UCRL-13717

PHASE I REPORT

PRODUCTION OF MULTIFILAMENTARY Nb_3Sn
COMPOSITES INCORPORATING A HIGH TIN BRONZE

Contract No. 1695603

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A. Petrovich
B. A. Zeitlin
M. S. Walker

MASTER

INTERMAGNETICS GENERAL CORPORATION

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A. Petrovich

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Study Commissioned By: Lawrence Livermore Laboratory
Livermore, California

Study Performed By: Intermagnetics General Corp.
Guilderland, New York

August 20, 1976

(Revised 12/17/76)

IGC Report No. 876-6

ABSTRACT

The economics and processing methods have been examined for the fabrication of multifilamentary Nb_3Sn using a high tin bronze reactive matrix. Four conductor configurations utilizing the high tin bronze were compared with a conventional Cu - 13 wt % Sn bronze. The most promising of these designs is potentially 40% lower in cost per ampere meter than the conventional composite. Large hydrostatic extrusion facilities, which are required for the high tin processing, are not presently available in this country but can be made by conversion of conventional presses. They exist in Europe. Experiments were conducted to investigate the applicability of hydrostatic extrusion, and billet components were successfully prepared using the hydrostatic extrusion technique. We have concluded that the economics, availability of facilities and initial fabrication results are favorable for this type of conductor and that the next stage in this program of scale up to extrusion and drawing of 2"-3" diameter composite billets should be undertaken.

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1.0 INTRODUCTION

1.1 Purpose of the Present Study

The CTR program at Lawrence Livermore Laboratory envisions a high field version of FERF (Fusion Engineering Research Facility) involving a multifilamentary Nb_3Sn composite capable of carrying 10,000 Amperes in a field of 12 Tesla. A conceptual design of the Ying-Yang type mirror magnets which will be an essential part of this facility involves on the order of 7×10^4 kg of multifilamentary superconductor.¹ In view of this quantity of material, the following factors in the fabrication of the conductor become very important:

1. The cost of manufacturing a conductor in large quantities. This is determined by the quantity of materials necessary to produce a given number of amp-meters of conductor, the cost of these materials and the cost of the fabrication steps such as: billet preparation, extrusion, drawing and heat treatment. The number and nature of these fabrication steps in turn depends on the material components of the conductor.
2. The maximum single length of conductor of a given current carrying capacity which may be produced. Because of the present limitation on rod drawing facilities of about 60 meters, the weight of a single length of composite is limited to about 250 kg. The construction of a magnet such as that for FERF would necessarily involve joining of several lengths of conductor. Conductor joints add to the difficulty and expense of magnet construction as well as increase the ohmic dissipation which must be carried off by the cryogenic system. However, the problem of conductor joints can be mitigated to some extent by increasing the billet yield in amp-meters by reducing the quantity of reaction matrix (bronze or copper) necessary to produce a given quantity of Nb_3Sn .

The purpose of the present study is to examine a new technique of conductor design and fabrication which has become commercially feasible because of the

increasing commercialization of cold hydrostatic extrusion. The present study will emphasize the design of the conductor and its fabrication. The two factors in the conductor's fabrication mentioned above will be critically examined.

1.2 Description of the Proposed Method of Fabricating Multifilamentary Nb₃Sn

Multifilamentary Nb₃Sn composites are presently produced by the reaction of niobium filaments with an α -bronze matrix provided either by coldrawing bronze with niobium or by the diffusion of externally applied tin to copper/niobium composites. While tin bronzes of composition about 13-15 wt % tin require anneals after each 40% to 90% reduction in area, copper and niobium are sufficiently ductile to withstand almost unlimited drawing without intermediate anneals. Consequently, composites involving the external application of tin to a drawn niobium/copper/tantalum composite are potentially more economical than drawn bronze/niobium/tantalum composites. However, there is a reservation to the application in FERR of a 10,000 A (12 T) MF Nb₃Sn superconductor produced by the external diffusion of tin into a copper/niobium composite (external diffusion method). Since a typical diffusion distance of tin in a copper composite is only on the order of 0.020" (.051 cm) at the reaction temperatures, a conductor of this current carrying capacity must be produced by cabling several strands of composite. In view of the tremendous crushing forces estimated for the proposed coil, cables are not preferred.

The present study has been conducted to develop a monolithic conductor having the fabrication advantages of a copper based composite. In particular, we will examine the potential of the proposed conductor for reducing conductor costs and increasing the amp-meter yield of an extrusion unit length of conductor.

The proposed conductor essentially involves the replacement of the conventional α -bronze in a monolithic conductor with a matrix of pure copper and filaments of a tin rich copper tin alloy (0 to 20 w/o copper).² Reaction of the niobium filaments proceeds by the diffusion of tin from the tin alloy filaments to form the α -bronze which surrounds the niobium filaments and provides a vehicle for their reaction. The technique has been used successfully by Hashimoto et al³ to produce short lengths of multifilamentary Nb₃Sn. Several advantages of this technique over the conventional α -bronze (up to 15 wt % tin)/niobium composite are readily apparent:

1. A greater quantity of tin may be included in the reaction matrix. In order to be workable copper rich bronzes cannot exceed 15 wt % tin. Beyond this concentration bronze becomes a two phased alloy consisting of α -bronze and the very brittle ϵ phase.² The result of the increased matrix tin concentration resulting from the proposed technique is an increased overall composite current density, a reduction in the quantity of materials necessary for a given ampere meters of conductor, and an increase in the ampere-meter yield of the billet. These factors result in a reduction in the conductor fabrication cost as well as longer conductor lengths per billet.
2. As demonstrated by Hashimoto et al³, the composites consisting of pure copper, tin-20% copper and niobium may be drawn to their final diameter without a single anneal. The replacement of the α -bronze matrix with such a two element matrix would eliminate the costly and time-consuming annealing schedule necessary to reduce α -bronze composites to their final diameter. The net result would not only be a reduction in conductor cost but also a decrease in the time from billet construction to final conductor.
3. Casting of α -bronze to form the elements for billet preparation would be replaced by the casting of the lower melting point tin rich alloys and fabrication of pure copper elements. Here as well there is a potential cost savings since OFHC copper is more easily worked and the cost of casting tin rich alloys is less than that for α -bronze.

Although the work of Hashimoto et al³ has demonstrated the feasibility of drawing and reacting the proposed conductor, several questions must be answered regarding the large scale production of such composites. Among these are:

1. The ability to extrude composites consisting of copper, niobium, tin rich alloy and tantalum. Pressures required for the conventional extrusion of copper based composites at room temperature are prohibitively high. The billet preheating to at least 550°C which is generally applied to reduce these pressures is significantly above the melting point of tin (232°C) and would therefore disrupt the composite. A reasonable alternative may however be found in room temperature hydrostatic extrusion. Although reductions of 15/1 in area⁴ have been accomplished on OFHC copper by cold hydrostatic extrusion, the effect of billet heating resulting from dissipation of the energy of plastic deformation during cold hydrostatic extrusion must be examined.
2. The feasibility and procedure for producing the elements for billet stacking. These elements include hexagonal rods of the tin rich alloy. The drawing of pure tin or the tin rich alloy by itself is made difficult by the softness of pure tin and the brittleness of the tin-copper alloys. The amount of jacketing with copper and the soundness of the drawn jacketed rods must be determined.
3. The soundness of the tin or tin alloy filaments after reduction to the final diameter must be established.
4. The size and distribution of the tin alloy filaments which will ensure a sound conductor and uniform diffusion must be determined. Limitations on the size of these filaments may result from development of Kirkendall voids which should not engulf groups of niobium filaments. As tin and copper interdiffuse prior to reaction, non α -bronze phases tin-copper alloys necessarily form. Previous investigations suggest that Nb₃Sn is not formed when niobium filaments are in contact with copper tin alloys other than α -bronze. The extent of their growth is therefore an important consideration in the design of an optimal conductor.

5. The cost and availability of hydrostatic extrusion facilities and its impact on overall conductor fabrication cost must be established.

The first phase of this study is intended to answer those fundamental questions. Having determined those essential features of the conductor fabrication, this report will describe viable conductor options, will provide an assessment of the production economics of the proposed approach, and will suggest the details of further development of full conductor composites to be carried out in the second phase of this program.

The remainder of the report is divided into five chapters which will deal with the following aspects of the study:

Chapter 2 will provide background information on the construction of composites consisting of tin rich alloys and hydrostatic extrusion of copper.

Chapter 3 will describe the analysis and experimentation conducted to answer the critical questions mentioned above.

Chapter 4 includes descriptions of model conductor.

Chapter 5 will provide an economic comparison between the proposed conductor designs and a composite based on a 13.5 wt % bronze matrix.

Chapter 6 will provide conclusions on the present study and recommendation for further development.

2.0 BACKGROUND

In this chapter we will provide a background to discussions presented in subsequent chapters. Pertinent aspects of hydrostatic extrusion such as the status of existing facilities, the nature of the process and heat generation during extrusion are discussed. In connection with the design of a MF Nb₃Sn composite including a high tin bronze we will not only discuss previous successes in the area but also some aspects of the diffusion of tin in tin-copper alloys and the growth of alloy phases. Previous studies on the mechanical properties of tin-copper alloys are also summarized in this chapter.

2.1 Hydrostatic Extrusion

2.1.1 The Capabilities of Hydrostatic Extrusion

The fundamental difference between hydrostatic and conventional direct extrusion is illustrated in Figure 1. Instead of being in contact with the container walls as in conventional extrusion, the billet in hydrostatic extrusion is supported by a fluid over all surfaces except that in contact with the die. The extrusion driving force in hydrostatic extrusion is not provided directly to the end of the billet as in conventional extrusion. Instead the force is applied to the billet as a pressure applied over all surfaces exposed to the hydrostatic fluid. This mode of applying the extrusion driving force has at least three fundamental advantages:

1. The hydrostatic pressure considerably enhances the ductility of the material being extruded. This aspect of metals which has been extensively investigated by Bridgeman⁵ and others, results from the prevention of pores and microcracks which are involved in the mechanism of fracture. Consequently, a hydrostatic process permits the extrusion of materials which are too brittle to be extruded conventionally. There is, therefore, much greater assurance of producing a sound extrusion of copper or copper alloy composites at room temperature by hydrostatic extrusion than conventional extrusion.

Figure 1. Schematic representation of the hydrostatic and conventional extrusion processes.

2. The fact that the billet is supported by a fluid in the extrusion container rather than a container wall eliminates an important component of friction and thereby considerably reduce the extrusion pressure necessary for a given conductor. This fact is particularly important to the composites in question which contain low melting temperature alloys of tin. The temperature rises occurring in these composites during extrusion are roughly proportional to the work expended or pressures. The peak temperature will undoubtedly be the factor limiting the permissible reduction ratios.
3. When the fluid is continually in contact with the billet up to the die as it is in hydrostatic extrusion, there is a possibility of fluid being carried into the die when the billet velocity exceeds a critical value. This situation, often referred to as hydrodynamic lubrication leads to a reduction in die friction and consequently a reduction in extrusion pressures. As will be discussed later, the existence of a lubricating film in the die allows a greater range of die angle and therefore greater possibilities for reducing undesirable effects observed in conventional extrusion such as the piping defect and distortion.⁶

The ability of hydrostatic extrusion to reduce copper at room temperatures is essential to the proposed conductor because of the low melting point of tin rich copper-tin alloys (solidus: 227°C). However, even with hydrostatic extrusion there is concern over billet heating occurring as a result of dissipation of the work of deformation. If the reduction rate is high enough, the tin phase may acquire the latent heat necessary to cause melting. The reduction ratio necessary to bring about melting and the effect of such melting on the integrity of the composite will be established in this study. If the limiting reduction is that which melting occurs, such a factor will be important to establishing the economics of the process.

2.1.2 Existing Commercial Facilities

With the increasing awareness of its unique capabilities cold hydrostatic extrusion has become a fully commercial method of reducing production size billets to rod and wire. ASEA (Allmänna Svenska Elektriska Aktiebolaget) now offers a range of production hydrostatic extrusion presses extending up to a capability of 290,000 psi with a container which may accommodate a billet 7 1/8" diameter and 47" long (1900 cu in).^{7,8} With the capability of 20 cycles per hour, this hydrostatic extrusion press is comparable in production rate to a conventional extrusion press. A major production application of hydrostatic extrusion of large billets is in the manufacture of copper clad aluminum wire. For example, the National Standard Company in Scotland is involved in the production of such wire using a 4000 ton extrusion press built by ASEA of Sweden.⁸ In addition to this, there are other large ASEA hydrostatic extrusion presses in Japan, Holland and Sweden.

In addition to the extrusion of large diameter billets, there are several schemes for the reduction of rod and wire either by a purely hydrostatic extrusion or a combination of hydrostatic extrusion and tensile forces on the exiting wire (augmented hydrostatic extrusion).^{9,10} An example of a technique for wire drawing which relies on continuous hydrostatic extrusion is that presently under development at Western Electric Company.¹¹ Shown in Figure 2, their machine provides a continuous track loop. As shown in the diagram, the four continuous tracks provide four chamber segments through which the rod is extruded. Rather than gripping the rod directly, a viscous liquid (e.g. polyethylene) transfers pressure from the chamber segments to the rod. With traction also provided in this manner, the rod is drawn into a higher pressure region further in the machine where diameter reduction is accomplished on the rod. Conventional wire drawing techniques involving tensile forces pulling the wire through the die is capable

MOD III ENDLESS CHAMBER EXTRUDER

FIGURE 1

Mod III Endless Chamber Extruder: a continuous hydrostatic extruder under development at Western Electric Company (reproduced from "Western Electric Company Continuous Hydrostatic Wire Extrusion", Paul Andrus and Glenn Schmehl, Manufacturing Engineers, February 11, 1976, Philadelphia, Pennsylvania).

of only 10 to 30% reduction in area because of the limited tensile strength of metals. This machine at Western Electric on the other hand reduces aluminum rod to wire with a reduction ratio of 325 and a rod speed of 3 feet per minute.¹¹ Having only a 5/16" (.79 cm) bore in the pressure chamber, this machine cannot be used for either billets or the rod resulting from the extrusion of an 8" to 10" (20-25 cm) diameter billet.

Large extrusion presses such as those produced by ASEA represent a significant capital investment of on the order of tens of millions of dollars. To our knowledge there is no American company contemplating the purchase of such a press in the near future. Battelle Laboratories, however, have developed a means of converting conventional extrusion presses to a hydrostatic extrusion facility and have applied this modification to their own 2500 ton press. Costing on the order of \$100,000 for the conversion of an appropriate conventional press to one capable of extruding 7" diameter copper composite billets, this procedure is the most feasible alternative for the relatively small scale requirement of FERF.

In addition to these facilities there are many small experimental extrusion presses in this country. These facilities will be enumerated along with available production size facilities in Appendix A.

2.1.3 Factors Affecting Pressures Necessary for Hydrostatic Extrusion

The cold hydrostatic extrusion of copper, aluminum and other materials has been extensively studied. Figure 3 shows the necessary extrusion pressure as a function of reduction ratio for copper and several other materials. In a manner analogous to conventional extrusion the analytic expression relating extrusion pressure to reduction ratio for hydrostatic extrusion is:

Figure 1. Examples of the reduction obtainable by hydrostatic extrusion through a single die. (Reproduced from Anon., "Hydrostatic Extrusion - A Viable Method of Metal Forming", Metalworking and Metal Forming, October 1971, p. 325).

$$P = A \ln R + B$$

(1)

where P is the pressure, R is the reduction ratio and the constant A , B depend on such factors as die angle, condition of friction in the die and billet diameter.⁶

An important factor determining the extrusion pressure is the die design. Dies commonly used in practice are conical in shape with a cone angle chosen according to the material properties, the reduction ratio and the condition of friction prevailing at the die. For a given set of conditions such as coefficient of friction at the die, material yield stress and reduction ratio there is a die angle which corresponds to a minimum in the extrusion force. In conventional extrusion the optimal die angle usually increases with increasing extrusion ratio and coefficient of friction. This feature has in fact been demonstrated analytically in the text of Avitzur⁶ and is expressed in a formula relating driving stress to reduction ratio, die angle and coefficient of friction.

Another factor determining extrusion force is the strain rate of the material being deformed. Even without strain hardening, deformation stresses generally increase with increasing strain rate. A third factor in determining extrusion force which is particularly important to the process of hydrostatic extrusion is the possibility of hydrodynamic lubrication. This phenomenon, which is characterized by a continuous film of lubricant separating the billet from the die, will occur when the lubricant is sufficiently viscous, the velocity of material at the die is sufficiently high, and the extruded rod diameter is sufficiently small.

Hydrodynamic lubrication is more readily maintained in cold hydrostatic extrusion than in conventional warm or hot extrusion because of the stability of the lubricant at lower temperatures and the greater availability of the

Figure 4a. Example of the piping defect occurring during the conventional extrusion of a composite billet.

Figure 4b. Distortion of filament pattern occurring near the ends of the extruded rod.

extrusion fluid under pressure as a die lubricant. Since the velocity of the material at the die generally increases with decreasing die angle for a given reduction ratio and since a minimum velocity is necessary to maintain hydrodynamic lubrication, the phenomenon is more likely associated with smaller die angles.⁶

Hydrodynamic lubrication provides an important benefit to the extrusion of superconducting composites. As mentioned earlier, the optimal die angle increases with increasing friction and extrusion ratio. At higher reduction ratios (e.g. 20/1) the extrusion force increases rapidly as one reduces die angle from the optimal value. However, the defects which occur near the ends of the extruded rod such as distortion of the filament pattern and the pipping defect (see Figure 4) are more severe as one increases the die angle. In conventional extrusion, we are therefore forced by the necessity of reducing extrusion force to choose a die angle which results in a more extensive region of the extruded rod characterized by defects. In a typical extrusion of a bronze/nickel composite up to 20% of the extruded rod must be discarded because of these defects. The existence of hydrodynamic lubrication during hydrostatic extrusion results in a reduction of friction and therefore a reduction in the optimal die cone angle. We therefore have good reason to believe that billet discard will be reduced when conventional warm extrusion is replaced by cold hydrostatic extrusion of copper based composite billets.

2.2 Heat Generation During Extrusion

Because of the existence of a low melting temperature materials in the composite billets of the proposed approach there is concern over temperature rises resulting from the dissipation of the work of deformation. We must therefore understand the effect of extrusion rate, heat conduction, and billet size on

the peak temperature reached by the billet. The analysis of the thermal problem during extrusion is complicated by the simultaneous processes of heat generation, transport of heat by moving material and conduction of heat by thermal diffusion. However, several investigations have made progress in estimating heating effects during conventional and hydrostatic extrusion through conical dies. By using a finite element technique for the calculation of temperature and determining the velocity and strain fields determined from a viscoplasticity experiment, Altan and Kobayashi¹² were able to calculate non-steady state temperature along the length and cross section of the billet at particular stages of the extrusion. Using a similar means of analysis Guha and Lengyel¹³ calculated the temperature distribution occurring in a billet during hydrostatic extrusion/drawing. Carrying out their calculations by assuming properties of high conductivity copper, they theoretically established some interesting aspects of temperature distribution during the extrusion process. Figure 5 is a reproduction of their curves showing the variation of temperature over the cross section of the extrusion product at the die exit for several values of coefficient of friction and billet velocity. As one would expect, there is peaking in the temperature at the surface of the extruded rod. However, reducing the extrusion speed not only reduces the average temperature achieved but also tends to eliminate the peak in temperature at the surface resulting from friction. Figure 6 showing their curves of temperature rise of the material as a function of the progress of the extrusions indicates that a steady state temperature is rapidly achieved during the extrusion process. Temperature measurements of Singer and Al-Samarrai¹⁴ on materials exiting an extrusion die confirms the qualitative temperature variation theoretically predicted by Guha and Lengyel¹³. Figure 7 showing their measurements of the rise in emergent temperature as a function of ram travel for lead demonstrates the temperature plateau reached early in the extrusion

as well as the variation of this steady state temperature with extrusion speed. Figure 8 shows their curves for the rise in emergent temperature as a function of ram travel for tin billets subjected to various reduction ratios. The variation of temperature with extrusion ratio is roughly proportional to the rate of deformation energy generation as predicted by equation (1).

For the purpose of this study, detailed calculations of the temperature distribution as carried out by the previously mentioned investigations would be excessively time-consuming and not particularly enlightening. In order to control the temperature rise in the material we must understand the effect of the following factors on peak temperature achieved in the extrusion process:

1. Billet speed
2. Heat transferred from the extruded rod
3. Heat conduction from the deformation region
4. Reduction ratio
5. Billet diameter
6. All other factors determining the extrusion pressure

For this purpose we have constructed a mathematical model which neglects the temperature variation over the cross section and deals only with the steady state temperature. As shown in Figures 5, 6, 7 and 8, these specifications are well justified at sufficiently low speeds and low coefficient of friction. Figure 9 shows a schematic representation of the extrusion die and the position coordinates to which all of the formulation will refer. We will start by writing the steady state heat balance for the billet and the extruded rod outside of the deformation zone. In the billet we have:

$$k \pi a_B^2 \frac{d^2 T}{dx^2} - \pi v_B C a_B^2 \frac{dT}{dx} - 2 \pi a_B h_B T = 0, \quad (2)$$

where T is the temperature of the billet at position x along its length,
 k is the average thermal conductivity of the billet material,

Figure 5. Calculated curves of the temperature variation over the cross section of the extrusion product at the die exit for several values of coefficient of friction and billet velocity. (From Guha, R. M., Lengyel, B., Vol. 54, p. 117, Jan, 1974).

Figure 6. Calculated curves of temperature rise of the extruded material as a function of the progress of the extrusion. (From Guha, R. M. Longyel, B., Vol. 54, p. 117 (Jan. 1974).

Figure 7. The rise in emergent temperature as a function of ram travel for lead as measured by Singer, Al-Samarrai, Journal Institute of Metals, Vol. 89, p. 225, reduction ratio: 29

Figure 8. Experimentally determined rise in emergent temperature as a function of ram travel for tin billers subjected to various reduction ratios. (From Singer Al-Samarrai, Journal Institute of Metals, Vol. 89, p. 225).

Figure 9. Schematic representation of the extrusion die, billet die and position coordinates referred to by equations 2.2 through 2.5.

a_B is the radius of the billet,
 v_B is the speed of the billet,
 C is the heat capacity of the billet material,
 and h_B is the coefficient of surface heat transfer between the surface of
 the billet and the hydrostatic fluid medium.

A similar expression can be written for the extruded rod:

$$k \pi a_R^2 \frac{d^2 T}{dx^2} - \pi v_R C a_R^2 \frac{dT}{dx} - 2 \pi a_R h_O T = 0, \quad (3)$$

where now

h_O is the coefficient of surface heat transfer between the rod and
 whatever medium surrounds it,
 a_R is the radius of the extruded rod,
 and v_R is the speed of the extruded rod.

In both of the above expressions we have assumed a uniform temperature distribution
 over the cross section of the billet or rod. The first term in the above
 expressions represent the process of heat conduction along the billet or rod.
 The second represents the transport of heat by the moving rod or billet and
 the last term the heat transferred from the surface. In the deformation zone
 the heat balance equation is more involved. Not only is the billet reducing
 in diameter as it passes through the die but also heat is being generated at
 a rate which is related to the rate of deformation at any point in the
 deformation region. The differential equation within the die which occupies the
 length l along the x axis is:

$$\begin{aligned}
 k \pi (\tan \alpha)^2 (b-x)^2 \frac{d^2 T}{dx^2} - v_B a_B^2 C \frac{dT}{dx} \\
 - 2 \pi h_O \tan \alpha (b-x) T + W(x) = 0,
 \end{aligned} \quad (4)$$

where

d is the die semi cone angle,

h_0 is the surface heat transfer coefficient between the billet and die surface,

b is the constant equal to $a_b/\tan \alpha$

and $W(x)$ is the deformation energy dissipated per unit length along the die.

To determine the steady state temperature as a function of position we must solve the differential equations 2, 3 and 4 and apply the boundary conditions which are:

$$T = 0 \text{ at } -\infty \text{ and } +\infty$$

$$T_I = T_{II} \text{ at } x = 0$$

$$\frac{dT_I}{dx} = \frac{dT_{II}}{dx} \text{ at } x = 0$$

$$T_{II} = T_{III} \text{ at } x = l$$

$$\frac{dT_{II}}{dx} = \frac{dT_{III}}{dx} \text{ at } x = l \quad (5)$$

Analytic expression for T_I and T_{III} are easily obtained for the corresponding homogeneous differential equations. However, an expression for T_{II} is considerably more difficult.

For the sake of establishing the effectiveness of cooling the extruded rod in reducing the peak temperature experienced by the composite, an expression will be derived from these equations relating peak billet temperature to billet speed and reduction ratio.

2.3 The Nature of Alloys in the Tin-Copper System and the Reaction of Such Alloys with Niobium

In anticipation of our analysis and design of conductors including pure tin or high tin copper tin alloys we will discuss pertinent aspects of the diffusion and growth of phases in the tin-copper system, the composition dependence of the rate of Nb_3Sn formation and the mechanical properties of the various tin-copper alloys.

The dependence of the rate of Nb_3Sn formation on the composition of the matrix in solid state reaction in bronze has been clearly established by Suenaga et al.¹⁵ Up to 13 wt % tin in copper, the bronze matrix remains a homogeneous α phase throughout the processing of multifilamentary composites and generally the rate of Nb_3Sn formation increases up to this concentration. As may be seen from the phase diagram in Figure 10, concentration of tin exceeding 13.5 wt % at typical reaction temperature of 700°C to 800°C correspond to two-phased microstructures including both the α phase and δ phase.¹⁶ These duplex structures are usually avoided in multifilamentary niobium/bronze composites because of their poor working properties and the possibility that δ phase interferes with the growth of Nb_3Sn .¹⁷

Kinetic studies of Suenaga et al.¹⁵ suggest that the rate of Nb_3Sn formation is severely reduced in the composition range corresponding to this two-phased structure.* Whether this effect is the result of unfavorable kinetics of tin diffusion to the niobium filaments in the formation of the A-15 phase or a thermodynamic effect involving the development of non Nb_3Sn phases is not definitely known. However, investigations of Zwicker and Rinderer¹⁸ have

*Recent work of K. Ralls presented at the October 1976 AIME suggest that this is not true of the entire composition range of this two-phased structure.

Figure 10. Phase diagram for the Tin-Copper system.

clearly established that non A-15 phases are formed when niobium reacts with tin copper alloys having a higher tin concentration than α -bronze.

There are several phases in the tin-copper system which are too brittle to be worked. For example, the ϵ phase, characterized by a narrow composition range of homogeneity around the stoichiometry Cu_3Sn , has been shown to be extremely brittle. This is probably true as well of the other phase of narrow compositional range, the η phase, which like the ϵ is stable at room temperature. Alloys in equilibrium at room temperature which range in composition from 45 wt % tin to 79 wt % tin are characterized by a two-phased structure of the η phase and a tin solid solution saturated with copper. These alloys are also characterized by a ductility roughly proportional to their tin concentration. In spite of the fact that alloys of this compositional range are not as ductile as either pure copper or pure tin, composites including such alloys as shown by Hashimoto et al³ can readily be drawn through significant reductions without the need for intermediate anneals. This is probably a consequence of two fortunate qualities of these tin-rich copper-tin alloys: they are softer than the copper matrix and the hydrostatic stress provided by the matrix is sufficient to prevent fracture of the alloy phase.

In view of the suspected adverse effects of non α -bronze copper-tin phases on the growth of Nb_3Sn at the niobium filaments we are taking the precaution in our proposed conductor designs of avoiding the growth of such phases among the niobium filaments. Consequently, the composite must be optimized with proper regard to two conflicting considerations. On the one hand, one would like to eliminate as much of the copper matrix as possible to increase current density and, on the other hand, enough copper must be left as a buffer between the tin alloy regions and the niobium filaments.

The work of Kawakatsu et al¹⁸ provides some important information regarding the growth of phases in a system consisting originally of pure copper and pure tin saturated with copper. The phases appearing in diffusion couples generally include at least some of the phases appearing in the equilibrium phase diagram at the given temperature. As expected, the study of Kawakatsu et al¹⁸ showed the orderly development of only the ϵ and η phases up to 410°C. Unexpectedly, however, the η phase still existed at 430°C when the phase diagram indicates a maximum temperature of 415°C for the η phase. The preferential growth of phases richer in tin such as η is beneficial to the processing of the proposed conductor. The more concentrated the tin alloy resulting from heat treatment the more compact these non α phases which are detrimental to Nb_3Sn formation. An optimal homogenization heat treatment involves the greatest confinement of the non α phases which still permits the rapid diffusion of tin through α -bronze.

2.4 Previous Work on Multifilamentary Nb_3Sn Composites Including Tin Rich Copper-Tin Alloys

The composite produced by Hashimoto et al³ involved pure copper, tin - 20 wt % copper and niobium in the ratio of .673, .151, .176 respectively. After reducing the composite to about 0.005" (.127 mm) diameter without a single anneal, the composite was heat treated at 720°C for 50 hours. The photomicrograph of the composite following the heat treatment showed a cross section with no apparent void formation. However, in view of the small number of niobium filaments compared to commercial conductors now available, the composite produced by these authors is far from optimized. The development of a commercial process for this composite concept and the optimization of the overall current density in the composite is the goal of the present study.

3.0 ANALYSIS OF CONDUCTOR AND PROCESSING

The present chapter will describe experimental and analytic studies performed to answer several critical questions in the design of composites involving a *reaction matrix of pure copper and a tin rich copper-tin alloy. Among these critical aspects are the following:*

1. The size and distribution of the tin rich elements. Tin must be distributed sufficiently to allow diffusion throughout the reacting matrix. The size of the tin alloy elements and their proximity to niobium filaments is restricted by the need to prevent growth of non α -phase copper-tin alloy phases among the niobium filaments. The size of the tin alloy elements will also determine the distribution of Kirkendall voids. Present in all types of reacted multifilamentary composites, these voids should not be so large or extensive that they interfere with the transport of tin to the niobium filaments.
2. The heat treatment which will minimize the spreading of non α phases during the homogenization heat treatment prior to reaction. The more compact the tin rich regions after homogenization of tin the larger the tin rich elements may be.
3. The procedure for producing elements for billet packing and billet extrusion. Conductor fabrication usually begins with an extrusion of a composite billet made up of hexagonal rods consisting of the conductor elements. The number of extrusion stages, the nature of the components at each stage of billet extrusion and the extrusion reduction ratio are all important to the cost of conductor fabrication and will therefore be considered in detail. The maximum extrusion ratio which may be accomplished by hydrostatic extrusion of billets *containing high tin alloy will be studied through several experimental extrusions.*
4. Control of billet heating during operation. The minimum billet extrusion cycle time will be determined by the likelihood of melting of the tin rich alloy. In this study we have observed the effects of temperature rise during the extrusion of a limited number of composite

billets. By applying the formulation of Chapter 2 we will be able to extend our results to predict the heating effects at larger billet diameters, over a greater range of speeds, and over a greater range of reduction ratios.

The following chapter will include the description of four model conductors based on the information we have assembled in this phase of the program. Each of the model conductors will be capable of carrying 10,000 Amps at 12 Tesla and their processing will be described in detail to facilitate the comparison of the economics of their production to that of a bronze composite.

3.1 Drawing of Composites Including Tin or a Tin Rich Copper-Tin Alloy

Figures 11 and 12 show the cross section of the composite used in our diffusion studies having been drawn to a 0.015" (.38 mm) diameter and 0.008" (.20 mm) diameter respectively. The composite consists of a core of a tin 1.7% copper alloy in a pure copper jacket. As one may see from the figures, the core exhibits a duplex structure consisting of a matrix region of copper saturated tin and particles of η phase as well as particles of η phase surrounding cores of ϵ phase. The existence of the ϵ phase is the result of coring during solidification of the alloy. The cast structure of the starting tin alloy is shown in Figure 13. There as well we see the duplex structure which exists as a dendritic structure with regions of the copper rich phases consisting of cored regions having ϵ in the center and η on the outside. A feature worthy of note is the considerable degree of refinement of the particles of the copper rich phases as one draws the composite from its original diameter of 0.500" to the final diameter of 0.008" (.20 mm). This refinement of the brittle phase apparent from Figures 11 and 13 represents an approximate average of reduction in cross sectional area of the grains by a factor of 200.

Figure 11. Experimental composite used in diffusion studies consisting of a core of Sn - 16.7% Cu within a jacket of pure copper composite diameter of 0.015" (.38 mm). Magnification: 300X

Figure 12. Same experimental composite as shown in Figure 11
but drawn to a diameter of 0.018" (.20 mm).
Magnification: 500X

Figure 13. As cast structure of the Sn - 16.7% Cu alloy used to produce the composite drawn in Figure 11 and 12. Magnification: 200X

In spite of the existence of the brittle phase, the 16.7 wt % copper-tin alloy in a pure copper jacket may be drawn through significant levels of reduction without the appearance of drawing defects such as chevroning which is characterized by void regions near the center of an extrusion or drawn rod of a brittle material. The photomicrographs in Figures 14 and 15 show sections along the length of the composite having the cross section shown in Figure 11. Not only is there no evidence of chevroning or other defects, there is no disturbance of composite uniformity by the more brittle phase.

In our design of a composite including a tin rich region in the reaction matrix we have been more inclined towards a tin rich tin-copper alloy in the two phased region of the equilibrium phase diagram rather than pure tin. This preference is based on several considerations involving orderly interdiffusion during homogenization heat treatment and the integrity of the composite. The work of Hashimoto et al³ involving a composite including such an alloy (tin - 20% copper) demonstrated the successful reduction of a composite with a two phased tin alloy constituent. The difference in hardness between pure tin and pure copper is large enough to lead to problems during extrusion of a composite including both constituents. To avoid the distortion, which can occur when a softer constituent such as pure tin is drawn in a harder material such as copper, a small amount of copper (up to 20%) may be added to the tin to increase the hardness of this constituent. Another advantage of the tin-copper alloy over pure tin is that the material can be contained more readily if melting occurs during hydrostatic extrusion. Rather than melting entirely at a single temperature a tin rich alloy containing copper will begin to melt at slightly below the melting temperature of pure tin but will exist below the liquidus temperature as a partly molten material with a distribution of a solid phase which impedes the flow of the molten portion of the alloy. A third possible advantage of the tin-

Figure 14. Photomicrograph of a longitudinal section of the composite shown in Figure 11. Magnification: 300X

Figure 15. Photomicrograph of a longitudinal section of the composite as shown in Figure 11. Magnification: 90X

copper-alloy over pure tin is a more orderly interdiffusion resulting from saturation of the tin solid solution phase with copper. When the gradient in concentration is reduced between two components of a diffusion couple, generally the degree of Kirkendall void formation near the original interface is considerably reduced. This is important to our composites because Kirkendall voids occurring near the original interface could conceivably interfere with diffusion of tin throughout the composite.

3.2 Interdiffusion of Tin and Copper During Homogenization of the Tin Rich Constituent

The heat treatment of the proposed composite will have two stages. The first stage will allow the homogenization of tin throughout the reacting matrix in preparation for the reaction to be carried out in the second stage of heat treatment. Since reaction should not occur in the first stage, it must be carried out at a temperature below 600°C. An important consideration in the selection of the heat treatment time and temperature is that at the chosen temperature the tin must exhibit a sufficient rate of diffusion in α -bronze and the whole process must be completed with the greatest degree of confinement of non α phases. The optimal homogenization heat treatment may involve two or more stages and will be the subject of further investigation. However, we have performed some experiments to determine the important features of the diffusion process.

3.2.1 Diffusion in Experimental Composites

The composite used in our studies is that shown in Figure 11. The overall diameter was 0.015" (.38 mm) and the diameter of the tin rich regions was 0.0092" (.234 mm). After a heat treatment of 400°C for 20 hours, the composite cross section had the configuration of phases shown in Figure 16. The center region is the original two phase mixture of tin and η phase. The next ring of material

Figure 16. Photomicrograph showing the cross section of the composite wire after a heat treatment of 20 hrs. at 400°C . Magnification: 300X

going outward is pure η phase followed by ϵ phase and finally the α phase. From the pinkish color of this phase one may conclude that at this temperature tin had not diffused to an appreciable extent in copper. The data of Oikawa and Hosoi¹⁹ indicating a diffusion distance* for tin in copper of 4×10^{-5} cm after 20 hours at 400°C confirms the sluggish diffusion of tin in copper at this temperature. The heat treatment at 400°C was continued and the result is shown in Figure 17. As this figure shows, after 68 hours at 400°C all of the original tin rich phase mixture has been eliminated, the ϵ phase has grown while the η phase which now occupies the center has reduced. The outer region of almost pure copper still does not show any appreciable extent of tin diffusion into the copper. If the heat treatment at 400°C were allowed to continue, all the η would probably be converted to ϵ phase before even a small fraction of the tin could diffuse into the copper.

Figure 18 shows a sample of the composite shown in Figure 11 after a heat treatment of 68 hours at 600°C . Two phases are apparent in this photomicrograph. The yellowish phase near the outside is a bronze through which an appreciable amount of tin has diffused. The greyish blue region with the specked appearance consists of the ϵ phase and small regions of α -bronze. The inner region has this phase mixture because it is the product of the decomposition of the δ phase which is formed at the heat treatment temperature (600°C). Judging from the quantities of the two phases shown in this section, the composite must be close to equilibrium.

3.2.2 Implications of These Diffusion Studies on Composite Design

The distribution of the ϵ phase shown in this photomicrograph is quite irregular most likely as a consequence of growth of the non α phases and subsequent decomposition of such phases as diffusion of tin into the copper is allowed to

*Diffusion distance is defined as $(\text{diffusion coefficient} \times \text{time})^{1/2}$

Figure 17. Photomicrograph showing the cross section of the composite wire after a heat treatment of 68 hrs. at 400°C. Magnification: 300X

Figure 18. Photomicrograph of a sample of the composite shown in Figure 11 after a heat treatment of 61 hrs. at 600°C. Magnification: 300X

proceed. The circle fully containing the remanent ϵ phases is the region in which no niobium filaments should exist in a superconducting composite including all three constituents. For the sake of selecting a heat treatment which will result in the greatest confinement of the ϵ phase, a comparison of the extent of ϵ phase resulting from the two heat treatment temperatures will be useful. From the photomicrograph of Figure 17 we may calculate the ratio of the diameter of the circle fully circumscribing the non α phase region (d_f) to the diameter of the original tin alloy filament d_i :

$$d_f/d_i = 1.46 \quad (6)$$

(after a heat treatment of 68 hours at 400°). At this point in time during the interdiffusion of tin and copper the η phase has not been completely converted to ϵ phase. The final extent of the ϵ phase is therefore expected to be worse than that indicated by expression (6). A similar ratio may be established for the heat treatment carried out at 600°C as represented by the photomicrograph of Figure 18:

$$d_f/d_i = 1.340 \quad (7)$$

(after a heat treatment of 61 hours at 600°C). The results would tend to recommend the 600°C heat treatment over a lower temperature heat treatment such as one at 400°C for homogenizing the composite prior to reaction. The advantage of a higher temperature probably results from a high rate of diffusion of tin in copper occurring simultaneously with the growth of the other phases. A homogenization carried out at a temperature greater than 600°C may result in even greater confinement of the ϵ or δ phase but would present the danger of premature reaction and consequently a poor distribution of Nb_3Sn over the groups of niobium filaments. Although the homogenization heat treatment is subject to

further optimization, we will accept these preliminary results for the design of our composites. Accepting 600°C as the homogenization temperature, we will use the relationship of expression (7) as an indication of the region from which niobium filaments must be excluded.

Kirkendall voids are always present after reaction of a multifilamentary Nb_3Sn composite. However, bronze/Nb composites, externally tinned copper/niobium composites and copper/niobium/tin alloy composites differ in the nature and distribution of these voids. In bronze/niobium composites voids generally become distributed throughout the niobium filaments. In externally tinned composites or composites containing a tin rich alloy in copper, Kirkendall void formation is usually restricted to the interface between the α regions and the δ phase which forms early in the interdiffusion process. In the composite of Figure 18 these voids exist on or somewhat outside the circle of diameter d_f . If in the design of a composite one distributes the niobium filaments up to the circle of diameter d_f , one is permitting only an insignificant fraction of the filaments to be affected by voids. The percentage of niobium filaments affected by voids in such a composite will undoubtedly be less than that in a typical bronze/niobium composite after reaction.

The Kirkendall voids must not be extensive enough to interfere with the diffusion of tin throughout the composite. The observation of many sections of the composite of Figure 18 revealed no void regions so extensive. Appendix B of this report contains photomicrographs of several other sections of this heat treated composite.

3.3 Billet Construction

The construction of billets in the production of large quantities of superconducting composite generally involves the stacking of hexagonal elements into a hollow cylindrical can. In the preparation of the billets used in the hydrostatic extrusion experiments we therefore used such a stacking method. Hexagonal elements consisting of cores of pure tin and a tin - 16.7% copper alloy were prepared. Both of these elements had cores occupying 70% of their cross sectional area as may be seen in Figures 19 and 20. Groups of seven hexagonal elements were stacked into the billet shell as shown in the schematic representation of the billet cross section in Figure 21. The dimensions of the composite billet are shown in Figures 21 and 22. The tail cap and nose of the billet were secured to the body of the billet by electron beam welding. Photographs of these welds are shown in Figures 23 and 24.

A feature worthy of mentioning is the very successful drawing of a composite containing pure tin and copper. This may suggest that the precaution of alloying the tin with copper to increase its hardness is not necessary. If this is generally true, there would be much greater freedom in designing composites and undoubtedly a reduction in conductor cost.

The important consideration with regard to these composite billets is the maximum reduction ratio permissible before some disruptive effect such as the melting of the tin alloy occurs. The work of extrusion is converted almost entirely to heat which is partly dissipated and partly contributed to billet heating. In order for the tin to melt enough of the mechanical energy of extrusion must be absorbed by the billet to raise its temperature above the melting point of tin. Also, the tin alloy must have time to absorb the latent heat of fusion. With all these factors involved we cannot immediately accept

Figure 19. Cross section of the hexagonal elements used in packing the billets used in the study of hydrostatic extrusion. The dimensions of this hexagonal rod is 0.177" (.450 cm) side to side. The core, which is a Sn - 16.7% C. alloy, occupies 70% of the cross section.

Figure 20. Cross section of the hexagonal element having as its core pure tin. The dimension of the hexagonal rod is 0.177" (.450 cm) side to side. The core occupies 70% of the composite.

Figure 21. Cross section of billet showing the stacking of elements.

Figure 22. Drawing of the billet used in the hydrostatic extrusion experiments.

Figure 23. Photograph of weld at the tail section of the experimental billet.

Figure 24. Photograph of the weld at the nose section of the experimental billet.

the adiabatic temperature calculated from the extrusion pressure as an indication of the temperature achieved by the billet and we cannot assure that merely reaching the melting point results in billet disruption. Most likely the billet temperature must exceed the melting point with a sufficient margin that the latent heat is accepted by the tin during the deformation of the composite.

A superconducting billet containing niobium, tantalum, soft copper and the tin alloy will most likely have a flow stress between hard and soft copper. To provide a difference in component hardness not less than that existing in an actual composite billet, hard copper rather than soft copper was used in the experimental extrusions. The choice of hard copper also guaranteed that the calculated adiabatic temperature rise would exceed the melting point of the tin alloy for the extrusion ratios available to us. The purpose of these preliminary extrusions was to establish the possibility of producing a round extrusion in a composite billet containing the tin alloy and to gain a rough idea of the limitations on permissible extrusion ratio.

3.4 Extrusion of Composite Billets Containing the Tin Alloy

Because of the presence of the low melting point tin alloy the extrusion must be carried out with billets at room temperature or below. Because of the extremely high pressures associated with the cold conventional extrusion of copper and the other composite constituents, hydrostatic extrusion is absolutely essential. Although this extrusion method is not commercially practiced on large billets in the United States, the use of a converted conventional extrusion press in the manner developed by investigations at Battelle seems to be a very practical possibility.

The extrusion should reduce the billet to a diameter less than 5 inches (12.7 cm) which is the limit of presently practical draw bench drawing. The higher the reduction ratio of the extrusion the more economical the process since higher extrusion ratios eliminate more of the draw bench drawing which must be carried out in successive passes with limited reductions per pass.

Of the three extrusion ratios attempted only two 4.7 and 9.5 to 1 reduction in area could be accomplished because of the limitation in pressure (235,000 psi). The extrusions were interrupted when about 4 cm of the billet remained. This allowed us to examine the region remaining in the die. Figure 25 showing the billet extruded at 4.7/1 reduction in area reveals some chatter as a result of uneven and inadequate lubrication. The 9.5 to 1 reduction in area on the other hand revealed a smooth surface at the die interface as shown in Figure 26. Apparently at the higher pressures necessary to carry out the higher reduction ratios, lubrication of the die/billet interface by the extrusion fluid is more effective. The cross section of the rod extruded at 4.7/1 reduction ratio showed regions of nonbonding as did the rod extruded at 9.5/1. Cross sections of the two rods are shown in Figures 27 and 28 respectively. The 9.5 to 1 reduction resulted in melting and rupture of the billet. The results of the hydrostatic extrusions are summarized in Table 3.1.

The extrusion pressures corresponding to the extrusion ratios of our composite billets is shown in the graph of Figure 29 along with estimates of pressure for the extrusion of soft copper. The corresponding adiabatic temperature rises are likewise indicated on the ordinate of this graph. The 4.7 to 1 reduction falls below the pressure corresponding to the melting temperature of tin. The 9.5 to 1 reduction, however, is significantly above this pressure.

Figure 25. Region remaining in die after interruption of the 4.7 to 1 extrusion (6 ft/min billet velocity).

Figure 26. Region remaining in die after interruption of the 9.5 to 1 extrusion (3 ft/min billet velocity).

Figure 27. Cross section of rod extruded with a 4.7 to 1 reduction ratio and a billet speed of 6 ft. per minute.

Figure 28. Cross section of rod extruded with a 9.5 to 1 reduction ratio and a billet speed of 6 ft. per minute.

Figure 29

Table 3-1

SUMMARY OF HYDROSTATIC EXTRUSION EXPERIMENTS

<u>Reduction in Area Attempted</u>	<u>Extrusion Pressure</u>	<u>Peak Pressure at Beginning of Extrusion</u>	<u>Billet Speed</u>	<u>Estimated adiabatic Temperature Rise*</u>
1. 4.7 to 1	100,000 psi	no peak	6 ft/min.	200°C
2. 9.5 to 1 (melting)	153,000 psi	200,000 psi	6 ft/min.	305°C
3. 9.5 to 1 (melting)	145,000 psi	200,000 psi	3 ft/min.	290°C
4. 16 to 1	The initial peak pressure prevented this reduction			

*This temperature is that occurring when no conduction of heat occurs along the billet or rod or to the tooling. It will be the peak temperature experienced by the material in the limit of high extrusion speeds.

In the extrusion of a superconducting composite we can be sure of accomplishing at least a 4.7 to 1 reduction ratio. This would correspond to a 10" (25 cm) diameter billet extruded to a 4.6" (11.7 cm) diameter rod which can be readily handled by existing draw benches.

An alternative to accepting the 4.7 to 1 reduction ratio and continuing the reduction with bench drawing is carrying out the extrusion at a higher ratio with cooling of the extruded rod. The crucial consideration in the evaluation of the possible economic advantage of the latter alternative is the required extrusion speed necessary to allow sufficient conduction of heat from the deformation zone through the extruded rod to the cooling medium. Using the formulation of Chapter 2 with several simplifying but conservative assumptions we arrive at the following expression for the maximum temperature achieved by the extruded billet:

$$T_{\max} = \frac{p}{C} \left\{ \frac{1}{2} + \frac{1}{2} \left[1 + \frac{8 h k}{C^2 v_R^2 a_R} \right]^{1/2} \right\}^2, \quad (8)$$

where C is the heat capacity of the billet material (51 Btu/°F/ft³ for copper)
 v_R is the velocity of the extruded rod
 a_R is the radius of the extruded rod
 k is the thermal conductivity of the composite material (219 Btu/hr ft °F for copper)
and h is the surface heat transfer coefficient to the cooling medium.

Using values for pure copper we have calculated the temperature rise corresponding to the extrusion of a billet at a speed of .13 ft/min for a range of extrusion ratios. The extrusion pressure as a function of area reduction ratio used in the calculation are those corresponding to the trend followed by our composites consisting of hard copper and tin - 16.7% copper elements. The value of h was

determined from the data for boiling water heat transfer of McAdams²⁰ along with the assumption that the heat originates from a surface at half the radius of the extruded rod. The latter assumption approximately takes into account the volume of material that heat must conductor through to reach the cooling fluid. The resulting value for h was 2700 Btu/ft² °F.

The results of these calculations are shown in Figure 30 along with the data from the extrusion of our experimental composites.

Temperature rise corresponding to water cooling at .12 ft/min billet speed ($^{\circ}\text{C}$)

Figure 30. Temperature rise as a function of reduction ratio for a composite billet extruded at a speed of .13 ft/min with water cooling of the exiting rod.

4.0 MODEL CONDUCTOR AND ECONOMIC CONSIDERATIONS

4.1 Design of a 10,000 Ampere (12 Tesla) Conductor Using the Proposed Technique

For the sake of making concrete economic comparisons of the proposed technique to the conventional method of fabricating high current carrying capacity multifilamentary Nb_3Sn conductors, we are presenting four conductor examples all of which include a reactive matrix of pure copper and tin alloy. These conductors, designed to carry 10,000 Amperes at 12 Tesla, 4.2 K, will be based on information gathered in the present study as well as previous experience with bronze bearing and externally diffused composites. Among the considerations in the design of a composite using the proposed method are the following:

1. The tin rich filaments should be distributed and of such size as to avoid the engulfing of niobium filaments by alloy phases such as ϵ or δ resulting from the homogenization heat treatment. The diffusion experiments described in the previous section will provide a guide in selecting the proper tin alloy filament size. Assuming a heat treatment at 600°C , the growth factor in expression (7) may be used. Increasing the surface to volume of the tin alloy filament by reducing its size is expected to enhance the rate of transport of tin by diffusion into the copper relative to the rate of growth of the other tin alloys. Consequently, we expect the growth factor (i.e. the ratio of expression (7) to reduce with decreasing tin alloy filament diameter. Since the tin alloy filaments in the model conductors are smaller than those of the diffusion study, we expect expression (7) to be a conservative estimate of the actual growth factor.
2. The tin rich filaments should be distributed so as to allow homogenization of tin throughout the reaction matrix in a reasonable time. Our past experience with external diffusion indicates that homogenization may occur in a reasonable time at 600°C if all niobium filaments are within 5 mils (.127 mm) of the tin region. Such a distribution of tin would allow sufficient homogenization to occur in a period less than 100 hours.

3. The niobium filaments should be sufficiently spaced from one another to allow diffusion of tin between the filaments and prevent welding between the niobium filaments as the composite is drawn to its final diameter. From previous experience we have selected a minimum spacing between the niobium filaments of one half the filament diameter.
4. High conductivity (OFHC) copper distributed throughout the conductor is useful in providing stability by slowing down flux jumps thereby allowing more time for the heat generated to diffuse away. A rule of thumb proposed by Wilson²¹ for the distribution of the copper is that no Nb₃Sn filament in the bronze should find itself more than 200 μ away from a region of pure copper.

The four conductors presented will involve two stages of extrusion. When a conductor with such high current carrying capacity is constructed with a bronze matrix, three extrusion stages are generally advisable. However, because fabrication of hexagonal rod or tube elements of OFHC copper is widely practiced by existing manufacturers, we may eliminate this first extrusion by using commercially fabricated elements and increasing the number of elements stacked in the two extrusions. There are at least three advantages of such an approach:

1. The cost of the extrusion of a specially prepared bronze composite billet is replaced by the use of more efficiently produced standard commercial hexagonal copper rods and tubes.
2. The loss of material in a first composite extrusion stage due to the typical 80% billet yield is eliminated.
3. The amount of matrix material in the final conductor can be reduced.

Offsetting these advantages, however, is the increased expense of fabricating the smaller and more numerous elements for the remaining stages.

All of the proposed model conductors will contain high conductivity copper occupying about 30% of the cross section and will fulfill all four of the requirements mentioned above. Since the first model conductor includes the tin alloy in the second stages only, the first stage may be carried out either by hydrostatic extrusion or conventional extrusion. On the other hand the second model conductor includes the tin alloy in both stages and therefore both stages must be carried out by hydrostatic extrusion. The advantages and disadvantages of the two approaches will be discussed. In order to produce a sufficient quantity of Nb_3Sn of high critical current density, filaments on the order of 4μ diameter will be included in the design. From the value of critical current for Nb_3Sn at 12 Tesla and 4.2 K:

$$J_c (\text{Nb}_3\text{Sn}; 12 \text{ T}; 4.2 \text{ K}) = 2.02 \times 10^5 \text{ A/cm}^2$$

we may readily calculate the total cross sectional area of Nb_3Sn necessary in the conductor

$$4.95 \times 10^{-2} \text{ cm}^2 \text{ of } \text{Nb}_3\text{Sn}.$$

From this value and the size of the filaments we find that we will require on the order of 500,000 filaments for the conductor. This is not an unreasonable figure for packing in two stages.

The proposed conductor models are not intended to represent optimal conductors but rather good candidates based on careful consideration of design restrictions. Furthermore, they sufficiently represent the advantages of the proposed method to be compared to conductors prepared by conventional means.

4.2 Model Conductor I

This conductor is produced in two stages:

First stage: Elements of niobium cores in copper with a composition ratio of 2 Cu to 1 Nb and including on the order of 500 Nb filaments are produced. This ratio of copper to niobium takes into account the minimum spacing mentioned previously as well as the need for a copper can which occupies 15% of the cross-sectional area of the billet. Containing no tin alloys, these elements can be prepared by conventional extrusion of composite billets. Hexagonal elements of tantalum protected copper must also be prepared for the second billet stacking. These elements may be prepared either by the coextrusion of tantalum sheathed copper or by the insertion of hexagonal copper rods into hexagonal tantalum tubes. Also needed for the second stage billet are copper clad tin or copper tin alloy hexagonal rods for stacking into the second stage billet. These elements may be prepared either by drawing a composite rod produced simply by inserting a tin alloy rod into a copper tube up to 2" (5 cm) outside diameter or by hydrostatically extruding a billet of larger diameter.

Second stage: The hexagonal rod elements produced in the first stage for second stage packing will be about 0.22" (.56 cm) side to side. The tin alloy cores of the copper clad tin alloy rods are of largest size possible but not large enough to allow non α tin-copper phases to engulf the niobium filaments during the homogenization heat treatment. This consideration dictates that the Sn - 16.7% Cu cores not be greater in area than 68% of the copper clad hexagonal element. The billet can will consist of a tantalum inner sheath protecting an outer shell of OFHC copper. The second stage billet cross section is represented schematically in Figure 31. The regions of tantalum protected copper distributed throughout the conductor and on the outside totals about 35% of the cross-

sectional area. A unit cell of the packing is represented in Figure 32. This unit cell contains 6 units of tantalum protected copper, 6 units containing the tin alloy filaments and 24 elements of the Nb/Cu composite.

The details of billet packing and the characteristics of the final conductor for Model Conductor I are summarized in Table 4.1. In calculating the quantity of Nb_3Sn resulting from reaction we have assumed a residual 4% Sn in the reactive matrix and a 40% growth of the original Nb as a result of reaction to Nb_3Sn .

4.3 Model Conductor II

First stage: Rather than producing the niobium/copper and copper/Sn - 16.7% Cu composite elements separately in the first conductor, a single billet containing all three elements is extruded in the first stages of Model Conductor II. Unlike the first conductor, the size of the tin alloy filament is not restricted by the region of non α phase resulting from homogenization but rather by the requirement that all hexagonal elements be of the same size. The copper clad tin alloy elements used in the first stage billet will have 80% of their cross section occupied by the tin alloy. A schematic representation of the first stage packing is shown in Figure 33. A unit cell of the first stage billet hexagonal rod stacking is shown in Figure 34.

Second stage: The second stage billet represented schematically in Figure 35 has a pure copper can with a tantalum sheath serving as a diffusion barrier in the final conductor. Within the two concentric cylindrical tubes is the group of tantalum clad copper and Nb/Cu/Sn - 16.7% Cu hexagonal elements. A unit cell of the packing in the second stage billet is shown in Figure 36.

4.4 Model Conductor III

This conductor is likewise produced in two stages. In the first stage as shown in Figure 37 a niobium/copper composite is produced having 735 niobium cores.

The ratio of copper to niobium of this first stage composite is 1.5. This composite is drawn to a hexagonal rod and clad with pure tin. The clad rods are redrawn through a hexagonal die and stacked in the second stage billet along with hexagonal rods consisting of tantalum clad copper as shown in Figure 37. The billet packing and conductor characteristics are summarized in Table 4-3.

4.5 Model Conductor IV

In this conductor the superconducting filaments consist of niobium tubes each surrounding a region of the tin alloy and pure copper. The first stage billet shown in Figure 38 consists of 735 niobium tubes in a copper matrix. This billet is extruded hydrostatically and drawn to a hexagonal rod for restacking into a second stage billet as shown in Figure 39. This billet is drawn to the conductor whose characteristics are summarized in Table 4-4.

4.6 Processing of Conductors

Calculations in the previous chapter indicate that some increase in extrusion ratio is gained by cooling the extruded rod. However, in order for the measure to be effective the extrusion speed must be substantially reduced. By applying cooling and reducing the extrusion speed to .13 ft/min, the extrusion ratio of an 8" diameter billet can be increased from 4.7 to about 9 (assuming the properties of hard copper). The option of extrusion with a ratio of 4.7 and continuing the reduction to total ratio of 9 to 1 by drawing would probably be more expensive in view of the considerable amount of handling involved. In any event the difference between the two options would have little impact on the total cost of the processed conductor in view of the many other processing steps involved.

There may be more effective means of removing heat from the extruding billet. One may be by the direct cooling of the die region but this would undoubtedly involve the design of a special press. Another means may be to reduce the billet temperature below room temperature prior to extrusion. These measures should be considered in the optimization of the extrusion.

The use of a hydrostatic extrusion press such as that built by ASEA with a chamber of about 50" length would be preferred. However, since none presently exist in this country, the use of a converted extrusion press in the manner developed by Battelle is the most likely alternative. The cost of converting such a press is a very small fraction of the total conductor cost for such a large device as FERF. The cost of operating such a press will most likely be less than for a conventional press in view of the reduced die wear because of the cold extrusion.

The extruded rod is drawn on a conventional draw bench to either a hexagonal rod if an intermediate stage is involved or to the final conductor. No anneals are required and reduction will proceed with much fewer problems than with either NbTi/Cu composites or bronze/Nb composites because of the higher ductility of the components in the proposed design.

4.7 Comparison of Conductor Designs

The first two model conductors show immediate fabricability based on our experiments. The third could undoubtedly be made with some modification of this design if not by the specific procedure outlined. The fourth is an adaptation of a design presently under development.

The first model conductor involving only one hydrostatic extrusion appears to have at least two advantages over the second. One advantage is that the first model conductor involves only one hydrostatic extrusion whereas the second involves two. In view of greater complexity of the hydrostatic reduction process, one may speculate that there is an economic advantage to the process relying the least on hydrostatic extrusion. Another important advantage of the first model conductor is that it requires less reactive matrix for the production of a given quantity of Nb_3Sn than the second model conductor. This is due to the fact that the second model conductor requires more superfluous copper sheathing in the construction of the first billet. However, innovations in billet preparation techniques may eliminate this disadvantage. An advantage of the second model conductor however is that because of the reduced tin alloy filament size a reduction in the homogenization heat treatment time would be realized.

The most interesting of these conductor options is the fourth. An obvious advantage of this approach is the significant reduction in the quantity of reactive matrix over a bronze composite. Other advantages relate to the larger area ratio of the niobium tube to the reactive matrix as compared to an analogous composite using 13 wt % Sn bronze. Construction of billet elements involve the use of niobium tubes with a larger wall thickness to diameter ratio than that which would be used in a similar composite involving a 13.5 wt % Sn bronze. The use of heavier walled tubes considerably reduces the likelihood of tube fraction which could be a considerable problem in view of the fact that ~500,000 tubes are used. In addition to this the cost of niobium tube on a per pound basis would be cheaper for heavier walled tubing.

Table 4-1

SUMMARY OF MODEL CONDUCTOR I

FIRST STAGE

1. Nb/Cu elements drawn to a hexagonal cross section for stacking into the second stage billet have a Cu to Nb ratio of 1.9 to 1 and a total of 750 niobium filaments.
2. Cu/(Sn - 16.7% Cu) hexagonal composite rods having 68% of their cross section occupied by the tin alloy core prepared for the second stage billet.
3. Hexagonal tantalum clad copper elements having 80% of their cross section occupied by copper are prepared for the second stage billet.
4. If the second stage billet is 8" (20.32 cm) diameter, the hexagonal elements produced in the first stage will have the dimensions 0.216" (.549 cm) side to side.

SECOND STAGE

5. Percentage of the cross sectional area of the second stage billet occupied by copper can: 18%
6. Percentage of cross sectional area occupied by tantalum sheath: 5%
7. Number of Nb/Cu elements in the second stage packing: 576
8. Number of tantalum protected copper regions in the second stage: 144
9. Number of copper/(Sn - 16.7% Cu) rod elements: 144

CONDUCTOR CHARACTERISTICS

10. Total number of niobium filaments: 432,000
11. Nominal diameter of filaments: 4.0μ
12. Critical current at 12 Tesla, 4.2 K: 10,000 Amps
13. Percentage of cross sectional area which is tantalum protected high conductivity copper: 35.8%
14. Percentage of area which is Nb: 17.7%
15. Percentage of area which is reactive matrix: 46.5%
16. Area of niobium prior to reaction: $5.44 \times 10^{-2} \text{ cm}^2$
17. Area of Nb₃Sn following reaction: $4.95 \times 10^{-2} \text{ cm}^2$
18. Percentage of original niobium filament reacted: 65%
19. Cross sectional area of final conductor: $.3073 \text{ cm}^2$
20. Cross sectional diameter of round conductor: .626 cm
21. Cross sectional dimensions of conductor with 2:1 aspect ratio:
.784 cm x .390 cm

Table 4-2

SUMMARY OF MODEL CONDUCTOR II

FIRST STAGE

1. Cross sectional area of first stage composite billet occupied by copper can: 13%
2. Percentage of cross sectional area occupied by Nb in the first stage composite billet: 25%
3. Percentage of first stage billet occupied by Sn: 16.7% Cu alloy: 12%
4. Percentage of first stage billet occupied by Cu: 63%
5. Number of niobium filaments in the first stage billet: 745

SECOND STAGE

6. Number of hexagonal elements containing Nb, tin alloy and copper: 630
7. Number of hexagonal elements containing tantalum protected copper: 105
8. Percentage of cross sectional area occupied by copper can: 18%
9. Percentage of cross sectional area occupied by tantalum sheath: 5%

CONDUCTOR CHARACTERISTICS

10. Area occupied by tantalum protected copper: 34%
11. Area occupied by niobium filaments: 16.5%
12. Percentage of area occupied by reactive matrix: 49.5%
13. Area of reactive matrix to area of niobium filament: 3.0/1
14. Area of Nb_3Sn after reaction: $4.95 \times 10^{-2} \text{ cm}^2$
15. Percentage of niobium filament reacted: 60%
16. Critical current at 12 Tesla, 4.2 K: 10,000 Amps
17. Nominal diameter of filaments: 4.0μ
18. Number of filaments: 469,000
19. Area of niobium prior to reaction: $5.89 \times 10^{-2} \text{ cm}^2$
20. Conductor cross sectional area: $.357 \text{ cm}^2$
21. Dimensions of round conductor: .574 cm diameter
22. Dimensions of conductor of 2:1 aspect ratio: .845 cm x .422 cm

Table 4-3

SUMMARY OF MODEL CONDUCTOR IIX

FIRST STAGE

1. Construction of composite billet including 745 niobium cores having a copper/niobium ratio of 1.5 to 1.

SECOND STAGE

2. Number of tin clad Nb/Cu hexagonal elements: 630
3. Number of hexagonal elements containing tantalum protected copper: 105
4. Percentage of cross sectional area occupied by copper can: 18%
5. Percentage of cross sectional area occupied by tantalum sheath: 4%

CONDUCTOR CHARACTERISTICS

6. Area occupied by tantalum protected copper: 34%
7. Area occupied by niobium filaments: 23% ($5.89 \times 10^{-2} \text{ cm}^2$)
8. Percentage of area occupied by reactive matrix: 43%
9. Area of reactive matrix to area of niobium filaments: 1.87
10. Area of Nb₃Sn intermetallic reaction: $4.95 \times 10^{-2} \text{ cm}^2$
11. Percentage of niobium filament reacted: 60%
12. Critical current at 12 Tesla, 4.2 K: 10,000 Amps
13. Nominal diameter of filaments: 4.0μ
14. Number of filaments: 469,000
15. Area of niobium prior to reaction: $5.89 \times 10^{-2} \text{ cm}^2$
16. Conductor cross sectional area: .256
17. Dimensions of round conductor: .571 cm diameter
18. Dimensions of conductor of 2:1 aspect ratio: .715 x .358 cm

Table 4-4

SUMMARY OF MODEL CONDUCTOR IV

FIRST STAGE

1. Number of niobium tubes: 745
2. Percentage of first stage billet occupied by niobium tubes: 48%
3. Percentage occupied by pure copper outside niobium tubes: 10%
4. Percentage occupied by tin - 16.7% copper: 18.6%
5. Percentage occupied by pure copper inside niobium tubes: 23.4%

SECOND STAGE

6. Percentage of area occupied by niobium: 38.4%
7. Percentage occupied by copper outside tubes: 28%
8. Percentage occupied by copper inside tubes: 18.7%
9. Percentage of area occupied by tin - 16.7% Cu: 14.9%

CONDUCTOR CHARACTERISTICS

10. Ratio of reactive matrix to niobium: .875
11. Area of Nb_3Sn after reaction: $4.95 \times 10^{-2} \text{ cm}^2$
12. Percentage of niobium tube reacted: 60%
13. Number of tubes: 469,000
14. Area of niobium prior to reaction: 5.89×10^{-2}
15. Conductor cross sectional area: $.153 \text{ cm}^2$
16. Dimension of round conductor: .443 cm diameter
17. Dimensions of conductor of 2:1 aspect ratio: .277 x .553 cm

Figure 31. Schematic representation of the second stage of billet packing for Model Conductor I

Represents Nb/Cu composite elements produced in first extrusion stage

Represents Ta/Cu composite elements produced in the first stage

Represents Cu/Sn - 16.7% Cu elements produced in the stage of composite billet preparation

Figure 32. Unit cell of billet stacking for second stage extrusion of Model Conductor I

Niobium filament in
a copper sheath

Outer copper shell
occupying 15% of the
cross sectional area

Tin alloy in a copper
sheath

Figure 33. Schematic representation of the first stage of
billet packing for Model Conductor II

Represents Regions of Tin Alloy

Represents Niobium Filaments

Figure 34. Unit cell of the first stage of packing of Model Conductor II

Figure 35. Schematic representation of the second stage
billet of Model Conductor VI

Represents the Nb/Cu/Sn alloy hexagonal rods
produced in the first stage of extrusion

Represents the Ta clad copper elements included
for stabilization

Figure 36. Unit cell of stacking of hexagonal elements in
the second stage billet of Model Conductor II

Figure 37. Conductor III: First stage and second stage packing

Figure 38. Conductor IV: Unit cell of first stage packing.

Figure 39. Conductor IV: Second stage billet preparation.

5.0 ECONOMIC CONSIDERATIONS

There are several factors which affect the cost of a multifilamentary Nb_3Sn conductor. Among these are:

1. The amount of reactive matrix necessary to produce a given quantity of Nb_3Sn . The bronze in conventional composite serves only to carry the tin which is used to react the niobium filaments. Following the reaction the depleted bronze serves no useful purpose. The use of a tin rich alloy in copper provides hope of reducing the volume of this reactive matrix thereby reducing the amount of material which must be carried through the processing to produce a given quantity of Nb_3Sn superconductor.
2. The critical current density of the Nb_3Sn . Increasing the critical current density of Nb_3Sn also increases the amp-meter yield per pound of material processed.
3. The cost of the individual processing steps.
4. The yield per extrusion.

In this chapter we will evaluate these aspects of the conductor designs described in Chapter 4.

5.1 Quantity of Reactive Matrix Necessary to React the Niobium Filaments

The most tangible increase in conductor yield results from the reduction of matrix required to produce a given quantity of Nb_3Sn . To facilitate the comparison of the conductor models with a composite including a 13.5 wt % bronze, Table 5.1 has been constructed. This table lists the matrix to niobium ratio for 60% and 100% reaction of each of the model composites and a 13.5 wt % bronze composite.

For 60% reduction only conductors 3 and 4 provide a reduction of conductor size over a 13.5 wt % Sn bronze composite for the same current carrying capacity.

For 100% reaction all of the model conductors provide a reduction of conductor

size from a 13.5 wt % bronze. This reduction ranges from 17% to 64% for model conductors 2 and 4 respectively.

Since the cost of the conductor per pound is roughly the same for all of these conductors and since the cost of processing is considerably more per pound than the raw materials, the cost reduction is roughly proportional to this reduction in conductor volume.

5.2 Cost Differences Resulting From Modifications of the Processing

The processing of the model conductors differ in several significant ways from that of a composite consisting of bronze, niobium and pure copper protected by a diffusion barrier. Each of the model conductors of Chapter 4 involve at least one and in some cases two hydrostatic extrusions. Fabrication of a composite including a 13.5 wt % bronze must be carried out in these conventional extrusions. Since the model conductors are all primarily copper, the frequent anneals required for bronze composites are eliminated. Model Conductor IV has two special features which affect its cost of fabrication. It involves niobium tubes which are more costly to fabricate than niobium rod and it has no tantalum sheathing which usually comprises about 7% of the composites. Table 5.2 summarizes the processing differences from the 13.5 wt % Sn bronze for each of the model conductors and their impact on the cost of processing per pound of conductor.

5.3 Other Factors Affecting Conductor Cost

In addition to the two factors discussed, there are at least two other factors which may result in a cost advantage of the proposed conductors over a bronze composite. One is the result of higher critical current densities of Nb_3Sn resulting from improved reaction kinetics and the other results from the improved billet yield possible with hydrostatic extrusion.

There has been speculation that reaction of the niobium filaments should be carried out to only a limited extent such as 60% or less because beyond that the strain corresponding to an unacceptable level of degradation may be too low. For this level of reaction conductors 1 and 2 provide no reduction in reactive matrix from that in a 13.5 wt % Sn bronze. However, as a result of the ability to increase the quantity of tin available with the relatively small increase in the volume of the reactive matrix, one may maintain tin concentrations close to the maximum solubility of tin in copper over most of the reaction. In a bronze composite, however, the tin concentration decreases from its saturation level as the reaction proceeds. The result is a generally lower rate of Nb_3Sn formation for the 13.5 wt % Sn composites. Lower rates of Nb_3Sn formation mean longer reaction times and consequently lower critical current densities in the Nb_3Sn for the bronze composites. The yield per unit of niobium or per unit of material processed is therefore expected to be lower for 13.5 wt % Sn composites even for limited reaction of the Nb filaments.

As discussed in Chapter 2, reduced extruded rod discard is expected per extrusion for hydrostatic extrusion because of the reduced die angles possible. This reduction in discard may be as much as 10% per extrusion which result in a cost savings of as much as 17%.

Table 5.1

MATRIX TO SUPERCONDUCTOR RATIO FOR A 13.5 WT %
BRONZE COMPOSITE AND THE FOUR MODEL CONDUCTORS

	60% Reaction	90% Reaction
1. 13.5 wt % bronze composite	2.55 to 1	3.82 to 1
2. Conductor 1	2.84 to 1	2.94 to 1
3. Conductor 2	3.0 to 1	3.02 to 1
4. Conductor 3	1.87 to 1	1.91 to 1
5. Conductor 4	.91 to 1	*

*not advisable to react to 90%

Table 5.2

PROCESSING MODIFICATIONS FOR THE MODEL CONDUCTORS
AND THE RESULTING PERCENTAGE CHANGE IN
COST OF PROCESSING PER POUND OF MATERIAL¹

	<u>Conductor</u> #1	<u>Conductor</u> #2	<u>Conductor</u> #3	<u>Conductor</u> #4
1. Cost change resulting from reduction of the number of extrusions. (Including the consideration of the increased yield from the starting materials).	-14%	-14%	-14%	-14%
2. Cost change resulting from differences in raw materials.	0%	0%	+7%	+21% ²
3. Cost reduction resulting from the elimination of intermediate anneals.	-4%	-4%	-4%	-4%
4. Cost increase resulting from the small extrusion ratio which necessitates additional rod drawing	+5%	+5%	+5%	+5%
NET CHANGE	-13%	-13%	-2%	+8%

¹Compared to a 13.5 wt % bronze/niobium composite designed for 60% reaction.

²Includes the addition due to cost of niobium tubes and the reduction due to the elimination of the tantalum

6.0 SUMMARY & CONCLUSIONS

6.1 Economic Advantages

1. Four practical conductor configurations containing a Sn - 16.7% Cu high tin bronze reactive matrix were designed and analyzed to assess the potential economic advantage offered by the high tin bronze compared to a conventional multifilament Nb_3Sn conductor produced with a Cu - 13.5% Sn low tin bronze.
2. The most significant cost advantage of the high-tin bronze is associated with the reduction in the area of the conductor cross section, and consequently in the conductor weight, required to produce a specified critical current. The reduction in weight of material per ampere meter is a direct consequence of the utilization of a much smaller overall quantity of bronze to provide roughly the same amount of : for reaction to form Nb_3Sn .
3. Although only two of the four designs showed a potential improvement in amp-meter yield per pound over conventional composite for 60% reaction of the Nb filaments, all of them showed an improvement for 90% reaction.
4. Conductor 4, the economically most attractive of the four conductors has the potential for providing a 40% cost savings per ampere meter of conductor when compared to the conventional composite. This cost reduction is the net difference between a cost increase of 8% (per pound of conductor) and an approximate factor-of-two reduction in the area of conductor cross section required to produce a specified critical current. The 8% cost increase is associated with the added cost of fabricating with expensive Nb tubes. The cost comparison is made between conductors which contain islands of bronze and Nb_3Sn within copper, where the minimum amount of copper that permits fabrication, about 30% of the overall cross section, has been utilized in each case. Reaction of 60% of the Nb has been assumed, and the fraction of the cross section which is Nb_3Sn is consequently higher for Conductor 4. The influences of increased Nb_3Sn fraction and filament configuration upon the mechanical properties of the conductor has not been assessed.

6.2 Hydrostatic Extrusion

1. Because the high tin bronze is relatively soft and may become liquid during extrusion, fabrication by hydrostatic extrusion and drawing are required to process conductor from this material.
2. The economics of high tin bronze processing is therefore related to the availability of hydrostatic extrusion facilities and the capabilities of those facilities by comparison with processing by conventional means.
3. Although four hydrostatic extrusion facilities capable of extruding 7" diameter billets have been produced in Sweden, none of these presses are in the United States. However, an alternative to the purchase or construction of hydrostatic presses is available by the conversion of a conventional press in the manner developed at Battelle Laboratory. For example, the cost of conversion of a conventional press to a hydrostatic extrusion press capable of extruding billets of 8-10 inch diameter would be about \$100,000. This represents less than 1% of the cost of the 7×10^4 kg of multi-filamentary conductor to be used in FERF.
4. Additional potential economic benefits resulting from the high tin bronze hydrostatic extrusion process are reduced discard of the extrusion product and elimination of costly anneals characteristic of processing bronze composites.

6.3 Advantages for Coil Construction

The largest single length of conductor which can be manufactured is very important to the construction of a coil. The shorter the conductor lengths the more frequently joints must be made and the more frequently joints are made the more difficult coil construction becomes. Increasing the unit lengths of conductor can be accomplished either by increasing the critical current density of the composite or by increasing the volume (i.e. billet size) of the single unit.

The maximum volume of the single unit is determined by the largest available draw bench and the same limitation exists for both conventionally and hydrostatically extruded composites. Therefore, the use of a high tin bronze multifilamentary Nb_3Sn composite, which results in an improvement in current density over a low tin bronze composite, will lead to greater unit lengths of conductor, and advantages in coil construction.

6.4 Experimental Results

1. The preliminary composite billet extrusions carried out in this study indicate that sound extrusion of a hard copper and tin alloy composites can be accomplished at billet speeds of 6 ft/min and an extrusion ratio of 4.7 to 1. Higher reduction ratios will require lower speeds and fluid cooling of the tooling and extrusion product or the replacement of hard copper with annealed copper.
2. Our experiments indicate that sound composites consisting of at least 70% tin or tin-copper alloy can be produced for billet stacking.
3. We also verified the work of Hashimoto et al³ showing that a composite containing a tin rich copper tin alloy can be drawn to small diameters (0.2 mm) without disturbing the tin alloy filaments.

7.0 RECOMMENDATIONS

Having shown that multifilamentary composites containing a reactive matrix of pure tin or tin - 16.7% copper has a considerable potential for reducing conductor cost and having demonstrated the ability to fabricate billet components, we recommend that as the next stage in the study of this type of composite IGC continue with the construction of 2"-3" diameter full composite billets. The recommended designs are those of Model Conductors 3 and 4 which provide the greatest potential reduction in conductor cost.

Successful fabrication of a 10,000 amp conductor from the 2" to 3" diameter billets would then be followed by scale up to a commercial sized billet in cooperation with either Battelle Laboratory or the National Standard Company which presently operates a hydro extrusion press in Scotland.

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APPENDIX A

FACILITIES FOR HYDROSTATIC EXTRUSION

The largest hydrostatic extrusion presses in existence are those produced by ASEA of Sweden. Although four of these large presses are now in existence, none have been installed in the United States. One of the presses is located in Scotland and operated by a subsidiary of the American firm, National Standard Company. On a billet of 7" (17.8 cm) diameter and 50" (127 cm) this press is capable of providing over 200,000 psi extrusion pressure. Doyle Rausch of the National Standard Company informed us that the press could be made available for the hydrostatic extrusion of superconducting composites. National Standard Company would also gladly respond informally to requests for extrusion cost information on specific billet sizes and extrusion parameters.

Hydrostatic extrusion could also be accomplished through the conversion of a conventional extrusion press in the manner investigated at Battelle. Individuals at Battelle indicate that the conversion of a press for the hydrostatic extrusion of a billet 7" (17.8 cm) diameter at a pressure on the order of 200,000 psi would cost in the order of magnitude of \$10⁵. There are several conventional presses in this country which could be converted for the hydrostatic extrusion of billets of this size. The Battelle technique has been demonstrated by the conversion of a 2500 ton conventional press to a hydrostatic press capable of extruding 5" (12.7 cm) diameter, 16" (40.6 cm) length billets.

In addition to these full scale facilities there exist several experimental extrusion presses which might conceivably be used for the extrusion of superconducting composite billets. Several of these facilities are summarized in Table A-1.

Table A-1

SOME HYDROSTATIC EXTRUSION FACILITIES EXISTING IN THE UNITED STATES

<u>Location</u>	<u>Billet Diameter</u>	<u>Billet Length</u>	<u>Pressure At Given Diameter</u>	<u>Comment</u>
1. Westinghouse R&D Center Pittsburgh, Pennsylvania	1.5" (3.8 cm)	8" (20 cm)	150,000 psi at 1.5" 300,000 psi at 1"	
2. Battelle Laboratory Columbus, Ohio	5" (12.7 cm)	16" (40.6 cm)	250,000 psi	Converted 2500 ton conventional press
3. Battelle Laboratory Columbus, Ohio	2 3/8" diameter	12" (30.5 cm)	300,000 psi (700 ton press)	
4. Stanford University	0.75" (1.91 cm)	8" (20 cm)	250,000 psi at 0.75" dia 500,000 psi at 0.375" dia	
5. Benet Weapons Laboratory Watervliet Arsenal Watervliet, New York	1.0" (2.54 cm) No information available	6" (15.24 cm)	300,000 psi at 1.0" dia	Vertical extrusion press

APPENDIX B

VOID FORMATION IN INTERDIFFUSED COPPER/TIN-16.7% COMPOSITES

Chapter 3 includes a photograph of a 0.015" diameter composite consisting of pure copper and tin - 16.7% copper after interdiffusion at 600°C for 60 hours. The photomicrograph shows some degree of void formation. The void formation after interdiffusion should not be of an extent which prevents the diffusion of tin into the filament region. Several additional photomicrographs were taken of other diffused composite cross sections and are shown in Figures B-1 to B-3. As indicated by the uniform yellow color in the α -bronze region, the diffusion of tin at 600°C was not hindered by the void formation.

Figure B-1

Figure B-2

Figure B-3

Figures B-1 to B-3. Photomicrograph of a 0.015" diameter copper/Sn ~ 16.7% Cu composite interdiffused at 600°C for 60 hours.

NOTICE

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