MASTER

**FABRICATION AND PROPERTIES OF CONDUCTORS
FOR FUSION MAGNETS**

**ANNUAL REPORT
OCTOBER 1, 1976 - SEPTEMBER 30, 1977**

June 1978

**METALLURGY AND MATERIALS SCIENCES DIVISION
DEPARTMENT OF ENERGY AND ENVIRONMENT**

**BROOKHAVEN NATIONAL LABORATORY
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Table of Contents

Fabrication and Properties of Conductors for Fusion Magnets (Mechanical Properties)

	Pages
Summary	1
I. High Field Test Facilities.	1
II. Monofilamentary Nb ₃ Sn Wires	2
III. Multifilamentary Wires.	6
IV. Effects of Additives to Nb ₃ Sn	7
V. Mechanisms for Degradation.	8

Annual Report

(Oct. 1, 1976-Sept. 30, 1977)

Summary

The objectives of this project are to develop suitable and economical conductors for fusion magnets, in particular, to develop methods for improving the mechanical properties of Nb_3Sn conductors. This includes the measurement and study of degradation mechanisms of Nb_3Sn conductors under mechanical strain.

Our investigation of degradation in the superconducting properties of Nb_3Sn conductors under mechanical stresses for FY 1977 can be divided into the following areas: 1) monofilamentary Nb_3Sn wires, 2) multifilamentary Nb_3Sn wires and conductors, 3) effects of additives to Nb_3Sn , 4) mechanism for degradation, and 5) construction of high field test facilities. Our effort in FY 1977 has been concentrated in the investigation of T_c , J_c and H_{c2} variations in monofilamentary Nb_3Sn wires. The most important finding in this study is that a Nb_3Sn wire can sustain mechanical strain well beyond "1%" if a proper ratio of the matrix to the Nb core was chosen.

In the area of multifilamentary wires and conductors, a series of seven wire litz conductors was prepared. These conductors will be used to study the mechanical and superconducting properties of Nb_3Sn wires when they are fabricated into a litz conductor. Also, a series of five experimental unreacted Nb_3Sn composite wires was purchased. These five different wires will be used to investigate the effects of variations in Nb to normal metal ratio, Nb filament size and Nb-core composition on the mechanical behavior of Nb_3Sn composite wires. These results will then be compared with those of monofilamentary wires.

In order to gain an understanding of the fracture mechanism of Nb_3Sn layers in the composite, optical and electron microscopic studies of stressed Nb_3Sn wires were initiated. Finally, the description of the high field test facility is given.

I. High Field Test Facilities

1. Mechanical Properties Measurements

For simultaneous measurements of stress and strain for various wires at 4.2 K and of critical currents in magnetic fields, a 4.0 tesla split pair magnet, a load frame with current leads, and a dewar to be used with an Instron testing machine were available from an existing program at BNL, and these are shown in Figs. 1 and 2. However, an appropriate light weight extensometer for measurements of elongation of the wires was needed for this investigation.

An extensometer, which was developed for this investigation, is shown in Fig. 3. This incorporated standard strain gauges attached to thin Cu-Be deflection bars. The specimen was soldered to the deflection bars as indicated

in the figure. Each extensometer was first calibrated in liquid helium before attaching to the specimen. A gauge factor of 1.2×10^{-2} in/mv (.3 mm/mv) is available with an accuracy of $\pm 5 \times 10^{-5}$ in (10^{-4} cm).

2. 10 Tesla Test Facility

Since conductors in magnetics for plasma confinement operate at magnetic fields near or above 10 tesla, it is necessary to examine the behavior of Nb₃Sn conductors as near 10 tesla as possible. Thus, we have initiated development of a high field test facility. This involved construction of a 10 tesla split pair magnet as well as a new load frame. The status of the construction of the facility is given below.

Fabrication of all the components of the magnet support and load frame have been completed and assembly of these will begin shortly.

A new magnet is being built for the mechanical testing apparatus to raise the magnetic field into the 10 tesla range. The magnet is a split pair to provide vertical access to the high field region. Nb₃Sn composite conductor is used for the turns in the high field region and NbTi is used in the outer turns. Both conductors have identical dimensions and are formed by combining 11 wires of 0.3 mm diameter into a flat braid 2.5 mm wide and 0.4 mm thick. The Nb₃Sn wires are of the four component type consisting of Nb₃Sn filaments in a bronze matrix which is separated from the high purity stabilizing copper by a tantalum diffusion barrier. The NbTi composite has approximately 500 filaments of superconductor in a copper matrix which is enclosed in a cupro-nickel jacket. The magnet has an inner diameter of 6 cm and an outer diameter of 20 cm with a gap between coil halves of 2 cm. Anodized aluminum foil is used for interlayer insulation. Both types of conductor have been fabricated and one-half of the coil has been wound.

II. Monofilamentary Nb₃Sn Wires

In order to investigate mechanisms for superconducting critical current variation of A-15 superconductors under tensile stresses, it is necessary to examine how other properties, mechanical as well as superconducting, vary with the matrix prestrain under applied stresses. Accordingly, we have prepared a series of monofilamentary wires where the ratio of the bronze to the Nb core in the wire varied from 1.1:1 to 44:1. In this report, results of measurements on mechanical properties, critical temperature, critical currents, and critical magnetic fields are given.

1. Specimen Preparation

The specimen preparation consisted of inserting 1/8 inch Nb rods into a series of (Cu-13%Sn) alloy cylinders and drawing the composite to the desired sizes. The diameters of the alloy cylinders were chosen such that the bronze to Nb ratios would be 1.1:1, 3.4:1, 7.6:1, 15:1, and 44:1. Several lengths of these wires (30 cm long) were heat treated at 725°C for 6, 15 and 64 h to form ~1.5, 3, and 6 μ m thick Nb₃Sn layers. The cross sections of these wires are shown in Fig. 4 (a-e); (65 h at 725°C).

2. Mechanical Properties at 4.2 K

Presented in Fig. 5 are the stress-strain curves obtained at 4.2 K for the series of monofilament Nb_3Sn conductors. Measurements of strain in these wires were made by the strain gauge which was described above. The matrix to core diameter ratios for the wires are given. These samples were heat treated for 15 h at 725°C to produce $\sim 3\text{ }\mu\text{m}$ Nb_3Sn layers. Sample composites with 1.1:1 and 3.4:1 failed at the strains indicated while the remaining samples did not fail mechanically up to strains of 4%, the maximum strain investigated. Although there is little change in the initial slope of stress vs strain, the slopes associated with second stage deformation vary widely depending on the bronze to core ratio. For lower ratio samples, increasing slopes reflect mechanical strengthening from the core. According to a law of mixtures, second stage slopes in low ratio samples should approach a slope characteristic of the core, while slopes for higher ratio samples tend toward that for pure bronze.

Anomalous behavior is exhibited at intermediate strains between approximately 0.2 and 0.8%. Here a simple scaling according to the law of mixtures is obviously not operating. Within this range low ratio samples do not exhibit the reinforcement expected from the filaments. This effect is caused by internal prestrains in the matrix. Due to the relatively higher thermal contraction coefficient for bronze, internal stresses during cooling from 725°C to 4.2 K produce a tensile prestrain in the matrix. This tensile prestrain decreases with decreasing ratios. Lower ratio samples with significant tensile prestrain exhibit then, under tensile loading, an onset of plastic deformation at lowered strain values. Thus, the mechanical strength available from the bronze component is limited. In these composites tensile prestrains have the effect of lowering the yield strength of the bronze. Each composite curve in Fig. 5 therefore has a different constituent bronze component, different with regard to the mechanical strength of the bronze. A decrease in the yield strength of the bronze with decreasing ratios accounts in this way for the anomalous composite stress-strain relationships in the range 0.2 to 0.8% strain. Evidently such effects from matrix prestrain may occur in multifilament conductors as similar anomalous behavior has been observed earlier, but not explained, for multifilament Nb_3Sn conductors with differing bronze to niobium ratios.

Theoretical calculations of strain-stress behavior in these composites with the prestrain matrix have been initiated by Professor R. Chou of Lehigh University and the results will be reported later.

3. T_c Measurements

Measurement of the superconducting transition temperature under tensile loading was accomplished using concentrically wound inductive pickup coils. These coils were attached to a load frame for use with a 10,000 lb Instron tensile testing machine. In the T_c rig a temperature variation of less than 0.15 K was achieved along a 2.5 cm length of test wire. The temperature was monitored using a Cu-Fe/Au thermocouple. A calibrated strain gauge was attached directly to the wire specimens. Stress-strain curves were plotted on an x-y recorder and all T_c measurements reported here represent measurements made under an applied tensile load.

Figure 6 presents the superconducting transition temperatures for this series of single filament wires as a function of the applied tensile strain. The data in Fig. 6 are for the 15 h at 725°C heat treatment. The T_c values presented represent the temperatures corresponding to 80% of the total inductive change to the normal state. Each specimen's curve exhibits an increase in T_c for initial strains, reaches a maximum value, and eventually decreases at larger strains to T_c values less than the unstrained wire. If such behavior were to reflect first removal of compressive prestresses followed by the application of tensile strain, then the observed peak T_c value should be related to that seen when the bronze matrix is etched off an unstrained wire. In order to test this assumption, measurements were made to determine the changes in T_c for these wires, when the outer bronze matrix is removed by etching. As shown in Fig. 7 with increasing bronze to niobium diameter ratios an increase in ΔT_c is observed up to ~ 1.2 K at a ratio of 15:1. For ratios exceeding 15:1 the effect saturates and little increased in ΔT_c occurs. This saturation point represents the bronze to niobium ratio for which all the internal prestrain is taken up in the niobium and Nb₃Sn core. For lesser ratios a balance is struck between compression of the core and tensile strain in the matrix. In addition, following the mechanical tests at 4.2 K each sample's T_c was measured with and without the bronze matrix. It is evident in Fig. 7 from the small ΔT_c observed for the stressed samples that the mechanical straining effectively removed the prestresses.

To illustrate the relationship between the maximum changes achieved in T_c under tensile loading, ΔT_c^* , and changes in T_c after removal of the matrix, ΔT_c , ΔT_c^* was plotted against ΔT_c for the series of wires in Fig. 8. The best fit straight line through the data has nearly a 45° slope, supporting the above interpretation, e.g., the maxima in T_c in Fig. 6 represent the strain at which internal prestrains are removed by tensile loading. The magnitude of each prestrain can be estimated as the strain value associated with the T_c maximum, ϵ^* . The ϵ^* or prestrain values are 0.25, 0.55, 0.65, 0.85 and 0.95% for the ratios 1.1:1, 3.4:1, 7.6:1, 15:1, and 44:1, respectively. Figure 9 illustrates the relationship between ϵ^* and the ratios. A saturation of ϵ^* values occurs near the ratio 15/1 as is expected if indeed ϵ^* represents prestrain in the samples, see Fig. 7 for comparison. It may be surmised from the above discussions that presence of internal compressive prestresses are beneficial in resisting T_c degradation under tensile loading.

The curves in Fig. 6 are nearly symmetrical about their maxima suggesting a parabolic dependence of T_c on strain. Indeed such a parabolic dependence on strain has been suggested for Nb₃Sn by Testardi. Since we are able to make an association between ϵ^* and the amount of internal prestrain, the measured ΔT_c^* values should scale with $(\epsilon^*)^2$ if a parabolic law is operative. Figure 10 confirms such a relationship showing a straight line dependence of ΔT_c^* on $(\epsilon^*)^2$. This parabolic relation implies elastic tetragonal strain in the superconductor. Unfortunately there is insufficient low temperature x-ray diffraction work to permit conclusions regarding the possibility of reversible martensitic transformations under such tensile loading. Microscopic investigations together with a search for microcracking at strains below $\sim 1\%$ should aid considerably in understanding the nature of these T_c changes.

4. I_c Measurements at 4.0 T and 4.2 K

Measurements on the effect of applied stresses on the superconducting critical current, I_c , at 4.0 T and 4.2 K were initiated for these monofilamentary wires. In Fig. 11, variations in critical current densities for the set of wires which were heated for 15 h at 725° (~3 μm) are shown as a function of strain. Although only the result for measurements for one wire for each bronze to niobium ratio is shown in the figure, at least two wires for each set of specimens were measured. In most cases, the results for two wires are essentially identical.

Based on the area of Nb_3Sn and the 1 μV across approximately 1.5 in (4 cm) between the voltage contacts, the critical current densities were determined and plotted in Fig. 11 as a function of strain which was measured at the top portion of the wire.

As noted in the figure, the general behavior of J_c (4.0 T) is very similar to that of T_c measured by the inductive method as shown above. However, quantitatively, there exists some differences in the values of strain for wires reaching the maximum values of J_c and T_c for each wire. The strain to achieve the maximum J_c for the wires with the highest bronze to niobium ratio (44:1) was less than those for the wires with the ratio of 15:1. Furthermore, the J_c values for this wire did not come up to the values reached by other wires with smaller bronze to niobium ratio. Those wires heated for 64 h at 725°C (~6 μm Nb_3Sn layer) also behaved similarly to the above set of wires.

In order to elucidate the effects of the bronze to Nb ratio on the critical current behavior under tensile stresses, critical current densities without the stress, $J_c(\epsilon=0)$, and also the maximum critical current densities under strain, $J_c \text{ max } (\epsilon)$, for each wire were plotted as a function of the ratio in Fig. 12. Thus, it is clearly shown how $J_c(\epsilon=0)$ is influenced by the ratio but $J_c \text{ max } (\epsilon)$ are essentially the same for the wires with ~3 μm layers. However, when a similar plot is made for wires with ~6 μm Nb_3Sn layer thickness, it was found that $J_c \text{ max } (\epsilon)$ for the high ratio reach the values achieved by the low ratio. The $J_c(\epsilon=0)$ for these wires behaved essentially identical except somewhat smaller in J_c values than wires heat treated for 15 h. This difference between specimens with two different layer thicknesses is thought to be due to higher susceptibility for mechanical damage of thicker Nb_3Sn layers.

A clear indication for supporting the above statement can be seen in Fig. 13 where the strain to reach the maximum current densities for each wire were plotted as a function of the ratio. At all ratios, the thickness of Nb_3Sn layer did not influence the capacity to withstand mechanical strain of the wires.

Scanning electron microscopy will be performed to measure the difference in grain sizes in FY 1978. The results at the present assured that the variation in grain sizes among wires with the identical heat treatment were smaller than the variations which were found across a Nb_3Sn layer as shown in Fig. 14.

5. $J_c(H)$ and H_{c2} Measurements at 4.2 K

In order to increase understanding of the effects of stresses due to the differential thermal contraction between the bronze and the core, critical

current densities of the above sets of the wires were measured up to 18 tesla at 4.2 K. The variation in critical current densities for wire with various ratio of the bronze to the niobium is shown in Fig. 15a,b. In these figures, the pinning force, $J_c \times H$ rather than the critical current densities was plotted as a function of applied magnetic fields. From these data, the critical magnetic fields, H_{c2} , for these wires were also obtained by plotting $(J_c H)^{1/2} H^{1/4}$ vs H since at high magnetic fields the pinning force, $J_c H$, is in many cases proportional to $(H/H_{c2})^{1/2} (1-H/H_{c2})^2$. The functional dependence of H_{c2} values on the ratio (determined by this extrapolation method) for these wires are shown in Fig. 16. In general, the variations in H_{c2} due to the compressive stress on the Nb₃Sn are very similar with those in J_c (4.0 T) and T_c (Fig. 16). However, without measurements of H_{c2} as a function of elongation, it is difficult to determine whether variations in H_{c2} fits those in J_c better than those with T_c . Since at the present, there is no facility where the measurements of H_{c2} under tensile stresses can be performed we are preparing to measure H_{c2} after a wire is plastically deformed and released; however, it retains a permanent elongation which simulates a wire in tension. It is hoped that a few measurements on wires prepared this way will clarify the relationship between $J_c(\epsilon)$ and $H_{c2}(\epsilon)$.

6. Conclusion

The influence of internal prestrains on the mechanical and superconducting properties of Nb₃Sn composite superconductors has been elucidated. Originating from differential thermal contraction in the composite wires the prestrains amount to a compressive load on the core and a tensile load on the bronze matrix. This effect saturates for matrix to core ratios exceeding 10/1 but can provide for the application of tensile strains of the order of 1% before T_c and J_c (4.0 T) degradation occur. The general behavior of degradation in T_c , J_c , and H_{c2} due to the compression by the matrix is essentially identical.

Anomalously low load values for composites with relatively large volume fractions of high modulus material was shown to be associated with internal prestresses. As a function of the bronze to core ratio these prestresses reduce the yield strengths of the bronze matrices thus producing the low composite load value. The major questions still to be answered are 1) how H_{c2} vary under tensile stress, 2) what is the role of thickness (grain size) of Nb₃Sn in determining the superconducting behavior, primarily J_c , of Nb₃Sn wires under tension, and 3) how $J_c(\epsilon)$ vary with magnetic fields?

III. Multifilamentary Wires

Two main objectives in studying multifilamentary wires are: 1) to investigate effects of mechanical strains on superconducting properties of wires with very fine filaments and to see whether those effects, observed in monofilamentary wires, can be extended to fine filamentary wires, and 2) to investigate the effects of cabling on the mechanical properties of conductors in comparison with those of a single wire. For these studies, we have several wires with various wire parameters. They are tabulated in Table I, and optical micrographs of the cross sectional view for these wires are shown in Fig. 17a-d.

Some preliminary measurements of critical currents as a function of mechanical strains have been performed. However, the types of wires can be tested at 4.0 T

and 4.2 K are limited to low current wires such as Airco #3 because the wires become electromagnetically unstable at very high currents. With the use of the high field magnet, this problem should not exist for the most of the wires.

For this study, a series of cables using the wires in Table I were prepared. The compositions of these cables are given in Table II. Examples of the cross sectional view of these cables are shown in Fig. 18a. As shown in Fig. 19, these cabled conductors can be filled with low melting metals and alloys such as solders, indium, and lead. The effects of these fillers on the mechanical as well as superconducting properties will be investigated. In addition these conductors can be cabled with strengthening members such as Mo, W, or stainless steel wires. The effects of these strengthening wires on critical currents under mechanical straining will be measured.

IV. Effects of Additives to Nb₃Sn

It has been shown in Section III that the behavior of a superconducting wire under tensile strain is primarily determined by the prestrain applied by the non-superconducting member of the wire. However, it is still of great interest to improve the intrinsic mechanical properties of the Nb₃Sn compound. To reach this goal we have initiated an investigation of the effects of impurity element additions to the mechanical property of Nb₃Sn. We will take two approaches for this investigation.

- 1) Study monofilamentary wires by the bronze process. The third elements will be added to Nb₃Sn layers through the matrix or the Nb core.
- 2) Study microhardness of arc casted Nb₃Sn with controlled additives.

For the first study, a set of wires, which are similar to the monofilamentary wires studied in Section III, using a Nb-1 wt% Zr core were prepared and heat treated for the tensile and critical current tests. Depending on the initial test results, some or all of the wires with the bronze to (Nb-1 wt% Zr) ratios will be tested.

Ga can also be added in Nb₃Sn layers by using a Cu-Sn-Ga bronze rather than a Cu-Sn bronze for the matrix. A wire with the bronze to Nb ratio of 3:1 has been prepared and heat treated for the mechanical testing. Although Al cannot be incorporated in Nb₃Sn layers by the bronze route, we have a monofilamentary Nb₃Sn which was produced with a Cu-Sn matrix and a Nb-Al core. This wire will also be tested for the mechanical and superconducting properties. Although this will be a very limited effort, other Al5 wires will be tested to help understand the behavior of Al5 superconductors under mechanical strain.

The second portion of this study is to investigate possible softening of Al5 compounds (Nb₃Sn) due to additives by using the microhardness test technique. Proposed impurities to be added are: (1) Nb-Sn: (a) Nb₇₁Sn₂₉, (b) Nb₇₃Sn₂₇, and (c) Nb₇₅Sn₂₅; (2) Nb-Zr-Sn: (a) Nb₇₄Zr₁Sn₂₅, (b) Nb₇₃Zr₂Sn₂₅, and (c) Nb₇₂Zr₃Sn₂₅; (3) Nb-Sn-Ga: (a) Nb₇₅Sn₂₄Ga₁, and (b) Nb₇₅Sn₂₃Ga₂; (4) Nb₇₅Sn₂₄Al₁; (5) Nb₇₅Sn₂₄Ge₁; and (6) Nb₇₅Sn₂₄In₁. It is hoped that a correlation can be found between the results of mechanical tests on the wires and the hardness tests in these arc cast compounds.

V. Mechanisms for Degradation

In studying degradation of I_c and T_c under tensile stresses, one always faces a difficult question, e.g., what is the relationship between the fracture in Nb_3Sn layers and degradation in I_c ? In order to investigate this aspect of the degradation, we have planned to determine the number of cracks per unit length in the monofilamentary wires with predetermined strain. By such measurements, we expect to be able to predict a critical fracture initiation strain, and this critical strain can be related to the degradation in I_c .

A preliminary result has pointed out a very interesting fact, e.g., if a wire is strained in liquid helium temperature, there exists a substantial number of cracks which do not go through the Nb_3Sn layer (see Fig. 20a) while all cracks go through the layer if the same wire is pulled at the room temperature (see Fig. 20b). Thus, any study of cracks in the Nb_3Sn layer has to be performed on the wires which were pulled at 4.2 K. Further investigation on this subject will be carried out.

Table I

Wire Types	Comp. of Bronze	No. of Fil.	Fil. Size (μ m)	Wire Size (mils)	% Bronze	% Nb	% Cu	% Ta
Airco #2	10 w/o Sn	1045	~4	12 mil ²⁵	88	17	0	0
Airco #3	10 w/o Sn	361	~3.5	12	25.1	4.5	42.8	27.6
Airco #4	13 w/o Sn	1045	~4	12	41.4	17	27.6	14
Airco #221	13 w/o Sn	1159	~5	16,52	49	24	15	12
Airco #222	13 w/o Sn	703	~6	16,52	56	17	15	12
Airco #223	13 w/o Sn	1045	~4	16,52	57.5	15.5	15	12
Airco #224	13 w/o Sn	703	~6*	14,16,52	52	21	15	12
Airco #225	13 w/o Sn	361	~16*	40,52	52	21	15	12
MCA #1	13 w/o Sn	1045	~4	12	40	17	30	13
IGC #2	-	~210	~9	12	23	17	43	17

*These sizes are at the wire size of 16 mils.

Table II
Composition of Cables (Litz)

<u>Wire Types</u>	<u>No. S.C.</u>	<u>No. Stabil. (Cu-Ta)</u>	<u>Type of Strength</u>
Airco #2	4	2	Mo & W
	4	3	-
Airco #3	6	-	Mo & W
	7	-	-
Airco #4	4	2	Mo & W
	4	2	-
MCA #1	4	2	Mo & W
	3	2	-

Similar Litz and braided conductors will be made with Airco #221, #222, #223, #224, #225, and IGC #2.

Figure 1. A photograph of the tensile frame for measurement of critical current density as a function of strain.

Figure 2. A 4 tesla split pair magnet for critical current measurement used with the tensile frame.

Figure 3. A photograph of a small extensometer
for this study.

Figure 4. Optical micrographs of the monofilamentary wires with the bronze to niobium ratio.

Figure 5. Stress-strain relationships as a function of the bronze to niobium ratios.

Figure 6. Changes in the superconducting temperatures of monofilamentary wires under tensile strain.

Figure 7. Relationship between T_c changes occurring when the bronze matrix is removed by etching.

Figure 8. The relationship between the maximum T_c increase achieved in T_c under loading, ΔT_c^* and changes in T_c after removal of the matrix, ΔT_c .

Figure 9. The strain to achieve maximum in T_c as a function of the bronze to Nb ratio.

Figure 10. ΔT_c^* as a function of $(\text{strain})^2$.

Figure 11. Changes in the superconducting critical current densities (4.0 T and 4.2 K) as a function of tensile elongation for the wires heat treated at 725°C for 15 h.

Figure 12. J_c (4.0 T) as heat treated and the maximum J_c under strain as a function of the bronze and niobium ratios for the wires heat treated at 725°C for 6, 15, and 64 h.

Figure 13. Strains to achieve the maximum in critical current densities as a function of the bronze to niobium ratio.

Figure 14. Scanning electron micrographs of Nb_3Sn layers showing Nb_3Sn grains for the wires (the ratios 1.1:1 and 44:1) heat treated for 64 h at 725°C.

Figure 15. The pinning force ($J_c \cdot H$) as a function of applied magnetic fields for (a) 15 h and (b) 64 h at 725°C with various bronze and niobium ratios.

Figure 16. The superconducting critical magnetic fields as a function of the bronze to niobium ratio for the wires heated at 725°C for 6, 15, and 64 h.

AIRCO NO. 2

X250

AIRCO NO. 3

X250

1000X

1000X

Figure 17A. Photomicrographs of commercial produced multifilamentary wires which are going to be used for the cable studies. Airco No. 2 and No. 3.

AIRCO NO. 4

X250

MCA NO. 1

X250

1000X

1000X

Figure 17B. Photomicrographics of commercial produced multifilamentary wires which are going to be used for the cable studies. Airco No. 4 and Mac No. 1.

IGC NO. 2

X250

1000X

Figure 17C. Photomicrographics of commercial produced multifilamentary wires which are going to be used for the cable studies. IGC No. 2.

AIRCO

NO. 221A (16 MIL)

NO. 222A (16 MIL)

X75

X150

1000X

1000X

Figure 17D. Photomicrographics of commercial produced multifilamentary wires which are going to be used for cable studies. Airco No. 221 and No. 222.

AIRCO

NO. 223A (26 MIL)

NO. 224A (14 MIL)

X75

150X

1000X

1000X

Figure 17E. Photomicrographics of commercial produced multifilamentary wires which are going to be used for cable studies. Airco No. 223 and No. 224.

AIRCO NO. 255

X150

X1000

Figure 17F. Photomicrographics of commercial produced multifilamentary wires which are going to be used for cable studies. Airco No. 255.

AIRCO NO. 2

X100

X1000

Figure 18A. Photomicrographs of cabled Airco No. 2.

AIRCO NO. 3

X1000

X75

Figure 18B. Photomicrographs of cabled Airco No. 3.

AIRCO NO.4

X100

X1000

Figure 18C. Photomicrographs of cabled Airco No. 4.

MCA NO.1

X100

X1000

Figure 18D. Photomicrographs of cabled MCA No. 1 incorporating copper stabilizing wires in some cases.

Figure 19. Airco No. 2 cabled and filled with a Pb-Sn solder.

Figure 20A. Optical micrographs showing the cracks
in Nb₃Sn layers stained at 4.2 K.

Figure 20B. Optical micrographs showing the cracks
in Nb₃Sn layers stained at the room temperature.