of copper pyrophosphate and copper cyanide were found to be satisfactory for plating copper on a bare Nb_3Sn surface. Fig. 41 and 42 show the cross sections of copper-clad tapes made with, respectively, a pyrophosphate bath and a cyanide bath. The bonding appeared good between the Nb_3Sn and the copper plating. The surface was smoother for the cyanide-plated copper, possibly because of the high throwing power of the cyanide bath. The surface of the pyrophosphate-plated copper can be improved by adding the proper brightening agent and by adjusting the current density. Both pyrophosphate- and cyanide-plated copper, however, had low resistivity ratios in the range of 30 for the pyrophosphate-plated copper and 20 for the cyanide-plated copper. Annealing of these electroplated copper layers at 300°C for $1/2$ hr did not produce a significant change in resistivity ratio. The low resistivity ratio was therefore not due to residual strain in the plated copper but was probably due to the high levels of impurities in these coppers.

Several samples of etched Nb_3Sn tape were clad with sputtered copper. In all cases, the resistivity ratio of these coatings was low (about 28).

Among the investigated techniques of deposition of copper on Nb_3Sn tape, high-rate EB evaporation produced the most promising results. Copper that was clad by this technique with proper control of substrate temperature had a resistivity ratio as high as 200. Since the copper is evaporated onto the Nb_3Sn tape, a uniform adherent layer of copper can be deposited on the tape without any tracking problems.

Figure 41 Cross Section at 400X of Reacted Tape H(5)
with Electroplated Copper from a Copper
Pyrophosphate Bath.

Figure 42 Cross Section at 600X of Reacted Tape H(3)
with Electroplated Copper from a Copper
Cyanide Bath

The system that was used to EB coat intermediate lengths of tape, up to 100 ft long, is shown in Fig. 43. The tape to be coated is wrapped spirally around a 457.2-mm-diameter drum which is maintained at a constant temperature by an internal heater.

Two electron-beam guns are located below the drum. They deposited a uniform layer of copper on one side of the tape.

After the tape is loaded on the drum, the system is evacuated, the drum rotation is started and the temperature of the drum is stabilized. The copper is then EB evaporated and deposited on the heated strip.

By maintaining good vacuum conditions, Airco routinely produces copper-clad tape with a resistivity ratio of up to 200.

2.7 Properties of Bronze-Processed Nb₃Sn Tape

2.7.1 ac Loss Measurement

The bronze-processed Nb₃Sn tapes generally have low ac-loss properties even with thick Nb₃Sn layers. These properties were measured for several differently processed tapes by J. Bussiere at Brookhaven National Laboratory. The results are given in Table 6 and Fig. 44, 45, 46 and 47. The losses were low and ranged from 2-8.6 $\mu\text{W}/\text{cm}^2$ at a surface current density of 500 rms A/cm. Tape A(2) with thin Nb₃Sn layers from which the bronze had been removed by etching had the lowest loss of 2 $\mu\text{W}/\text{cm}^2$ at 500 rms A/cm. Samples with bronze layers on the surface had as expected, slightly higher losses. One specimen, which was passed through

Figure 43 1067-mm EB Box Coater with Internally Heated
"Squirrel" Cage Fixture.

Figure 44. ac Losses of Rolled Bronze-Niobium Composite Tape A(2) with a 1.6- μm -Thick Nb_3Sn Reaction Layer after Bronze Removal by Etching

Figure 45. ac Losses Vs Surface Current Density of Tapes A(1) and A(3) after Reaction at 650°C for 115 Hr.

Figure 46. ac Losses Vs Surface Current Density of Tapes G(1) and H(1) after Reaction at 650°C for 176 Hr.

a molten tin bath to remove the bronze layer, had higher losses at the low end of the range of induced surface currents (see Fig. 47) than the two tapes that were processed in another way. This increase in loss could have been caused by contaminants in the molten tin bath.

During our last report period, an ac test rig was set up at Airco Central Research Laboratories. Several samples, tested previously at Brookhaven National Laboratory, were retested. Our test data corresponded very well with Brookhaven's data.

Fig. 48 shows the ac loss versus surface current density of tape G(4) with bronze on the surface, bronze removed by etching and copper cladding. The ac losses at a surface current density of 500 rms A/cm are 3.8, 9.8 and 26 $\mu\text{W}/\text{cm}^2$ for, respectively, etched, as-reacted and copper-clad tape. The high loss in the copper-clad tape was due to the thick solder layer.

Fig. 49 shows the ac loss properties of tape H(3) and H(4). At a surface current of 500 rms A/cm, the bronze-clad H(4) tape had a loss of 5 $\mu\text{W}/\text{cm}^2$, and unclad H(4) tape had a loss of 5.6 $\mu\text{W}/\text{cm}^2$. The small difference is within the experimental error of the measurements. H(3) tape with copper deposited on Nb_3Sn by electroplating also showed low losses. The low resistivity ratio of electroplated copper could be partially responsible for this low-loss value.

Fig. 50 shows the ac-loss properties of tape G(3). At a surface current density of 500 rms A/cm, the HF-HNO_3 etched tape has a very low loss of 1.8 $\mu\text{W}/\text{cm}^2$. When the etched tape is coated with 20 μm of EB-evaporated copper having a resistivity ratio ($\rho_{273\text{K}}/\rho_{20\text{K}}$) of 175, the loss is only 3.4 $\mu\text{W}/\text{cm}^2$.

Figure 47. ac Losses Vs Surface Current Density of Tapes G(2) and A(4)

Figure 48. ac Losses in Bronze-Clad, Etched and Copper-Clad Tapes

Figure 49. ac Losses of Tapes H(3) and H(4)

Fig. 50 Effect of Surface Current Density on ac Losses of Tape G(3)

2.7.2 Jc vs B Properties

In critical-current tests of tapes that were electroplated with copper, volt-ampere curves had an initial resistive slope. This initial resistance appears to be due to inadequate bonding between the copper and superconductor surface, perhaps due to an oxide or some other partially insulating layer. When the copper between the current contacts on the sample was removed by etching to force current flow into the superconductor and the etched surface between the voltage contacts was then replated with copper for stabilization, there was no initial resistance.

With EB-deposited copper, the critical-current tests showed no initial resistive slope, indicating good bonding. Jc measurements are summarized in Table 6.

3. ELECTRON-BEAM-PROCESSED TAPE

3.1 Background

Work on EB-processed tape was terminated shortly after the start of the program so that more effort could be put on the development of the rolled bronze-niobium composite tape. The work that is reported here is therefore of a preliminary nature.

The EB bronze-deposition process is capable of producing a variety of tape configurations depending on the substrate, the deposited materials and the sequence of deposition. For example, Nb and Sn can be simultaneously deposited from two sources to form Nb₃Sn on a suitable substrate. Alternate layers of Nb and Sn can be deposited and reacted at a later time, or tin bronze can be deposited on a Nb substrate. This last approach is the one that was investigated.

Table 7 shows the configurations which have been produced.

TABLE 7
CONFIGURATIONS OF EB PROCESSED TAPES

<u>Substrate</u>	<u>1st Material Deposited</u>	<u>2nd Material Deposited</u>
Nb	Sn bronze	-----
Hastelloy B	Nb	Sn bronze
Copper	Nb	Sn bronze

Each of these will be discussed below.

3.2 Materials

Substrate materials which were used in the study are:

22- μ m niobium foil, 13- μ m niobium + 1% zirconium, 30- μ m Hastelloy B, 60- μ m copper, 25- μ m OFHC copper and 25- μ m molybdenum. Evaporation source materials are high purity niobium and cast rods of vacuum-induction-melted bronze with 15.1, 15.5 and 19.9 weight percent tin.

3.3 Equipment

The experiments were carried out in a 1.07-m box coater that was set up for two-source evaporation. A 76-mm, 30-kW, crucible gun was used for niobium evaporation and a 25-mm-diameter, 10-kW, rod-feed gun was used for the bronze. A stationary substrate heater and strip-holder assembly were constructed to heat and support the 165- x 89-mm substrates. Fig. 51 shows the position of the guns and the substrate in the vacuum chamber. Fig. 52 shows a typical thickness distribution of a deposit on the substrate when the deposit is obtained with one gun that is located off the center line of the substrate. The measurements of coating thickness that are shown in Fig. 52 were made on a deposit of bronze.

The samples that were produced were made with a deposit only on one side of a stationary substrate to demonstrate feasibility. Continuous deposition on both sides of a tape can be done as shown in Fig. 53.

3.4 Results

Only a few experiments have been made with niobium, Hastelloy B or copper substrates. Data on these experiments, including the conditions of deposition, are listed in Table 8. Table 9 lists the conditions of heat treatment to form Nb_3Sn and the current that the tapes could carry at magnetic flux densities of up to 7 T.

Figure 51. EB Gun and Substrate Positions

Fig. 52 Typical Thickness Distribution of a Deposit on a Substrate for a Source that is Offset from the Substrate Centerline

Fig. 53 Schematic Diagram of a System for EB Deposition of Material on Both Sides of a Tape

TABLE 8

SAMPLES PRODUCED BY EB DEPOSITION

Run No.	Substrate Thk.*, μm /Type	Substrate Temp. for Nb Deposit, $^{\circ}\text{C}$	Max. Nb Thk*., μm	Sn in Bronze, wt %	Substrate Temp. for Bronze Deposit, $^{\circ}\text{C}$	Max. Bronze Thk*., μm
504-111	22/Nb	--	--	15	512-568	61
504-112	22/Nb	--	--	15	496-540	28
504-151	61/Cu	893	45	15	493-540	56
504-161	30.5/Hastelloy B	887-929	45	15	443-576	56
504-171	13/Nb + 1% Zr	--	--	15	535-551	28
504-172	25/Cu	823-851	45	15	468-554	28
504-221	22/Nb	--	--	20	500-548	43
504-222	22/Nb	--	--	20	500-530	43
504-241	22/Nb	--	--	20	343-399	43

* Thk. = Thickness

TABLE 9

HEAT TREATMENT AND PROPERTIES OF TAPES

MADE BY THE EB BRONZE-DEPOSITION PROCESS

Sample No.	Substrate	Source Composition		Sn in Bronze Layer, wt %	Time @ 650°C, hr	Thickness of Nb ₃ Sn, μm	T _c , K	J _c @ 4.2K, 10 ⁵ A/cm ²		
		1st Coating	2nd Coating					5T	6T	7T
504-111	Niobium	15% Sn bronze		13.43	42	0.58	--	7.4	5.7	4.2
504-111	Niobium	15% Sn bronze		13.43	140	0.76	16.84	8.46	7.2	6.2
504-151	Copper (a)	Nb	15% Sn bronze	13.43	140	0.84	16.92	7.9	6.2	4.9
504-161	Hastelloy B	Nb	15% Sn bronze	---	140	1.52	--	8.95	6.9	5.2
504-172	Copper (b)	Nb	15% Sn bronze	---	140	0.84	15.51	3.2	---	1.6
504-221	Niobium	20% Sn bronze		11.17	140	0.93	17.06	---	15	11

(a) 0.06-mm thick
(b) 0.025-mm thick

The tin content of the deposited bronze was considerably less than that of the bronze evaporation source because a steady state was not reached during the process. A possible difference in the sticking coefficients of copper and tin also might have contributed to the difference in tin content. With longer periods of operation, the deposit and source composition would come into closer agreement.

3.5 Discussion

Insufficient work was done to establish the operating parameters, advantages or economics of the EB bronze-deposition process. The results that were obtained do suggest that this process may have advantages over the other processes that were studied such as a broader choice of tin content of the bronze and a cost saving of EB-deposited Nb over rolled Nb strip. In addition, substrates such as Hastelloy B, stainless steel and molybdenum can provide high strength reinforcement of the tape.

4. HIGH-RATE SPUTTERING OF Nb₃Sn

4.1 Background

As stated earlier, the work on high-rate sputtering was de-emphasized to permit the acceleration of the work on the rolled-bronze process. The limited amount of work that was done is reported in this section.

The study of the sputtering process was undertaken because of two possible advantages it might have over other processes: better control of deposit composition and long-term operating stability. Such advantages could make this process attractive for production of long lengths of product; however, not enough work has been done to determine whether these advantages can be obtained. If continuous-tape production could be developed for Nb₃Sn tape the procedure could be applied in the future to the manufacture of continuous Nb₃Ge tape.

4.2 Equipment

The equipment that was used is shown in Fig. 54. The system is evacuated by a turbomolecular pump that is backed up by a rotary oil pump.

A by-pass throttle valve that is located between the pumping system and the sputtering chamber allows the system to be operated at any pressure down to approximately the highest vacuum that can be produced with a turbomolecular pump. The cathode is a 152-mm-dia Nb₃Sn disc that is brazed to a water-cooled copper backing plate. The target to substrate distance is 75 mm. The temperature is controlled

Figure 54 Turbomolecular Pumped Sputtering System

by resistance heating of the 200-mm x 50-mm substrate up to 900°C; substrate heating by glow discharge is an available option.

4.3 Results

Insufficient data were obtained prior to the termination of this phase of the program to permit the drawing of any conclusions. This work was continued under an Airco funded program. Films with T_c of 18 K and lattice parameters 52.867 nm to 52.907 nm were produced. These samples carried a current density of $2 \times 10^5 \text{ A/cm}^2$ at 6 T.

5. PROPERTY-MEASURING SYSTEM

5.1 Loss-Measuring System

Loss measurements were made using the BNL-developed Low Power Factor Wattmeter, Model IH-744.

The measuring system, shown schematically in Fig. 55, consists of an adjustable ac power supply to energize the field magnet at the 60Hz line frequency and appropriate instrumentation for determining the magnet current and wattmeter output. Also included are reversing switches to obtain the necessary coil polarities for bucking the quadrature signal and shorting switches to prevent saturation of the amplifiers when the coils are disconnected.

Details of the sample holder are shown in Fig. 56. The magnet coil is 101.6 mm long and 38.1 mm in diameter; it is wound with four layers of 0.305-mm-dia. NbTi wire in a cupronickel matrix. Saddle coils were wound with #50 Awg copper wire and had typically 250 turns for 12.7-mm-wide tape samples and 150 turns for 6.35-mm sample widths.

The field coil was wound with 25 turns of #40 Awg copper wire. In order to determine the effect of eddy-current losses, a field coil that was wound with a non-magnetic resistance alloy also was used. Only several percent difference was found which is within the repeatability of the tests, and hence, the eddy-current losses due to the field coil were considered insignificant.

During initial tests with the wattmeter, steady output readings could not be obtained. This was found to be due to improper adjustment of phase splitting in the Y channel. With unequal mark-space ratio, the drift of the low-frequency amplifier was creating an apparent output

Figure 55. Instrumentation Interconnections

Fig. 56 Sample Holder Details

variation. Two other required adjustments were found to be the multiplier-output offset and the X-channel current splitting. These adjustments were made prior to each test after the initial test period. Multiplier nonlinearity can result if the output offset is not set to zero, but the error is not significant if the multiplier input voltage is greater than 0.1 V rms.

The finding by Brookhaven personnel that significant error can result from eddy-current losses in surrounding materials was confirmed in this work. The error becomes apparent at low applied fields when a polarity change in the multiplier output indicates an apparent power gain instead of a loss. It also can be seen in the sample-voltage wave form. Ideally, zero voltage coincides with the maximum of current, but it is offset from the maximum when eddy-current losses are present. This effect was minimized by replacing the support rods for the magnet and sample holder, which were originally brass and stainless steel respectively, with phenolic rods as indicated in Fig. 56.

Calibration of the system was checked by comparing measurements with BNL on a "standard" tape. A comparison is shown in Fig. 57. This is based on a magnet constant of 13 mT/A which is higher than the original 11.6 mT/A that was found in error due to a problem with the flux-density meter. Previously reported data have not been corrected for this, and hence, can be considered conservative since the losses will be somewhat less than indicated. As shown in Fig. 57, good agreement was found above a current of 300 rms A/cm; the comparison being within about 10%. Below 300 rms A/cm, Airco-measured losses are about 30 to 40% low. The reason for this has not yet been determined.

Fig. 57 Comparison of Airco and BNL Loss Measurements on BNL Standard Tape No. 1

5.2 I_c - and T_c -Measuring Apparatus

Critical-current measurements were made using a conventional four terminal method. Test samples were 57 mm long and were soldered to OFHC conductors on a phenolic holder. The criterion for I_c was taken as the current at which 1.0 μ V was measured across a 10-mm length of the sample.

Critical temperature measurements were made with either a four-terminal resistive method or an inductive bridge. The latter method, being noncontacting, is particularly useful for samples that cannot be conveniently soldered.

Measurements were made in a stainless steel insert which was placed in a Dewar flask that contained liquid helium. Samples were mounted on a holder with a programmable temperature control. A capacitance thermometer was used for control; a germanium thermometer, for measurement. Reported T_c data were taken at the midpoint of the transition.

6. CONCLUSIONS

Not enough work was done on the electron-beam (EB) bronze-deposition process and the high-rate sputtering process to permit the drawing of any conclusions. Conclusions about the rolled-bronze process are presented in the following paragraphs.

Nb_3Sn tape with thick reaction layers and low losses can be economically manufactured by the rolled-bronze process.

Billets for the rolled-bronze process can be extruded satisfactorily.

With three 1/2-hr, 550°C intermediate anneals, a 15.9-mm-dia extruded billet that contains 11.7 wt % Sn bronze can be rolled to the required thickness.

With four such anneals, a similar billet that contains either 13 or 15 wt % Sn bronze can be rolled to the required thickness.

Uniformly thick Nb_3Sn reaction layers can be produced with relatively low reaction temperature ($\leq 700^\circ\text{C}$) and short heat treatment time (≤ 100 hr) (see Fig. 38 and Table 6).

With proper tin-copper plating, very thick Nb_3Sn layers also can be produced with the same range of reaction temperature and time; the resulting small Nb_3Sn grain size leads to low ac losses.

A Nb_3Sn layer can be formed around the edge of a slit tape by providing a copper or tin-copper plating on the tape as a diffusion path through which tin can migrate from the top and bottom bronze layers to the edge of the niobium.

Nb₃Sn tapes that are fabricated by the rolled-bronze process exhibit ac losses of less than 10 $\mu\text{W}/\text{cm}^2$ at a surface current density of 500 rms A/cm.

Electron-beam deposition of copper on a Nb₃Sn tape has an advantage over the electroplating or solder bonding of copper in that the deposited copper will have a resistivity ratio of 100 or better and there will be no tracking problem during deposition.

7. RECOMMENDATIONS FOR FURTHER WORK

The rolled-bronze process, followed by bronze removal and EB deposition of high-purity copper, appears to give a superconducting Nb_3Sn tape with premium performance characteristics, at least in short lengths. Therefore, the costs of producing this tape by such a process in large quantities should now be investigated and compared with those of competitive processes, i.e., EB deposition and high-rate sputtering. This should be done for edge-coated as well as slit tape. The need for a high-strength reinforcing layer in the tape will be a factor in comparing costs.

The scale-up of the process does not seem to offer serious technical problems, but it will have to be carried out in the near future so that long lengths of material can be supplied for test. Only then will the reliability of the process and the extent of the required quality-control procedures be ascertained. In extrusion and rolling, the problems of scale-up from the 50-mm-dia. bronze billets that were used in this work are not expected to be serious because multifilamentary Nb_3Sn is now made from 200-mm-dia. extrusions. The scale-up of the bronze-removal and copper-deposition steps are expected to present problems in equipment construction and adaptation. If tape without edge coating is satisfactory, it can be made in wide strips which will minimize handling problems in vacuum systems. If the tape must be edge coated, tracking problems may appear in the copper-coating equipment. In both cases, however, registry problems between copper and superconductor, such as those that are encountered in the soldering approach, are nonexistent.

In a large-scale manufacturing operation, all of the manufacturing steps will have to be monitored carefully.

Maintenance of a uniform thickness of both the niobium and the reaction layer will be of prime importance. It also will be important to remove the bronze in a controlled and uniform manner and to replace it with a uniform thickness of copper over long lengths of tape.

Quality-control procedures, which could not be investigated in the present program because of time and manpower limitations, will have to be adopted once the equipment and manufacturing procedures for making the long lengths are available.