NBSIR 80-1629

DEVELOPMENT OF STANDARDS FOR SUPERCONDUCTORS

Annual Report
FY 79

F.R. Fickett and A.F. Clark
Thermophysical Properties Division
National Engineering Laboratory
National Bureau of Standards
Boulder, Colorado 80303

DECEMBER 1979

Work performed under Department of Energy contracts
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U.S. DEPARTMENT OF COMMERCE, Philip M. Klutznick, Secretary
Luther H. Hodges, Jr., Deputy Secretary
Jordan J. Baruch, Assistant Secretary for Productivity, Technology, and Innovation
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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Practical superconductors are complex materials and the determination of the parameters required for designing with them is a difficult task. Many approaches are possible for determining a given parameter and the results depend critically on which one is chosen. The goal of this program is to arrive at a set of useful voluntary standards for measurements on modern practical superconductors that will be acceptable to both manufacturers and users. Agreement on a set of standard definitions for the various parameters is also necessary. This report describes the status of the program and includes a brief historical introduction. The need for standards in this area is described in detail with particular attention paid to the need for consensus among all interested parties and our techniques for achieving it. Results from the experimental research by NBS and a review of the wire manufacturers' programs are presented.

Key words: Critical current; critical temperature; losses; magnetic property; standards; superconductor.

I. INTRODUCTION

The superconductor standards program is a cooperative effort funded by NBS and four divisions of DOE (Energy Storage, Fusion Energy, High Energy Physics, and Magnetohydrodynamics through the Francis Bitter National Magnet Laboratory). The goal of the program is to arrive at a set of voluntary standards for modern practical superconductors that will be acceptable to both manufacturers and users. The need for such a set of standards increases as more and more large superconducting magnet systems are designed and constructed.

The basis for the program was set several years ago at meetings called by NBS at The ASM Conference on the Manufacture of Superconducting Materials and the Applied Superconductivity Conference in 1976. The manufacturers, users, and researchers present all made extensive suggestions as to how the work should proceed. In the years that followed a small program was initiated, with NBS funding, to make a more formal survey of the needs and desires of the research community. From this study and several related meetings, the following conclusions were drawn:

For all concerned, standards were both necessary and desirable.

The small size and financial position of the wire manufacturing industry (and its competitive nature) precluded industrial development of standards in a reasonable period of time.

The NBS Cryogenics Division (now Thermophysical Properties Division) was an "unbiased third party" with the charter, the desire, and the expertise to carry out a superconductor standards program of a sufficient size that significant progress could be made in a time span of several years. The full program was started in mid-1979.

The development and promulgation of standards can be a very sensitive issue, for sound financial reasons. Because of this, the program relies heavily on continuing interactions between all interested parties to assure that, as far as possible, a consensus will be developed on any proposed standard. To this end a portion of the funding is subcontracted to each of the U.S. wire manufacturers to promote development of their research capability, to provide us with needed data, and to provide a source of funding for their participation in work associated with test development. Also, a new ASTM subcommittee on superconductors (ASTM B1.08) was formed early in 1979 with excellent participation from manufacturers, funding agencies, and the national laboratories.

An outline of the approach that we are attempting to follow in the determination of the standards is provided by the diagram of Fig. 1. The flow is self-explanatory but note that users and producers are involved in all aspects of the development. They provide input on current practices, perform round robin tests, make trials of new concepts and devices, and critique the final product. Furthermore, their active participation in the standards committees assures that they will have a direct hand in preparation of the final product.

The term "standards" as used in this report may indicate any or all of four quite different aspects of standardization:

1. Unambiguous definition of terminology,
2. Detailed description of measurement technique,
3. Development of common experimental apparatus,
4. Preparation and characterization of reference materials.

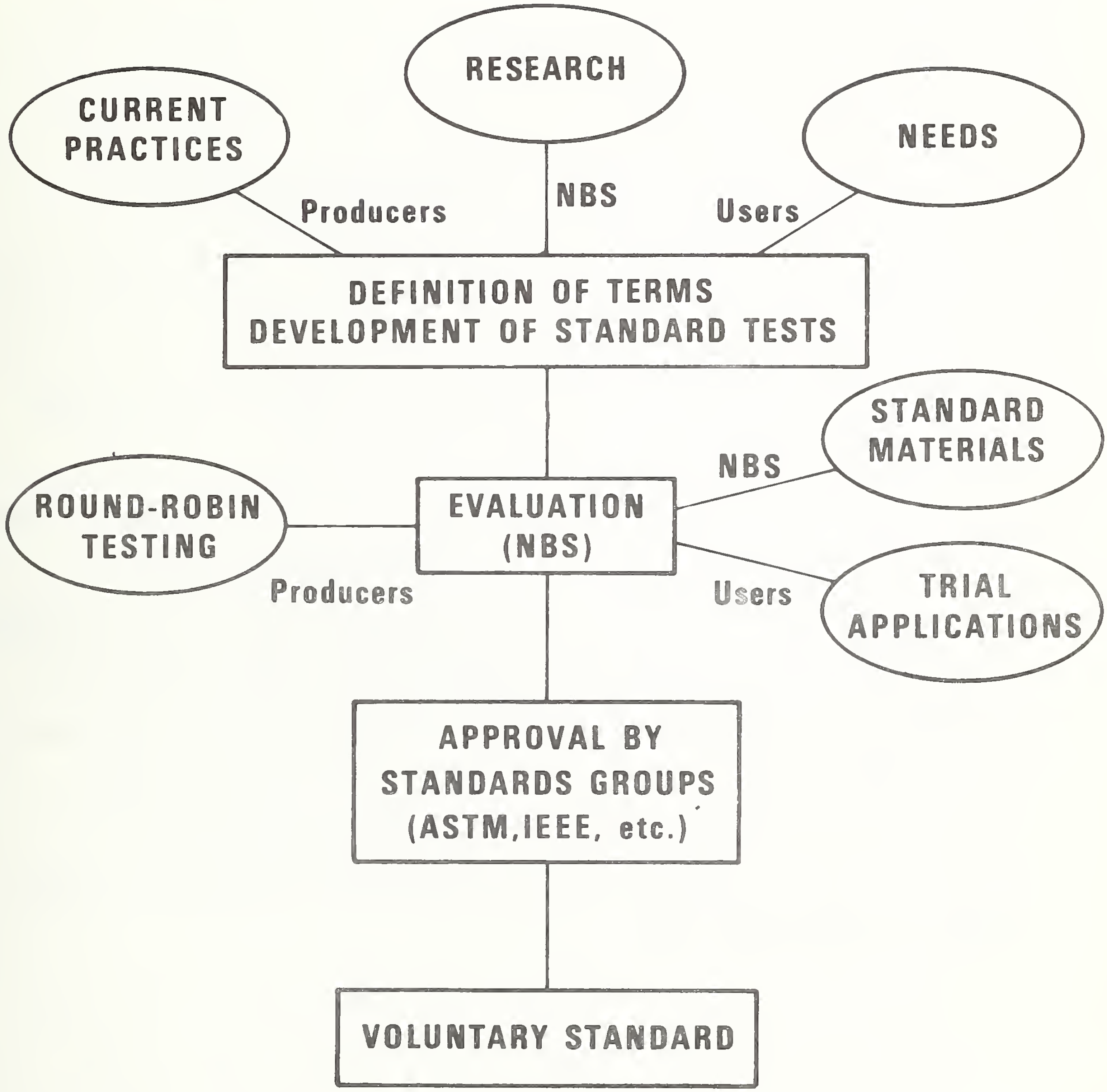

Figure 1. Diagram of the steps involved in production of voluntary standards.

The program will touch on each of these as they relate to the parameters of most common interest in the measurement of superconductor properties. These parameters are:

1. Critical current, I_c
2. Critical temperature, T_c
3. Critical field, H_c
4. Matrix properties, such as resistivity and stabilization
5. Transient losses, due to eddy currents and hysteresis.

The work reported here concentrates on the first two critical parameters, and more heavily on the critical current, since that measurement is the one most commonly used for characterization of practical conductors. In subsequent years, the other properties will be added to the program.

In the following sections we discuss our evaluation of the current status of measurement practices in the U.S. and elsewhere, explain in detail the standards development and dissemination efforts, and describe the experimental research program being carried out in support of this effort by NBS and the manufacturers of practical superconductors. The program was started rather late in the year and, as a result, progress on many of the experimental projects during FY 79 has been limited to construction and testing of apparatus. As of this writing (12/79) all projects are taking data and the research is progressing well.

II. EVALUATION OF CURRENT STATUS

One of the most important parts of the program in these early stages is to determine in some detail what techniques and definitions are now being used for the evaluation of practical superconductors. Furthermore, we would like to assess the comparability of the techniques used by the various groups. The first of these goals has been accomplished by surveys and visits and the second is being done by a round robin test program.

A. Survey Results

After discussions with manufacturers and users we developed a comprehensive questionnaire to be used in evaluating measurement techniques. The complete questionnaire is given in Appendix A. Many of the National Laboratories and all of the manufacturers of wire have been contacted either by phone or personal visits and their responses obtained. In general, the techniques now in use for critical current measurement are very simple, usually involving a hairpin geometry for the sample that allows insertion into a solenoidal magnet. All measurements are made at a temperature of 4K. There is no general criterion used for the voltage that defines the critical current. Methods used to constrain the samples vary widely and, as we will see below, may have a serious impact on the measurement. Most of the user laboratories tend to rely on the critical current data provided by the manufacturer; few in-house tests are made. Other parameters, such as critical temperature and critical field are seldom measured. Parameters relating to stability, such as matrix resistivity, self field losses and current transfer effects are not measured regularly, nor are the interactions between these effects and the measured critical current often taken into account. One should point out that these are now usually relatively minor, but will become of increasing importance as the size, and perhaps complexity, of the conductors increases.

We are evaluating the survey responses in hand and collecting more as the opportunities arise. If the final collection appears to be of sufficiently wide interest, it will be published as an NBS report.

A similar survey of measurement techniques in Japan was performed by Dr. G. Fujii, a guest worker at NBS from the Institute of Solid State Physics, University of Tokyo. The results have been compiled in a report [1] that will be published by Dr. Fujii. Since much of the extensive Japanese technology concentrates on high field materials, especially V_3Ga, this report makes an excellent complement to our own survey.

B. Round Robin Testing

Round robin testing is a time-honored method for evaluating the status of measurement systems. In our program, samples of three or four practical superconductors are sent to various laboratories for determination of their critical current. The materials will also be measured at NBS. Comparison of the results (early in 1980) should indicate the extent of the problem that we are addressing in the overall program. The materials being measured in the test are described in Table 1. We are contemplating the addition of another multifilamentary Nb_3Sn wire. Measurements are being made by all of the U.S. wire manufacturers. We may try to extend the program to some of the national laboratories in the next year.

Discussions are being held to decide if a round robin program should be undertaken with the critical temperature and critical field measurements. The number of laboratories involved would be very small, but their measurement techniques are quite different.

Table 1. Superconductors for NBS Round Robin Test

Sample 1

Multifilamentary NbTi.

Length: 1 m
Cross Section: ~0.53 x 0.68 mm
Approx. I_c @ 10T: 115 A
@ 4T: 285 A

Sample 2

Nb_3Sn Tape Conductor (Reacted).

Length: ~0.5 m
Cross Section: 2.3 x 0.2 mm
Approx. I_c @ 10T: 65 A
@ 4T: 175 A

Sample 3 (To be provided in December)

Nb_3Sn Multifilamentary Conductor (Reacted).

Length: ~1 ft. or as requested
Cross Section: 0.7 mm diameter
Approx. I_c @ 12T: 50 A
@ 7T: 150 A

Round robin testing is, of course, best accomplished with carefully characterized materials - standard reference materials. The acquisition and characterization of such materials is a major effort that we plan to undertake later in the program. As a first step we have made an informal inventory of available materials at various manufacturers. It appears that adequate NbTi for such a program is available, but that Nb_3Sn would present a problem today.

III. PREPARATION AND DISSEMINATION OF STANDARDS

To assure the success of our program, it is essential that we interact with all of the appropriate elements of the standards community. This process has already been described briefly. Here we present some details of our approach. The first order of business is to reach agreement on the terminology for practical superconductors. The involvement of the standards groups such as ASTM and IEEE is also necessary. The major detailed input to these groups must come from this program and an example of how this is accomplished is provided by our interactions on the critical current measurement techniques.

A. Standardization of Terminology

In an effort to develop a uniform terminology, an extensive compendium of existing terminology was made. From this review a set of standard definitions was prepared and informally criticized by more than 50 workers in the field both in this country and abroad. The result was four papers containing proposed definitions under the titles:

1. Fundamental states and flux phenomena [2]
2. Critical parameters [3]
3. Fabrication, stabilization and transient losses [4]
4. Josephson phenomena [5].

The first three are now in print and the fourth will be published early in 1980. Each of the papers solicits responses from the readers and, in addition, the ASTM committee described below is now reviewing many of the terms. Ultimately, all of the definitions will be collected in a NBS document that will serve as a guide for their application.

Lest the reader think that definitions are a minor problem, consider the situation illustrated in Fig. 2. Here is shown the effect of stress on the critical current of a commercial high field superconductor measured at NBS [6]. The separate curves indicate the critical current behavior one observes using the indicated criterion or definition for critical current. Note that not only the magnitude, but also the shape of the curve is affected by the choice. All of the definitions shown have been used at one time or another. (Our studies have led us to conclude that the use of either the electric field criterion or the resistivity criterion will provide a maximum of information with minimum effort.)

B. ASTM Committee

At the instigation of NBS, an ASTM Subcommittee on superconductors (B01.08) was formed under the Conductor committee. The organizational meeting was held on June 12, 1979 at ASTM headquarters. It was attended by more than 25 representatives from industry, government, and the national laboratories. A. F. Clark was appointed to the chairmanship. The Subcommittee was divided into six task groups: Definitions; Critical current; Physical and mechanical properties; ac losses; Critical temperature and critical field; and Stability. Members of the first four of these were chosen and specific tasks determined. The minutes of the meeting are included here in Appendix B. Since the organizational meeting, membership in the subcommittee has increased and now is near 50. Informal sessions were held at the Cryogenic Engineering Conference in August. The critical current task group chairman appointed three teams to prepare a first draft of an ASTM standard for the three common methods of I_c measurement. The next full meeting of the subcommittee is planned for the

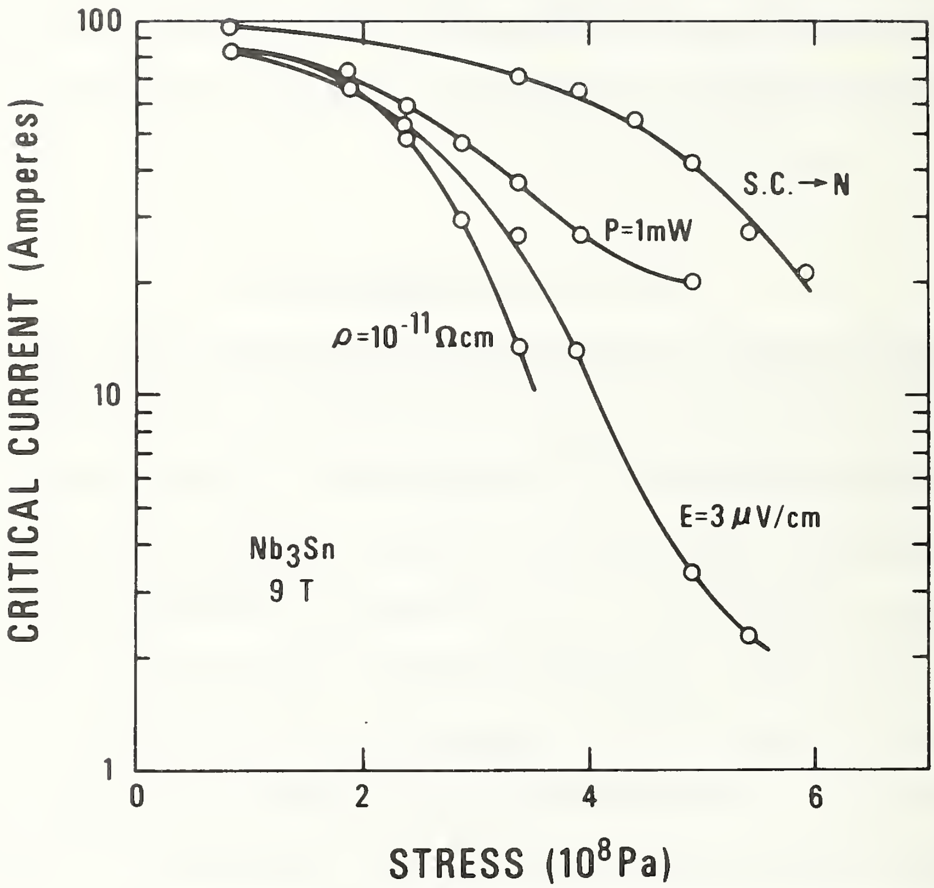

Figure 2. The critical current of a single Nb_3Sn multifilamentary conductor as a function of applied stress for various critical current criteria.

spring of 1980 with major reports due from the Definitions and Critical current task groups.

The enthusiastic response of the entire community to this subcommittee has been most heartening. The willingness of the members to volunteer time for the various projects is greatly appreciated.

C. Suggested I_c Test Specifications

To assist the critical current task group of the ASTM Committee, we have developed a comprehensive list of proposed test specifications for critical current measurement. This document, reproduced here as Appendix C, gives: the variables that might be specified by the user; the control parameters on the measurement; a series of operational checks for a valid test; and test apparatus design considerations. The list has been sent to the committee and to the manufacturers for their comments. Clearly, to follow each of the steps in a given test would involve an excessive amount of time. The goal is only to provide a paper for comment, and perhaps, to give a basis for a standards laboratory system. Following the manufacturers input, a revised list will be presented for discussion at the spring ASTM meeting.

IV. EXPERIMENTAL PROGRAM AT NBS

The measurement of critical parameters of superconductors (current, field, and temperature) as well as other phenomena of importance in applications (ac losses, effects of stress and fatigue, etc.) require complex apparatus that usually must be constructed by the experimenter. In such measurements it is not uncommon for the results from different laboratories to be quite different even though everyone agrees on the definitions of the appropriate terms and similar apparatus is used. One solution to this problem is the use of a very detailed and reproducible experimental technique that has been developed from extensive experimentation. This type of development is one of the strong thrusts of our program.

It is also often desirable to have a standard apparatus design available for a given test. Frequently the technique and apparatus descriptions are a single document (e.g. ASTM Standards). Care is needed in the design phase to insure that the device is suited to all potential users and that a given measurement can be completed in a reasonable time. Our first designs in this category are for a critical current apparatus. The final design will be subjected to a detailed evaluation by interested parties. If possible, the apparatus will then be sent to various laboratories for field trials of the design.

Another aspect of apparatus development occurs in the situation where widely different techniques are used to measure what is ostensibly the same quantity. Determining the causes of disagreement among the techniques can be a very difficult task. A specific example is provided by ac loss phenomena in superconductors. The losses may be determined by a calorimeter, a watt meter, or a flux integration technique. All of these measurements are difficult and agreement between any two is rare; among three it is essentially nonexistent.

The NBS research program is looking at each of these aspects of standards development. Most of our work this year has been to start the development of critical current test procedures and devices and to begin work on the critical temperature measurement evaluations (at NBS-Gaithersburg). Work has also been done on the evaluation of ac loss measurement techniques, primarily with Air Force funding, but also with some contribution from this program.

A. Critical Current Studies

Our main experimental studies this year were devoted to investigating the effect of various aspects of the sample holder on the measured critical current. To this end the I_c characteristics of commercial multifilamentary Nb_3Sn and V_3Ga wires were measured using copper, phenolic, and fiberglass epoxy (NEMA G-10) sample holders. For each of these materials, I_c was measured with the sample in a hair-pin geometry. The sample was supported in two different ways to prevent movement caused by the Lorentz force: first with the sample freely suspended in a slot machined in the support material, and second, with the sample frozen in place with vacuum grease, a common practice. For the copper sample holder, no difference was found in the magnitude of I_c between the grease and no grease method. For the composite materials, the I_c depended on the fiber direction in the sample holder. For the phenolic and G-10 holder materials with the fiber direction <u>parallel</u> to the sample, no difference in I_c was found between the grease and no grease method. For the phenolic sample holder with the fiber direction <u>perpendicular</u> to the sample, however, the grease method produced a 25% degradation of I_c at 7T (for Nb_3Sn), and 11% (for V_3Ga) (compared with the no-grease method). The complete curves are shown in Fig. 3. This relatively large decrease in I_c for the phenolic sample holder, with fiber direction perpendicular to the sample and with grease around the sample, is ascribed to compressive strain introduced by differential thermal contraction between the sample and the sample holder material. This conclusion is supported by calculation from measurements made of the thermal contraction of the superconducting wires and the holder materials (Fig. 4) and measurements of the strain degradation of the superconductor (Fig. 5). The measurements and conclusions are described in more detail in a recent publication [7].

Work has also been started on adapting a theoretical model by J. W. Ekin [8,9] describing current transfer into a superconductor to the practical wires and soldered joints between wires. An apparatus for testing the predicted behavior is being built.

B. AC Loss Studies

Many of the applications for superconductors require transient fields or currents. The resultant ac power loss in such conductors often influences the design of the system. There are a large number of variables which determine the magnitude of the effect and present theoretical models are not good enough to accurately predict the losses for all practical superconductors. Measurements of ac losses are necessary in basic research to further understand the loss mechanisms and for the characterization of commercial wire. Several techniques exist for making the measurements, but different results are often found depending on the technique used. The purpose of these studies is to compare, evaluate, and calibrate the various measurement methods. As mentioned earlier, this research is primarily funded by the Air Force, but it is also an

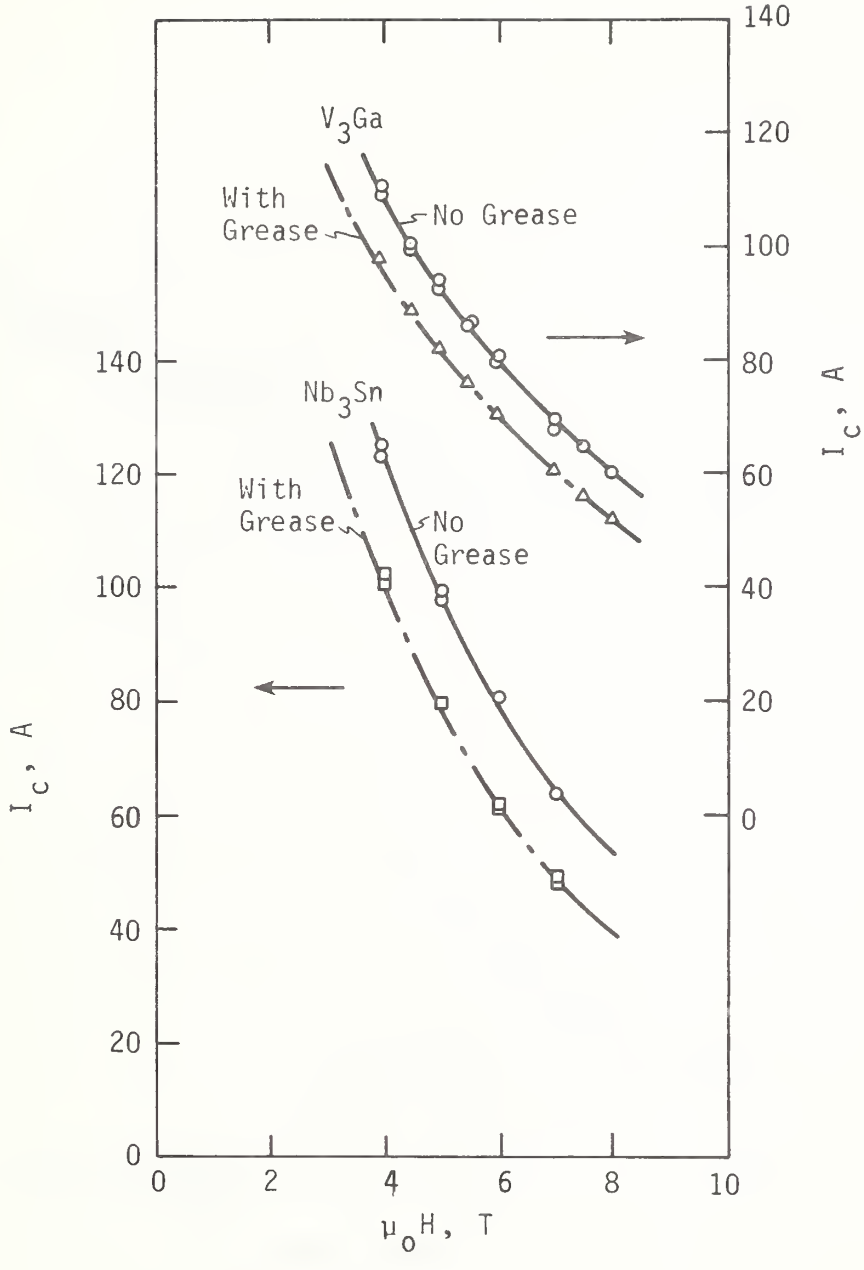

Figure 3. Critical current degradation of Nb_3Sn and V_3Ga wires when fixed with grease to a phenolic sample holder with fiber direction perpendicular to the sample.

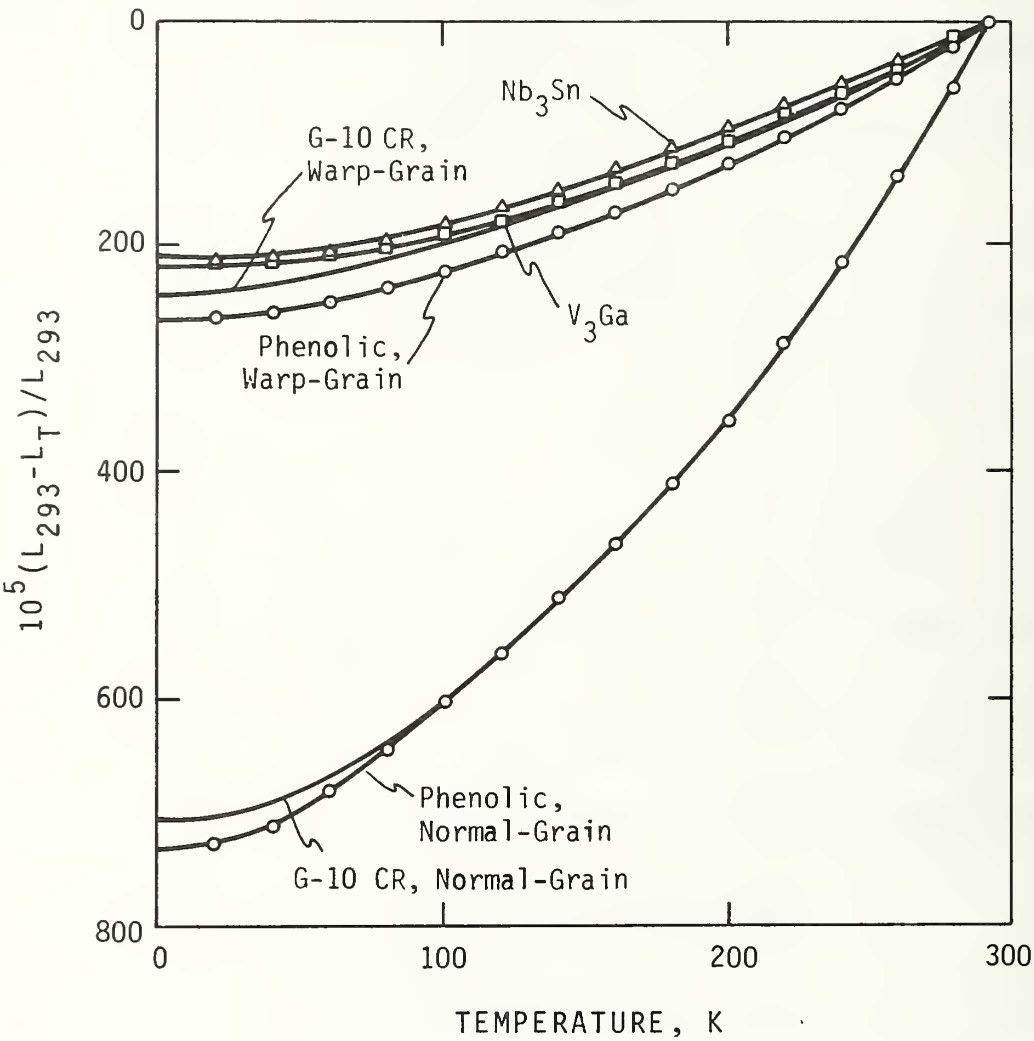

Figure 4. Thermal expansion of phenolic, fiber-glass epoxy (NEMA G-10CR), multifilamentary Nb_3Sn and V_3Ga. Warp-grain denotes the warp direction is parallel to the measured axis; normal-grain denotes the thermal expansion is measured perpendicular to the fiberglass cloth.

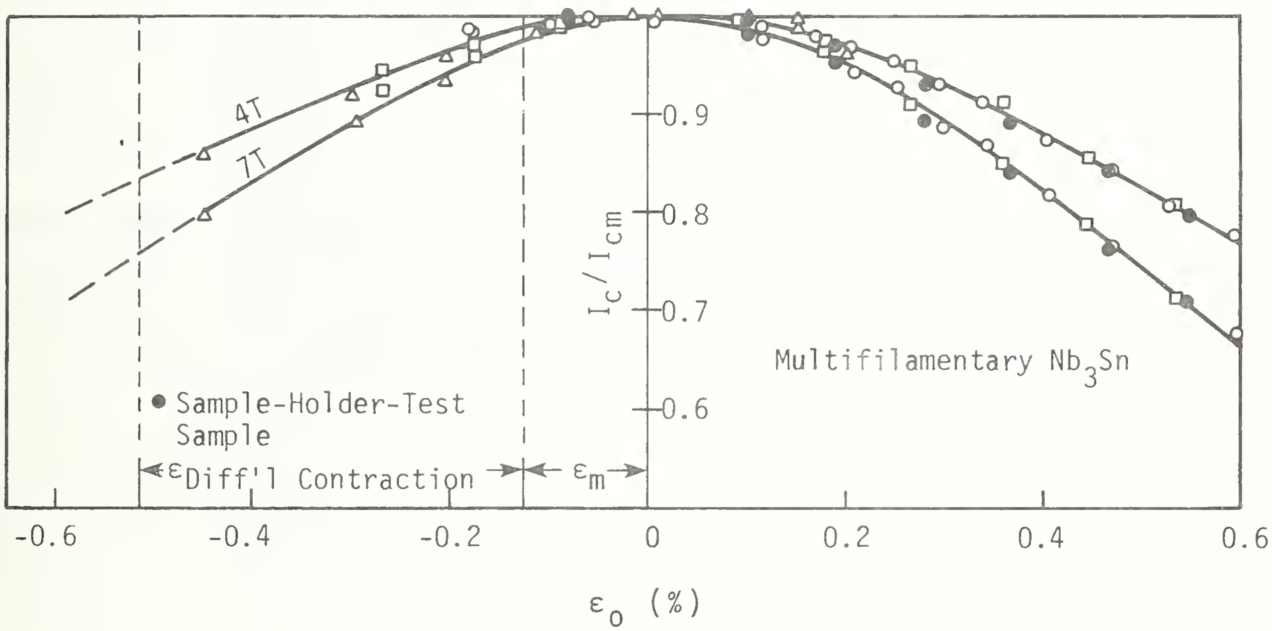

Figure 5. Relative change of critical current, I_c, with intrinsic strain ε_0. I_{cm} is the maximum value of the critical current. Positive ε_0 indicates tensile strain, negative ε_0 indicates compressive strain.

area of concern to the standards program since, ultimately, a system of standard ac loss measurement techniques will be needed.

The various methods of measuring ac losses can generally be divided into two categories: calorimetric and electronic. The most common calorimetric technique measures the helium boil-off rate produced by the ac losses. Though the technique is fairly straightforward, it becomes complex when sensitivities approaching 1 mW are required. In our program we are striving for a sensitivity of 1 mW or better to provide as wide an overlap as possible with electronic techniques that have sensitivities on the order of 1 mW and lower. To this end we have set up three experimental systems: a calorimeter; a digital oscilloscope technique; and a lock-in amplifier technique. The goal is to measure practical superconductors with special attention to the region of overlap and to analyze the various techniques to determine the reasons for the observed discrepancies. Some very preliminary results are shown in Fig. 6. The apparatus and their operation are described in detail in a recent publication [10].

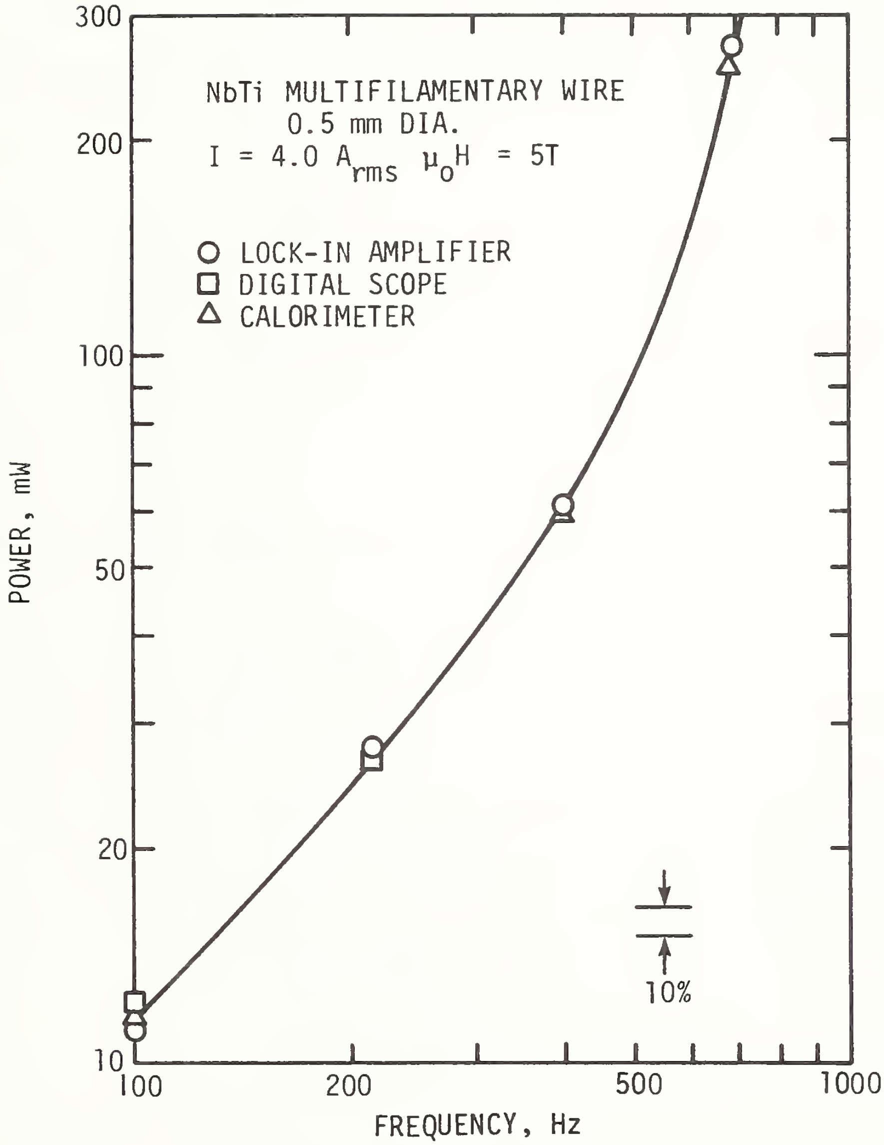

Figure 6. The ac loss as a function of frequency for a multifilamentary NbTi superconductor. A calorimetric value at 215 Hz is not shown since it agrees almost exactly with the digital value.

C. Critical Temperature Studies

"Definition of the Critical Temperature of Practical Superconductors"

J. F. Schooley and R. J. Soulen

Temperature Measurements and Standards Division

The transition from the normal (resistive) state of a metal to the superconductive state should occur over an extremely narrow temperature region (theoretical estimates vary from 10^{-9}K to 10^{-27}K). Carefully prepared specimens used for temperature reference standards fall short of this ideal (efforts at NBS yield samples with transition widths of 10^{-5} K) but ambiguities in the definition of T_c of this order are not generally of practical significance. Such is not the case, however, for the highly strained inhomogeneous materials of technical importance where the transitions often extend over several Kelvins.

Further complicating the ambiguity of the proper definition of T_c in the latter circumstances is that different methods of detecting the transition often give quite different temperature values. Measurements of the heat capacity anomaly, of the onset of magnetic flux exclusion (the "Meissner effect"), and of the disappearance of electrical resistance each lead to independent and often differing representations of the shape of the transition and of the definition of the transition temperature. In discussing the use of a particular superconductive material for a particular application, it is important that the manufacturer, the vendor, and the user agree upon a transition temperature which is consistent with the other parameters of engineering importance, such as the critical field and the critical current. In the following report, we summarize the progress which has been made by the

Temperature Measurements and Standards Division during FY 79 in identifying the superconductive transition temperatures of practical materials in a self-consistent manner. This progress includes the construction of an experimental test cryostat, measurement instrumentation, and several baseline measurements on relevant superconductive materials, including samples of industrial wires of niobium-titanium and niobium- tin alloys in copper or copper-alloy matrices.

Instrumentation

A cryostat was fabricated for this project in order to test specimens over a temperature range of 1K to 300K. It can be inserted into the gap of a magnet capable of generating dc fields as large as 2T (20 kG). Sufficient electrical leads are available for the simultaneous testing of five samples.

Temperature measurements are based upon the IPTS-68 Temperature Scale above 13K through the use of a capsule platinum resistance thermometer calibrated within the Division. Temperature reference below 13K is provided by both doped-germanium and rhodium-iron thermometers calibrated on the EPT-76 Provisional Temperature Scale. Any given temperature measurement throughout the test range is expected to lie within ten millikelvins of the defined temperatures on the two reference scales. We have developed a computer-based automatic acquisition system which can incorporate the following features:

*Programmable-rate ramping temperatures throughout the test range.

*Adjustable-level temperature plateau for measurement stability.

*Measurement of the low-frequency magnetic susceptibility, including graphical analysis of the transitions.

*Measurement of the dc electrical conductivity.

*Measurement of the heat capacity.

Measurements to Date

1. Niobium-Tin. We have examined two types of samples of this material. One was prepared in our own facilities by the vapor deposition of high-purity tin on a one-mm niobium wire of 99.9+% purity. It is identified as NBS #80, and its susceptibility-temperature curve is shown in Fig. 7. The second type of sample is from a copper-clad 0.7 mm diameter high-field magnet wire prepared by imbedding some 2800 Nb filaments in a bronze matrix and subsequently reacting the wire for 240 hours at 750°C. The sample was measured in its annealed state. Its susceptibility-temperature curve is shown in Fig. 8, with the data of NBS #80 superimposed for comparison. These results must be regarded as very preliminary, but they indicate that the bulk of the superconductive transition in the commercial material is substantially broader and occurs at a lower temperature than that which is characteristic of unstressed Nb_3Sn.

We expect to make quantitative correlations between the transitions in the two types of samples in terms of internal material stresses and proximity effect calculations.

2. Niobium and Niobium-Titanium. We have examined one sample of commercially-prepared niobium-titanium superconductive wire. This sample is a wire of rectangular cross-section 0.53 mm by 0.68 mm containing nearly 200 filaments of $Nb_{39}Ti_{61}$ imbedded in a copper matrix. The susceptibility-temperature curve for this sample is shown in Fig. 9. In view of the proximity of its transition temperature to that of pure niobium, we show also in Fig. 9 both susceptibility and heat capacity data for sample OR-1, a 3-mm

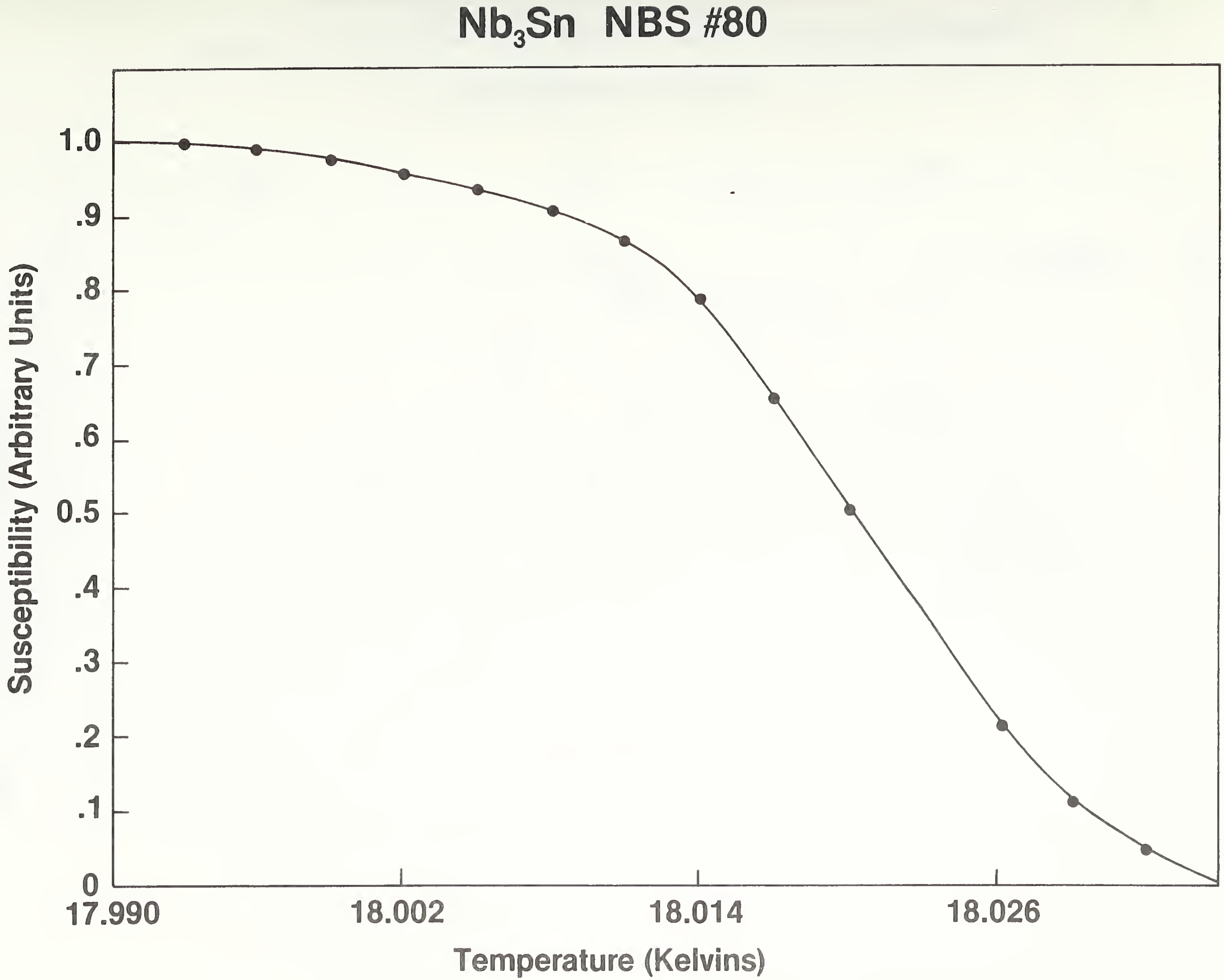

Figure 7. Susceptibility transition of Nb_3Sn prepared by vapor deposition of tin on niobium wire.

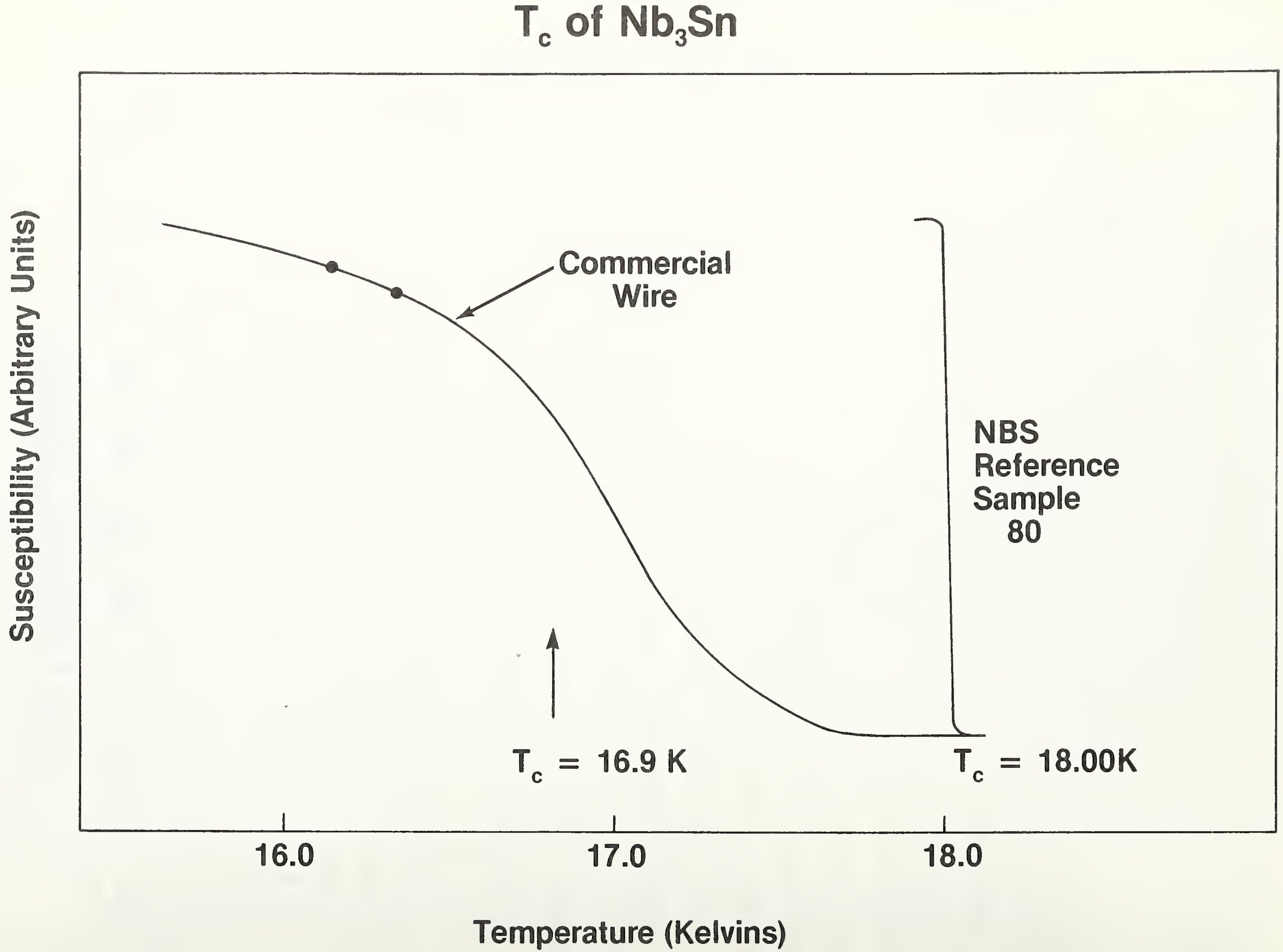

Figure 8. Susceptibility transition of commercial Nb_3Sn multifilamentary wire compared to the reference sample of Fig. 7.

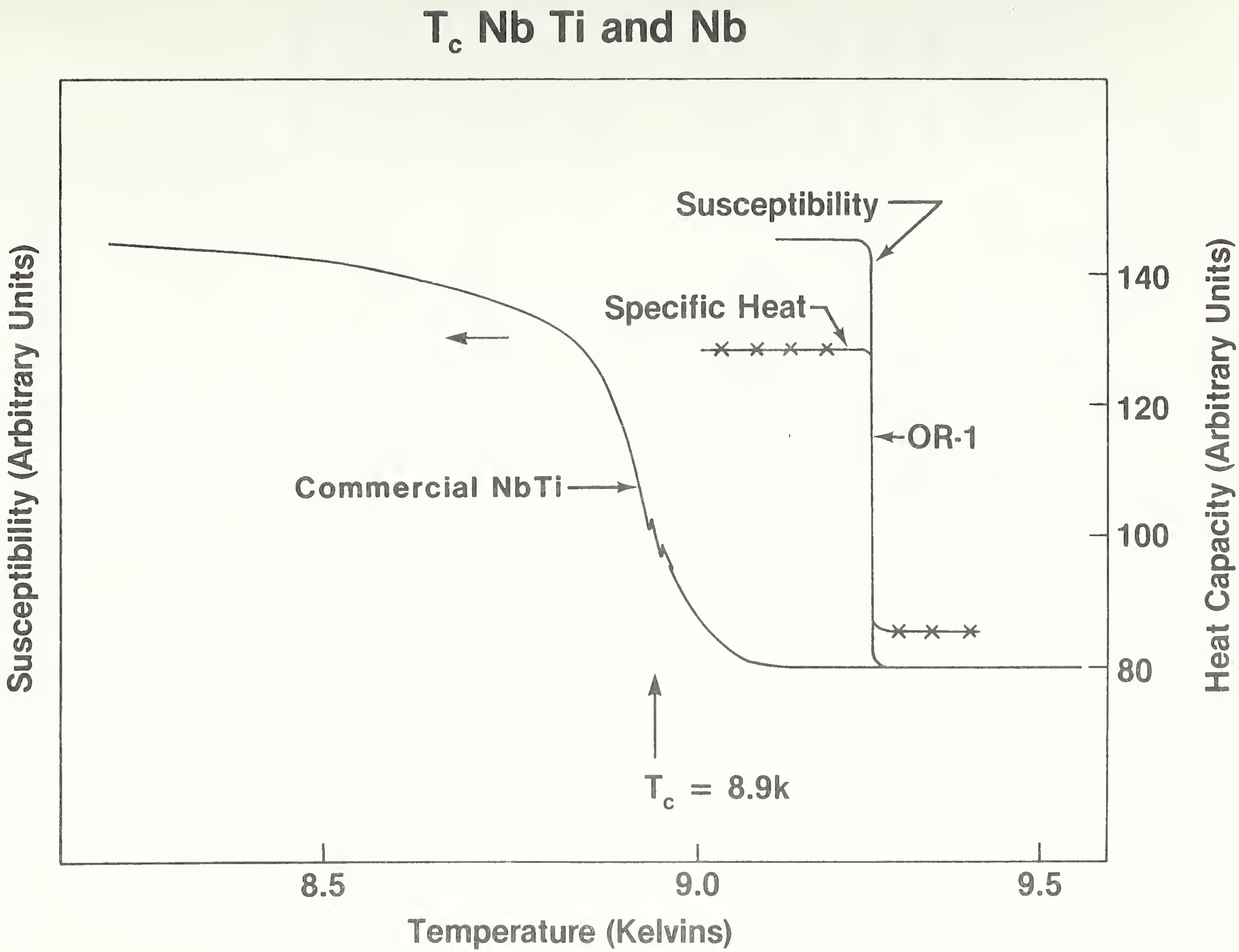

Figure 9. Susceptibility transition of commercial NbTi multifilamentary wire. Pure niobium is shown as sample OR-1.

diameter wire prepared from electron-beam zone-refined niobium. The strong difference in transition width between the two types of samples is not surprising, considering their very different compositions and states of anneal. We anticipate the testing of the commercial materials in much the same fashion, however, in order to establish the most meaningful definitions of the commercial material parameters.

D. Supporting Research at NBS

Since this is our first report on this program, we list here other research programs in the group that are related to this work. It is an important feature of the laboratory that we have people engaged in experimental work covering a wide range of properties at low temperatures. They provide us with a very valuable source of data and consultation on many aspects of superconductors and related materials. The projects, funded by a variety of agencies are:

Stress and fatigue effects in superconducting wires

Stress and fatigue effects in potted superconducting coils

Training of superconducting coils

Electrical, thermal and mechanical properties of stabilizing metals

New high field superconductors

In-situ processing of superconductors

Thermal expansion

Elastic properties

Thermal conductivity

Magnetic properties

The reader who is interested in more details of any of these programs is encouraged to call one of the authors.

V. CONTRACTOR PROGRAMS

Four industrial contractors, all manufacturers of superconducting wire, are working on the program (see Appendix D). To date most of their contribution has been in helping to staff the ASTM committee, collaborating with NBS in the formulation of the test program, and construction of test apparatus. Their experimental work has just started and, thus, most of the description here will be of their proposed programs. Some data has been received, but will be kept for a later report. All of the tests described are to be made on commercial wires, usually from the manufacturer's own stock. In addition, each contractor is participating in the round robin tests described in Section II and will critique the NBS-designed test fixtures.

A. Airco Superconductors

A report is in preparation comparing the critical current measured in strands with that found when the strands are cabled.

The experimental program will determine: a) the effect of power supply ripple on the I_c measurement; b) how different methods of constraint affect the measured I_c; c) how I_c varies with direction of an applied magnetic field with respect to the current; d) the effect of wire diameter on the current transfer length; and e) the effect on I_c of a variation of the magnetic field strength over the sample length. In each case the goal is to provide data allowing a judgement to be made of the measurement precision to be expected from a given standard test jig.

B. Intermagnetics General Corporation

This project is investigating the effect of self field on the critical current of relatively large (>5 kA) superconductors. Measurements are being made to evaluate the effect of twist pitch and matrix resistivity as well as terminal configuration. They are developing a test fixture specifically to allow accurate determination of the residual resistance ratio of the stabilizing metal in the composite superconductor. A first model has been constructed and a number of tests made.

C. Magnetic Corporation of America

A comprehensive series of short sample tests are being made on 25-30 NbTi wires. The wires cover a range of copper/superconductor ratios and several have high resistivity cupro-nickel matrices. The effect of the criterion chosen for defining I_c is also being studied in these tests. A number of the samples have been measured in three different types of sample holders (straight, hairpin, and noninductively wound spool) to determine if the sample configuration has an effect on the result. In addition, studies of current transfer through joints in superconducting wires are being made on about twenty samples. The samples are chosen such that the effect of varying wire diameters, filament twist pitch, matrix material, and matrix-to-superconductor ratio can all be evaluated. The emphasis of these measurements is on relatively large conductors (I_c > 1000A).

D. Supercon Inc.

This project is studying the variation of critical current found in a production run of NbTi superconductor. The variation of I_c along the final wire in both long and short segments is being determined. Similar measurements on samples from a number of other production runs will be made to give an indication of the lot-to-lot variation in wires processed by the same method. The second part of the study is an investigation of parameters effecting the stability of the wires, especially the effect of filament uniformity. To this end the concepts of recovery current and minimum propagation current are being reviewed and practical measurement practices developed.

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APPENDIX A

SUPERCONDUCTING STANDARDS PROGRAM

Questions to Users

The purpose of this questionnaire is to aid in the development of standard definitions and measurement practices for superconducting parameters. It will also be used in the writing of a document which discusses current measurement practices.

Is it okay for NBS to publish results of this questionnaire?

Specifications

1. What superconducting parameters are used in coil design?
2. How are specifications derived from design data?
3. What parameters are in specifications - get copy of specs, if possible (a) does ρ refer to area of superconducting part or overall conductor?
4. Do you perform measurements to check specs?
   (a) How many measurements?
   (b) How much time and money is spent on checking specs?
   (c) How often do you find material does not meet specs?
5. Who is supplier of superconductor?

Measurement Techniques
I_c measurements

1. What materials do you test, i.e. NbTi and/or Nb_3Sn?
2. What range of conductor sizes are tested?
   (a) What is largest size conductor you can test?
3. At what temperature are tests done, 4.2K or other?
4. Are only individual strands of large conductors tested?
   (a) if so, is I_c of overall conductor calculated as the sum of individual strands?
5. Method of Measurement
   (a) hair pin, coil geometry, or straight sections
   (b) length of sample
   (c) length between voltage taps
   (d) holder material - G10, phenolic, or other
   (e) holding method, grooves, grease, solder, thread, etc.
   (f) drawing or sketch of holder

6. Instrument Capability
   (a) dia. of magnet bore
   (b) max. magnetic field
   (c) was magnet calibrated?
   (d) maximum current for sample
   (e) voltage sensitivity, i.e. how many $\mu V/cm$? - noise level? what kind of amplifier is used?

7. What other parameters are measured?
   (a) T_c
   (b) H_{c2}, H_{c1}
   (c) AC losses
   (d) physical mechanical properties
   (e) stability

APPENDIX B

MINUTES
TECHNICAL MEETING

ASTM SUBCOMMITTEE B01.08 on SUPERCONDUCTORS

Held June 12, 1979
ASTM Headquarters, Philadelphia, PA

In the afternoon session, chairman Al Clark discussed the role of NBS and pointed out that it is not a regulatory agency but a research base which can be used as input to ASTM. Next the various tasks and priorities which need to be considered were discussed at some length. The tentative task group structure set up in the morning meeting was reviewed further. However, after further discussion it was agreed upon by the group that the expertise of the members might be better utilized in specific subject areas, each dealing with all the categories in the scope, except for standard definitions. On MOTION, duly seconded, the group voted to accept the task group structure shown in the table below. Since the work of Task group #1 (Definitions) covers all subject areas, the other task groups are to refer any recommendations regarding

Final Task Group Structure

Scope category \ Subject area	I_c	Phys. Mech. Properties	ac losses	T_c	H_c	Stability
Definitions			Task #1			
Test Methods						
Product Specs.	Task #2	Task #3	Task #4	Task #5		Task #6
Material Specs.						
Practices						

definitions in their subject area to Task group #1. Most of those present volunteered for service on the various task groups. As of this meeting the membership of each task group is as follows:

Task group #1 (Definitions): Steve J. St. Lorant - Chairman
Alan F. Clark
Roger Boom
Michael J. Superczynski, Jr.
Bruce P. Strauss
Roger J. Soulen

Task group #2 (Critical Current):	Bruce P. Strauss - co-chairman Jack W. Ekin - co-chairman Ronald M. Scanlon William A. Fietz Phillip A. Sanger Robert Schwall Robert N. Randall Henry Riemersma
Task group #3 (Phys. Mech. prop):	Phillip A. Sanger - co-chairman Bruce Zeitlin - co-chairman Jack W. Ekin Fred N. Mazandarany Robert N. Randall Robert H. Remsbottom Masaki Suenaga
Task group #4 (ac losses):	Meyer Garber - Chairman William Fietz (Stuart Shen) Ray Radebaugh Henry Riemersma (Richard Wagner) Joe D. Thompson (Michael Walker)

Task group #5 and #6: Not appointed yet.

Names in parentheses indicate those not present but volunteered by others. Each task group met separately for about an hour to decide on the proper course of action for their own groups. Reports from each task group were presented to the entire subcommittee. These reports are as follows:

Task group #1 (Definitions)

This group will start with the three sets of definitions published so far by the National Bureau of Standards (Cryogenics 17, 697 (1977), Cryogenics 18, 137 (1978), and Cryogenics 19, 327 (1979)). Irrelevant definitions will be deleted and others the group feels are important will be added. Chairmen of the other task groups were asked to submit to Dr. St. Lorant any definition changes or additions which relate to their specific task group. Both intellectually satisfying definitions and practical definitions will be considered. A preliminary set of definitions will then be ready by the next meeting of the subcommittee.

Task group #2 (Critical current)

1. All tests would be defined in terms of measurable variables such as current, voltage, magnetic field, and physical distance between the voltage taps.

2. The task group decided to write recommended tests of the following type:

    a. Hairpin

b. Coiled sample (either non-inductively wound or inductively wound)
c. Straight, short sample - simple solenoidal test magnet
d. Straight sample - split-pair test magnet

The range of these tests would be less than 600 amps so it could be defined with low noise power supplies. Future work would include tests for higher-transport-current samples.

3. At the ICMC conference in August, each member of the task group will submit a listing of suggestions, practices, and tolerances for specifying test methods in each of the above areas. The suggestions will be distributed among the members for preparation of first-draft test procedures.

Task group #3 (Phys. Mech. Prop.)

We divided into three groups and leaders assigned as follows:

Group I. Physical Properties

1. Component Percentages - Phil Sanger, Airco
2. Physical Dimensions and Workmanship - Bob Remsbottom, University of Wisconsin
3. Twist Pitch - Bruce Zeitlin, IGC
4. Configuration Bob Randall, Supercon

Group II. Electrical Properties

Resistivity or Resistance Ratio - Phil Sanger

Group III. Mechanical Properties

yield strength
ultimate strength
thermal contraction
modulus
stress/strain characteristics
residual stresses
fatigue properties (thermal and mechanical cycling)

Leaders: Fred Mazandarany, GE; Mas Suenaga, BNL. It was also suggested that John Zbasnik, LLL and Dewey Easton, ORNL be asked to serve on Group III.

We agreed that the objective for our next meeting is to have (a) a definition, (b) suggest a test method for measuring, (c) research the existing ASTM for present specifications (thanks to B. Remsbottom), and (d) suggest tolerances.

Our next meeting would then be used to critique and possibly assign a second member to specifically review individual tasks.

At the end of our June 12 meeting, it became apparent to one of us (BAZ) that Group III Mechanical Properties might better be served by a separate Task Group because of the lack of basic test data and procedures. This will be discussed at the next meeting.

In the longer range, we hope that once the specifications are defined for the wire, similar specifications will be defined for the more complex conductors such as braids, cables, etc.

Task group #4 (ac losses)

The group spent most of the time trying to organize the area of ac losses. The preliminary organization divides ac loss measurements into three categories: (I) type of sample, (II) type of excitation, (III) type of measurement.

Each of those categories is broken down as follows:

I. Type of Sample
   A. small or short sample
   B. long cables
   C. magnets
   D. ac motors, generators, transformers
   E. rf devices (linac)

II. Type of Excitation
   A. quasi-dc
   B. 20Hz - 20kHz
   C. pulses and ramps
   D. ripple on dc

III. Type of Measurement
   A. magnetization
   B. wattmeters (digital or analog multipliers, phasemeters)
   C. ac bridges
   D. lock-in voltmeter
   E. calorimeter (boil-off or adiabatic)

Future work will be to do more detail work on the outline. The first priority will be in small conductors at low frequencies. In many cases all measurements methods would be acceptable but in some cases certain methods may be preferable. We plan to study this further.

The next meeting of the ASTM B01.08 Subcommittee on Superconductors will be held at 4:30 pm on August 23, 1979 during the time of the CEC/ICMC meeting in Madison, Wisconsin. Most of the task groups will be meeting on Monday, August 20.

The meeting adjourned at about 3:30 pm.

Respectfully submitted,
Ray Radebaugh
Secretary, B01.08

APPENDIX C

NBS CRITICAL CURRENT TEST SPECIFICATION SUGGESTIONS

October 17, 1979

A. User Specified Variables and Suggested Tolerances

1. Critical current I_c

   a. reproducible precision of $\pm$ 2%
   b. accuracy of $\pm$ 5% for independent measurement

2. Applied magnetic field, H

   a. uniform to $\pm$ 2% between voltage contacts
   b. field ripple less than $\pm$ 2% peak to peak
   c. field accuracy $\pm$2%

3. Angle between current and magnetic field

   a. orientation constant to $\pm 2°$ between voltage contacts

4. Ambient temperature, T

   a. constant temperature, accurate to $\pm$2%

5. Electric field criterion, E_c, for defining I_c

   a. accuracy $\pm$10%

B. Control Parameters

1. Voltage current characteristics

   a. I_c, defined by E_c, reproducible precision of $\pm$2% for at least 3 runs at constant field
   b. V-I reversible up to 120% times the voltage at E_c, to give I_c with precision of $\pm$2%
   c. current ripple less than 5% r.m.s.
   d. r.m.s. noise voltage, a factor of 5 less than voltage at E_c
   e. current transfer voltage less than voltage at E_c by a factor of 2

2. Strain

   a. bend radius R and wire diameter d, such that d/2R < 0.05% for Nb_3Sn and < 1% for NbTi, this may require pre-reaction forming of wire to test configuration
   b. no stress risers between current contacts
   c. in the case of the sample fastened to the sample holder with adhesive or grease, the differential thermal contraction between sample and support low enough to give strain < 0.02% for Nb_3Sn and < 0.5% for NbTi
   d. in the case of a grooved sample holder, the groove

geometry will be such that the strain due to the Lorentz force is < 0.02% for Nb_3Sn and < 0.5% for NbTi

e. I_c sample will have the same initial stress state as user product, i.e. same initial stress from diffusion barriers, cladding and insulation

f. voltage taps will be strain free

C. Operational Checks for Valid Test

1. Quench protect circuit test

   a. quench sample 5 times and not change I_c by more than $\pm 2\%$

2. Lorentz force and trapped flux test

   a. cycling magnetic field doesn't change I_c by more than $\pm 2\%$

3. Current ramp rate test

   a. I_c independent of ramp rate, to $\pm 2\%$, for chosen ramp rate and half that ramp rate

4. Test for contact and current transfer heating affecting I_c

   a. measure sample power at thermal quench, for a factor of 5 range of I_c, will be the same to $\pm 20\%$

5. Contact and current transfer heating test

   a. measure power across current contacts, this will be an operational number that will indicate heating problems

D. Test Apparatus Design Concerns

1. Current transfer length dependence

   a. magnetic field gradient
   b. magnetic field orientation
   c. composite constituents (i.e. matrix resistivity, diffusion barriers, cladding)

2. Current solder joints

   a. low joint power

3. Sample protection from

   a. strain in handling and mounting
   b. strain upon cool down
   c. large powers upon quench

E. Options

1. Test configuration (provided strain criterion is met)

   a. cylinder
   b. hairpin
   c. straight

2. Sample holder

   a. matched thermal contraction of sample and holder when adhesive or grease is used
   b. grooved holder to prevent sample strain and movement from Lorentz force

APPENDIX D

STAFF AND CONTACTS

A significant amount of the work on this program is done under subcontract to NBS. We list here both the NBS staff and the technical contacts for the various contractors.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Practical superconductors are complex materials and the determination of the parameters required for designing with them is a difficult task. Many approaches are possible for determining a given parameter and the results depend critically on which one is chosen. The goal of this program is to arrive at a set of useful voluntary standards for measurements on modern practical superconductors that will be acceptable to both manufacturers and users. Agreement on a set of standard definitions for the various parameters is also necessary. This report describes the status of the program and includes a brief historical introduction. The need for standards in this area is described in detail with particular attention paid to the need for consensus among all interested parties and our techniques for achieving it. Results from the experimental research by NBS and a review of the wire manufacturers' programs are presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Critical current, critical temperature, losses, magnetic property, standards, superconductor.

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