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DEVELOPMENT OF STANDARDS FOR SUPERCONDUCTORS

Interim Report

October 1980–January 1982

A.F. Clark, L.F. Goodrich, F.R. Fickett, and J.V. Minervini
Electromagnetic Technology Division
National Engineering Laboratory
National Bureau of Standards
U.S. Department of Commerce
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Work performed under Department of Energy contract DE-AI01-76PR06010
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

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A cooperative program with the Department of Energy, the National Bureau of Standards, and private industry is in progress to develop standard measurement practices for use in large scale applications of superconductivity. The goal is the adoption of voluntary standards for the critical parameters and other characterizations of practical superconductors. Progress for the period October 1980 through January 1982 is reported. The major effort was the development of a standard test method for critical current, the necessary back-up research, and the coordination of the adoption of the test method and a standard terminology through the subcommittee level in ASTM.

Key words: critical current; critical parameters; losses; measurement methods; standards: superconductor.

1. INTRODUCTION

The development of standard measurement practices is essential to the success of any developing technology. In order to help assure success in the field of large scale applications of superconductivity the Department of Energy and the National Bureau of Standards have undertaken a program to establish a uniform terminology and reliable measurement techniques for the many new aspects of superconductivity that are essential to good design. This report is the third in a series summarizing the progress in this program which is jointly supported by National Bureau of Standards and three divisions of the Department of Energy (Fusion Energy, High Energy Physics, and Magnetohydrodynamics through the Francis Bitter National Magnet Laboratory).

The first two reports [6, 21]* summarized the progress in the first two years. This report covers an extended period ending in January 1982 to coincide with a change in the contract year. The first report included: a large effort on the standardization of terminology, a preliminary assessment

*Reference numbers refer to chronological listing in § 6, page 96.

of measurement capabilities in the United States, the formation of an ASTM Subcommittee on Superconductors, some preliminary transient loss measurements, a comparison of critical temperature measurements on practical superconducting materials, and extensive research on the many factors that affect critical current measurements. The second year of the program concentrated heavily on the development of a standard method for measuring critical current and included contracts to the four U.S. wire manufacturers for research on various aspects of this measurement. Thus, the second report includes a survey of the state-of-the-art of critical current measurements, including a round robin and an assessment of the criteria used, reports from the four wire manufacturers, the final publication of the definition of terms, and the development of a draft standard for the determination of critical current for superconductors with a critical current less than 600 amperes.

This third report includes an evaluation of the present status (§ 2), a summary of the progress in the adoption of the voluntary standards (§ 3), a review of the experimental effort (§ 4), and (as § 5) a paper reviewing all the parameters that can affect critical current measurements and an assessment of their importance. A list of the more than 20 research papers resulting from this program is included as § 6. The agenda, minutes, and list of attendees of the August 10, 1981 meeting of the ASTM B01.08 Subcommittee on Superconductors is included as Appendix A. The draft standards for "Standard Definitions of Terms Relating to Superconductivity" and the "Standard Test Method for DC Critical Current for Composite Superconductors" are included as Appendices B and C, respectively.

2. EVALUATION OF PRESENT STATUS

It is important in an interactive research program such as this to continually assess the results with respect to the direction of future efforts. The final goal is the adoption of voluntary standards for the determination of design parameters for practical superconducting materials. The progress toward this goal is summarized in § 3, The Preparation and Dissemination Standards. In this section we will summarize the background research efforts, point out significant research problems that have been encountered, and indicate future directions for the program.

2.1 Summary of Major Accomplishments

Listed below are highlights of the efforts to date and where more detailed results can be found.

a. Creation of ASTM Subcommittee on Superconductors

The ASTM Subcommittee B01.08 on Superconductors was created very early in the program in order to provide not only the means of adopting voluntary standards but also a forum for feedback on needed research and the practicality of proposed standards. Three meetings have been held and task groups have developed draft standards for definitions of terms and critical current test methods which have been modified and adopted by the subcommittee. (See § 3.)

b. Survey of Superconductor Test Techniques in U.S. and Japan

A detailed survey of test techniques applied to superconductors for all the critical parameters as well as other characterizations in the U.S. and Japan was performed [6, 21]. It showed that measurements were usually made to 10-15% accuracy at best, few laboratories have routine test facilities, critical current measurements if wrong are usually low, simple test practices often lead to dramatic errors, and both producers and consumers of practical superconductors desired a cooperative effort to develop standard test methods.

c. International Test Specification Survey

An evaluation of test specifications used by forty different laboratories in the U.S. showed a great diversity [21]. Little agreement was found for values of test parameters or accuracy, sample mounting techniques were a problem, transfer voltages and strain effects were not understood, accurate field measurements are badly needed, and the critical current criteria were not universally accepted.

d. Round Robin Critical Current Tests

A round robin test for critical current of three different conductors at five laboratories was conducted [21]. Inaccuracies of 30-40% were common, probably because no methods or criteria were suggested, the labs were free to choose their own. (A sixth laboratory recently volunteered additional measurements with no significant change in the results.)

e. Comprehensive Experimental Program on Critical Current Testing

A very thorough testing of all the parameters that affect critical current measurements was done by NBS and the four wire manufacturers [4-6, 12, 15, 17-22]. These effects were evaluated for:

- Sample holder type and mounting technique
- Joints and current transfer for various mounting methods
- Criterion type and magnitude
- Magnetic field angle and homogeneity
- Material type and structure
- Variability in material
- Power supply effects

The results of this research formed the basis for the standard test method as proposed to the ASTM subcommittee.

f. Critical Current Standard Test Method Developed

A draft standard for a test method for determining the critical current in practical superconductors for less than 600 amperes was developed jointly by NBS and the ASTM subcommittee. It has been unanimously approved by the subcommittee and is now in process for a main ASTM committee ballot. (See § 3.)

g. Standard Terminology for Superconductivity Developed

In a series of four publications in the international journal Cryogenics, detailed and theoretically accurate definitions of terms relating to superconductivity were presented for feedback and comment [2, 3, 8, 11]. Suggestions from more than 60 laboratories were incorporated.

h. Definitions of Terms for Practical Superconductors Adopted

Simple and useful terms relating to practical superconductors were drafted from the four publications above and adopted by the ASTM subcommittee for use with the critical current test method and any future standards.

i. Critical Temperature Measurement Techniques Evaluated

An experimental comparison of resistive, magnetic, and specific heat methods of determining critical temperature for practical conductors showed that they sample different parts of the conductor and can give widely varying results [6]. Further work was delayed in order to concentrate on other parameters deemed more important.

j. Preliminary Comparison of ac Loss Measurements

A preliminary comparison of several electronic and caloric methods of determining ac power losses showed a wide disparity of results and severe difficulties based on both experimental complexities and inadequate theoretical understanding [6, 16]. A low level of effort to improve the electronic methods continues.

k. Research Results Disseminated Through More Than 20 Publications

A primary goal has been to make the results of the research readily available. Other than these three comprehensive reports to the sponsor, the program has resulted in 17 research journal publications (eight of which were papers at major conferences) and four presentations to research advisory groups (three of which have been published). The publications are all listed in § 6.

2.2 Importance of Current Transfer

One experimental effect above all others that affect critical current measurements has shown to be important and even dominant in many experimental conditions. It is the voltage generated when current must transfer to or from the superconducting filaments through the resistive matrix. It arises at the current contacts, any joints in the conductor, or any place that the current is forced to redistribute within the composite conductor, such as where the magnetic field changes. This transfer voltage manifests itself in many ways, some obvious and some quite subtle. These are documented in several of the publications [4-6, 15, 19, 21-22], but listed below are some of the more important areas with regard to standard measurement techniques, some of which become critical for large conductor measurements. How to account for these effects is given in § 5 and also documented in more detail in a forthcoming paper devoted exclusively to current transfer and its effects.

a. Critical Current Criteria

The real increase in voltage as the critical current is approached is due to the start of flux flow. Any shift in the baseline from zero is probably due to a current transfer voltage. A current transfer voltage, because it is resistive, is proportional to the current although it need not be linear. This must be kept small and be properly accounted for if an accurate measure of the true critical current is to be obtained. Following the restrictions in the ASTM standard test method should minimize the transfer voltage, but the method also includes a limit on its size (Appendix C).

b. Sample Holder and Sample Configuration

In order to minimize the additional effects of current transfer voltages, the sample must be configured such that the current must be introduced a "long" distance from the voltage sensing contacts. In addition, any redistribution of the current due to a change in the magnetic field, such as changing from parallel to perpendicular to the electrical current, will introduce current transfer voltage. (This effect can introduce some long range anomolous voltages, but may also make possible a sample configuration that assures minimum transfer voltages [19].)

c. Joints

Any physical joint between two superconductors will force a redistribution of the current and thus result in a current transfer voltage [15]. This will add to the total power used in a magnet, for example, or disturb any nearby voltage measurements.

d. Sample Homogeneity

If a superconducting filament in a composite superconductor has a nonuniform cross section (e.g. a neckdown) and is operating near its critical current, it can force a current transfer through the resistive matrix into an adjacent filament. This will also add to a total power, but will also be important in developing a standard reference material.

2.3 Future Research

Both the sponsor and the ASTM subcommittee have indicated that extension of a standard test method to larger current capacity conductors should have first priority. Approximately 6000 amperes has been suggested as the next appropriate step. An evaluation of the past research for the first standard test method indicates that for large conductors many of the parameters studied will have little impact. Some effects, such as current transfer, however, will only be compounded and must be documented for bigger conductors. In addition, some of the parameters which have little effect on smaller conductors, such as aspect ratio and self field, will also have to be studied to assure minimum impact on accuracy. There are also some properties unique to large conductors that will be explored such as stranding or cabling. The development of a method for small laboratories to be able to determine critical current without extensive equipment will also be pursued.

Other areas of study include a continued low level effort on developing ac loss measurement techniques, a first look at the problems of magnetic field and field homogeneity measurements with the goal of a critical field extrapolation technique, an evaluation of the state-of-the-art for stability characterization of superconductors, and exploration of a method for determining critical current as a function of temperature. Of course, implicit in the program is a continuing effort to coordinate the adoption of voluntary standards. Included in this will be the development and characterization of a standard reference material for critical current for small conductors funded by NBS.

3. PREPARATION AND DISSEMINATION OF STANDARDS

The final goal of this program is the adoption of voluntary standards for practical superconductors. Two of these standards are well on their way to acceptance. After the formation of an ASTM subcommittee the first order of business was the adoption of a standard terminology. The next priority was a standard test method for critical current of small conductors. The progress in each of these as well as that toward a standard reference material are outlined below.

3.1 ASTM Subcommittee on Superconductors

Early in the program it was concluded that The American Society for Testing and Materials (ASTM) would be the proper format for any voluntary standards for characterizing practical superconductors. At the instigation of NBS, the B1 Committee on Electrical Conductors created the Subcommittee B01.08 on Superconductors and an organizational meeting was held at ASTM headquarters in 1979. At this meeting task groups were organized and the long process toward voluntary standards was begun [6]. At the next meeting, held in conjunction with the Applied Superconductivity Conference in 1980, draft standards were proposed for terminology and critical current tests were extensively discussed [21]. After appropriate modification and clarification by more research at NBS and the wire manufacturers these draft standards were sent to the subcommittee ballot. These were approved by the subcommittee but some negative votes had to be resolved at the next subcommittee meeting and are discussed in the appropriate sections below. The minutes of that meeting held in August 1981 in conjunction with the CEC/ICMC meeting in San Diego are included as Appendix A. Briefly, NBS researched the points of contention and proposed modifications or justified acceptance. The subcommittee then voted to accept, modify, or delete the points in question. Finally, the subcommittee approved both modified standards unanimously.

The adoption of voluntary standards by ASTM is a long and complex process with many checks along the way. First, the subcommittee must be balanced between producers and users, and then approval must be obtained at three levels. The subcommittee ballot must have two-thirds approval with a 60% return. Any negative ballot must be accompanied by an explanation which must be resolved before it can go to main committee ballot. The main committee ballot must obtain 90% approval within a 60% return and again any negatives must be resolved. The final society approval is a two-thirds affirmative with a minimum of 50 returns and is principally a canvas mechanism to pick up any missed negative votes which must again, however, be addressed by the subcommittee.

Thus, the next step for the standards will be for NBS to prepare them in the proper ASTM style and submit them to the main committee for ballot. The subcommittee also urged NBS to pursue the development of standard test methods for larger conductors and for ac losses and a standard reference material.

3.2 Standard for Terminology

Terms that were deemed useful for the critical current standard were selected from the four published articles of precisely defined superconducting terminology [2, 3, 8, 11] and from the Compilation of ASTM Standard Definitions (ASTM, Philadelphia, PA, 1979). These were put in a shorter, simpler form more appropriate to everyday language by the ASTM subcommittee task group and submitted for ballot. The ASTM Committee on Terminology also assessed the set of definitions and had three pages of suggested changes which were accommodated before going to ballot. The subcommittee ballot approved the draft standard (Appendix B) with a 93% affirmative vote and one negative ballot. Listed below is a summary of the objections from the balloting procedure and the NBS recommended resolution.

ASTM B01.08 SUBCOMMITTEE ON SUPERCONDUCTORS

SUMMARY OF OBJECTIONS FROM NEGATIVE BALLOTS

DEFINITIONS

Critical magnetic field strength, H_c. Definition is incorrect for H_c but appropriate for H_{c2}. Suggest changing to upper critical magnetic field, H_{c2}.

Recommend: Change as above.

Critical current density. For twisted conductors it needs to be specified with respect to orientation of the conductor.

Recommend: No change. Area needed is as defined - that perpendicular to the principle axis.

Cable. Limited to cables with central cores.

Recommend: Add specific composite conductors, including ones without central cores.

Composite conductors. Should be types of "materials" not types of "wire."

Recommend: Change wire to materials.

Matrix-to-superconductor-ratio. This term has no physical significance and is misleading for specifications. It also is non-linear.

Recommend: Substitute "Volume percent superconductor" defined as that part of a composite conductor by volume that is superconducting under normal operating conditions.

At the last subcommittee meeting these and other changes were all discussed and adopted unanimously. The next step will be for NBS to incorporate these changes and some changes in style required by ASTM and prepare the standard for the main B1 committee ballot.

As a point of interest, through the entire process of the preparation of the four articles, creation of the draft standard, and modification of the standard through the balloting procedure, individuals from more than 60 institutions throughout the world have contributed substantially. These are listed in Table I.

Table I. Organization Providing Input for Standard Definitions

Producers	
AIRCO	Intermagnetics General
ALCOA	Kabelmetal
AMAX	Magnetic Corp. of America
American Magnetics	Supercon
Brown-Boveri	Teledyne Wah Chang
Imperial Metals Industries	Vacuum Metallurgical
INCO	Vacuumschmelz
Users	
Air Force Materials	Lawrence Berkeley
Air Force Aero Propulsion	Lawrence Livermore
Argonne	Los Alamos
Brookhaven	Magnetic Engineering Associates
CEN - Saclay	National Accelerator
CERN	NASA - Lewis
CGE - Marcoussi	National Magnet
ERDA - DPR	Naval Ship Rsch. and Development
ERDA - MFE	Netherlands Energy Research
Garrett AiResearch	Oak Ridge
General Atomic	Rutherford
General Dynamic	Stanford Linear
General Electric	Westinghouse
Other	
Air Force Office of Scientific Rsch.	Naval Research
All Union Research Inst.-Moscow	Nihon University
Battelle	Rensselaer Polytechnic University
Chiba University	Singer Company
Freie Universitat	Stanford University
Gould	Sumitomo Electric
Harvard University	Union Carbide
Inst. de Rech. de l'Hydro Quebec	United Nations
Molycorp	University of Wisconsin
Moscow State University	Wichita State University

3.3 Standard for Critical Current Measurement

Following the second meeting of the ASTM Subcommittee on Superconductors where the draft standard for the test method for determining dc critical current in composite superconductors was created by combining the best from the three proposed, NBS addressed and resolved the remaining open questions and objections. After specific research for these problem areas a comprehensive draft was prepared and sent to the subcommittee members for comment. Following the incorporation of these comments a draft standard (Appendix C) was prepared for ballot, mailed to the subcommittee, and the resulting vote was an affirmative 73% with four negative ballots complete with further objections.

Listed below are the objections which were raised and the NBS recommendations for action based on further research. These were then considered at the next subcommittee meeting in August 1981 at San Diego.

ASTM B01.08 SUBCOMMITTEE ON SUPERCONDUCTORS

SUMMARY OF OBJECTIONS FROM NEGATIVE BALLOTS

CRITICAL CURRENT

1.2 Let contract negotiations determine which conditions apply not which ones are inappropriate. (2.)

Recommend: No change. The purpose of the standard is to set the conditions. Exceptions can always be made.

3.1.1 A bandwidth of periodic and random deviations must be specified. Suggest 10 Hz to 10 MHz. (3. & 4.)

Recommend: Add "within the bandwidth 10 Hz to 10 MHz."

3.1.3 A 20% accuracy for E_c yields more like 2% accuracy in J_c. (1.)

Recommend: Change 20% to 12%. (See variable list.)

3.3 Weather variations of pressure result in temperature accuracy of 2%. Against having to measure absolute pressure. (5.)

Recommend: No change. 99% confidence interval for 1 year is within ±0.5%.

3.4.1 Magnetic field uniformity of 1% not possible for large magnets and long or helical samples. Suggest 2% is adequate. (1.)

Recommend: Change to ±2%.

3.6 A shunt not in immediate contact with the specimen may make it impossible to measure high current density specimens. The answer should be the same if properly stabilized. (3. & 4.)

Recommend: Delete sentence in parentheses. Add after specimen "(when the specimen is in the normal state)."

5.1 Differential thermal contraction restriction would preclude using Nb_3Sn on copper or stainless steel holders. However, it has been shown this works. (3. & 4.)

Recommend: No change. Strain tolerance must be held.

5.5 A recheck such as this when used with large field variations would be time consuming and expensive. Suggest a recheck at each field level and begin with highest field. (1.)

Recommend: Need to discuss. Suggested options: recheck at highest current level, operational check. Some check is needed.

6.1 Suggest listing of all the variables and their effect on the final accuracy. (2.)

Recommend: Listing is provided but should not be part of the standard.

Remark: This standard is not for unreacted A15 material unless the preparation is specified and included in the report. (1.) Covered in 7.1.

Remark: More descriptive material is needed - a newcomer would be unable to make a satisfactory test. (2.)

Remark: Test procedure is not simple or economical. It should be readable by a purchasing agent. (2.)

Remark: An equation should be added for the current transfer length. (6.) Add reference to 6.2.1.

The subcommittee, after a great deal of discussion, adopted all of the recommendations except they deleted the recheck requirement of part 5.5.

To aid in the above discussion which involved some trade-offs between accuracy and ease of measurement, NBS prepared a listing of the accuracy tolerances required in order to result in an overall accuracy of 5%. These are shown in Table II along with the expected current dependence for each of the independent accuracies. It is valuable to note that the magnetic field, strain, and temperature measurements are the dominant sources of inaccuracy, none of which are the primary variable but all of which will have to be considered for the other superconducting critical parameters.

The next step in the process of adopting a standard test method for determining critical current will be for NBS to assimilate the subcommittee changes along with some changes in style for the draft standard to be mailed out for main committee ballot. Simultaneously, research will be continuing for the next standard test method for larger conductors with critical currents from 600 to 6000 amperes.

Table II. Accuracy Tolerance for Critical Current Variables

Variable	Accuracy, %	I_c dependency	ΔI_c, %
I	1	linear	1
I, PARD	5	unknown	1
E_c	12 (10% L, 6% v)	$E_c \alpha I^n$	1
H, magnitude	1	$\log I_c = a + bH$	2.5
H, PARD	1	unknown	0.5
H, uniformity	2	averaged	1.5
H, angle	7°	averaged	1
T	0.5	$I_c \alpha (T^* - T_{bath})$	2
ε, bending	0.1 Nb_3Sn 2 NbTi	scaling law	2
ε, tensile	0.05 Nb_3Sn 0.5 NbTi	scaling law	2
			$\sqrt{\varepsilon(\Delta I_c)^2} = 4.98$

3.4 Standard Reference Materials

A promise of support from NBS for the acquisition and characterization of a standard reference material (SRM) for critical current has been obtained. It will require estimating the probable number of units to be manufactured, establishing criteria limits on the various characterization parameters and pursuing the availability of such a conductor. Once a suitable length of conductor is located then a complete characterization will be done but it is intended that the SRM will be certified only for critical current at several magnetic field values.

4. EXPERIMENTAL PROGRAM

Study of the parameters affecting critical current have dominated the experimental effort during this period. The major portion of those results are given in § 5 which will be published as a journal paper in the open literature. Given below are a brief summary of those results, some work that was not included in § 5 and a short description of some progress on ac loss measurements.

4.1 Critical Current

In preparing the standard for measurement of critical current a large amount of research was required to insure that the various numerical limits called out in the standard were reasonable and necessary. As a result of the many experiments performed by NBS and by the wire manufacturers, sufficient data exist to make a persuasive argument for the particular values chosen for inclusion in the standard. All of the values are, of course, tied to the assumption of an overall accuracy of 5% for the critical current determination, and are summarized in Table II in § 3. Detailed results are given in § 5 for the phenomena that affect the measurement of critical current which fall into the three categories listed below.

(1) Those of most serious importance which, it turns out, are also the ones that can be accommodated. Experimental work has tended to concentrate on them in the recent past. They are:

Holder type
Sample mounting
Critical current criterion
Current transfer.

(2) The second group contains aspects of the measurement that are relatively difficult to control, but that turn out to not strongly affect the I_c measurement if moderate care is taken in design of the apparatus. They are:

Joints
Field angle

Field homogeneity
Sample current supply
Cabling effects.

(3) The final group consists of parameters associated with the production of the superconducting wire. In general the amount of variation observed is quite large, but it is not possible to say that this has a detrimental effect on the value of the critical current determination. The parameters investigated were:

Filament uniformity
Spool uniformity
Lot/billet/percent superconductor
Copper/superconductor ratio
Aspect ratio.

The last of these has some interesting features that still need to be evaluated, but again there is no direct effect on the determination of I_c for a given configuration for small conductors.

The paper included as § 5 is a compendium of all these results to date. It is intended to be an "everything you wanted to know about measuring critical current" paper that is available to anyone.

It was concluded from all the research that the data accumulated over the past three years and the interactions generated by the ASTM committee have allowed it to arrive at a set of parameter values for critical current measurements that are technically sound and entirely practical. The resulting standard is a reasonable first effort and the time has come to put it into practice.

4.2 Angular Dependence of Critical Current on Magnetic Field

a. Introduction

The dependence of the critical current, I_c, on the angle, θ, between the conductor and the magnetic field, H, was measured for three different types of superconductors; multifilamentary (MF) NbTi, MF Nb_3Sn, and tape Nb_3Sn. This dependence is important in determining the accuracy tolerance of this angle in I_c measurements. $I_c(\theta)$ is also useful in understanding current transfer in the hairpin geometry where the sample axis changes along its length from parallel, to perpendicular, to parallel with respect to the uniform applied magnetic field. The larger I_c in parallel field gives an additional safety margin for the ends of a hairpin sample. This advantage is also present in the long-straight geometry, but not in the short straight or coil geometries. This is a more complete treatment of these effects which are summarized in § 5.

$I_c(\theta)$ was measured for five samples to determine its dependence on the type of sample, filament twist, magnetic field, and critical current criterion, E_c. These samples are listed on Table III. $I_c(\theta)$ for the three types of superconductors had very similar shapes, but with different sensitivities. Two of the samples were MF NbTi; one with a rectangular cross section and the other round. The shapes of $I_c(\theta)$ for these two samples were essentially the same within 5%. The twisted MF Nb_3Sn sample was prepared by twisting a length of sample 3 (untwisted MF Nb_3Sn) prior to its reaction. The shapes of $I_c(\theta)$ for these two samples were very similar, within 3%, suggesting that twisting the filaments has little effect. The scaling of $I_c(\theta)$ with magnetic field was determined in order to interpolate or extrapolate the results to other fields. The data indicated that the empirical relation that scales the results with magnetic field is

$$[I_c(H) - I_{co}(H)]/I_{co}(H) = f(\theta), \qquad (1)$$

where I_{co} is the critical current at $\theta = 0$, I_c is the critical current at θ and $f(\theta)$ is a function of sample and θ but not magnetic field. In this paper the angle is zero when the conductor axis is perpendicular to the applied magnetic field. Scaling was also necessary in order to get agreement between the two NbTi samples which had different I_c's. This same scaling works for different critical current criterion where both I_{co} and I_c are calculated using the same E_c. Then $f(\theta)$ will be very similar for criteria differing by as much as a factor of ten. All of the data presented here will be normalized according to Eq. (1).

Table III. Samples

Sample Number	Type	Dimensions, mm	Number of filaments	Twist, cm^{-1}	Copper to non-copper ratio
1	Rectangular NbTi	0.53 x 0.68	180	0.79	1.8
2	Round NbTi	0.64	180	0.79	1.8
3	Round Nb_3Sn	0.70	2869	0	1.7
4	Tape Nb_3Sn	0.2 x 2.3			1.6
5	Round Nb_3Sn	0.70	2869	0.78	1.7

b. Apparatus

$I_c(\theta)$ of the round NbTi sample (#2) was measured in two ways. First, a series of coil samples was prepared with winding pitches ranging from 1 to 40°. Total sample lengths varied from 10 to 90 cm. The results of the I_c measurements gave $I_c(\theta)$ of the sample using the 1° data as the zero angle reference data. A more complete series of measurements were made using a rotating device that allows a single short (3.6 cm) sample to be rotated through an angle of nearly 120° while it was in the measurement configuration. This device allowed for the convenient and systematic measurement of all the samples including the Nb_3Sn based superconductors. Comparisons between these two techniques using sample #2 showed agreement within 1% (see § 5).

The rotating device was made with a housing, two sets of gears, a long actuator, dial indicator, sample table, and flexible current leads. The housing was a G-11 tube that supported the gear shafts and fit into the bore of the solenoidal magnet. Two sets of gears, worm-worm wheel and miter-bevel, were used to translate and step-down the rotation of the actuator and room temperature dial indicator. The gear ratio was 6.25 turns of the ten turn dial indicator for a 90° rotation of the sample. The gear lash was only about 1°. The sample table was made of G-11 and it was fastened to the worm wheel. Flexible current leads were made using four lengths of sample #2 (round NbTi) for each current lead. These two leads were tied together to help balance the Lorentz force and were soldered to a bus bar on each end. The table could be rotated through an angle of about 120°. It was set up so that it would rotate from about -20° to +100°, in order to check the zero angle and symmetry.

I_c was measured at a number of set points on the dial indicator of the rotating device. The set points were every 5° or 10°. The pattern of the measurements was the zero-angle set point first, then all of the positive angles, the zero angle again, then all of the negative angles and the zero angle last. I_c at the zero angle was checked in order to determine if there was any damage to the sample due to quenching or strain. There was only one case where the sample was strained significantly. This was during a measurement at 100° where the Lorentz force pulled the sample (MF Nb_3Sn) from the support and the zero-angle I_c was then 1.2% higher. Otherwise the value of I_c

at the zero angle was the same to the uncertainty of the I_c measurement ±0.3% indicating that the quench protect circuit and support were adequate.

The rotating device worked quite well, but, it had a couple of disadvantages. One disadvantage was that its current carrying capacity was limited to about 400 A by the flexible current leads. This limited most of the measurements to the lower angles (the angle is zero when the conductor axis is perpendicular to the applied magnetic field). A couple of measurements were made on a coil sample holder with the conductor axis parallel to the magnetic field in order to get some data at 90°. The other disadvantage of the rotating device was the limited sample length which caused some current transfer problems such as a negative voltages [19] on the NbTi samples and large current transfer voltage on the MF Nb_3Sn. These problems limited the sensitivity of E_c to 0.2 μV/cm for the MF NbTi and 5 μV/cm for the MF Nb_3Sn.

c. Experimental Results

The zero angle of the rotating device was somewhat uncertain due to the arbitrary experimental scale and variations in the sample mounting. It was, however, determined using the measured I_c as a function of angle around the zero angle and assuming it to be symmetric about the zero angle. Typical data are shown on Fig. 1. Notice that the curve is symmetric about -0.8°. The zero-angle shift was determined in this way for all of the samples and in all cases it was less than 2°. The results of measurements around 90° are shown on Fig. 2. This curve is fairly symmetric about 89° consistent with its zero-angle shift. The shape of the curve at the peak is not known. The lines drawn are only an attempt to estimate the value at the peak. The rest of the data presented here has been interpolated to round values of angles using the zero-angle shift and the shape of the curve. This was done in order to compare the measurements of different samples and different runs.

The scaling of $I_c(\theta)$ with magnetic field using Eq. (1) is shown for all five samples (see Table III) on Figs. 3-7. The slight irregularities in the low angle data are due to the I_c measurement uncertainty. The lack of significant dependence of the normalized I_c on magnetic field for each of these samples indicates this empirical relation works very well. This is amazing

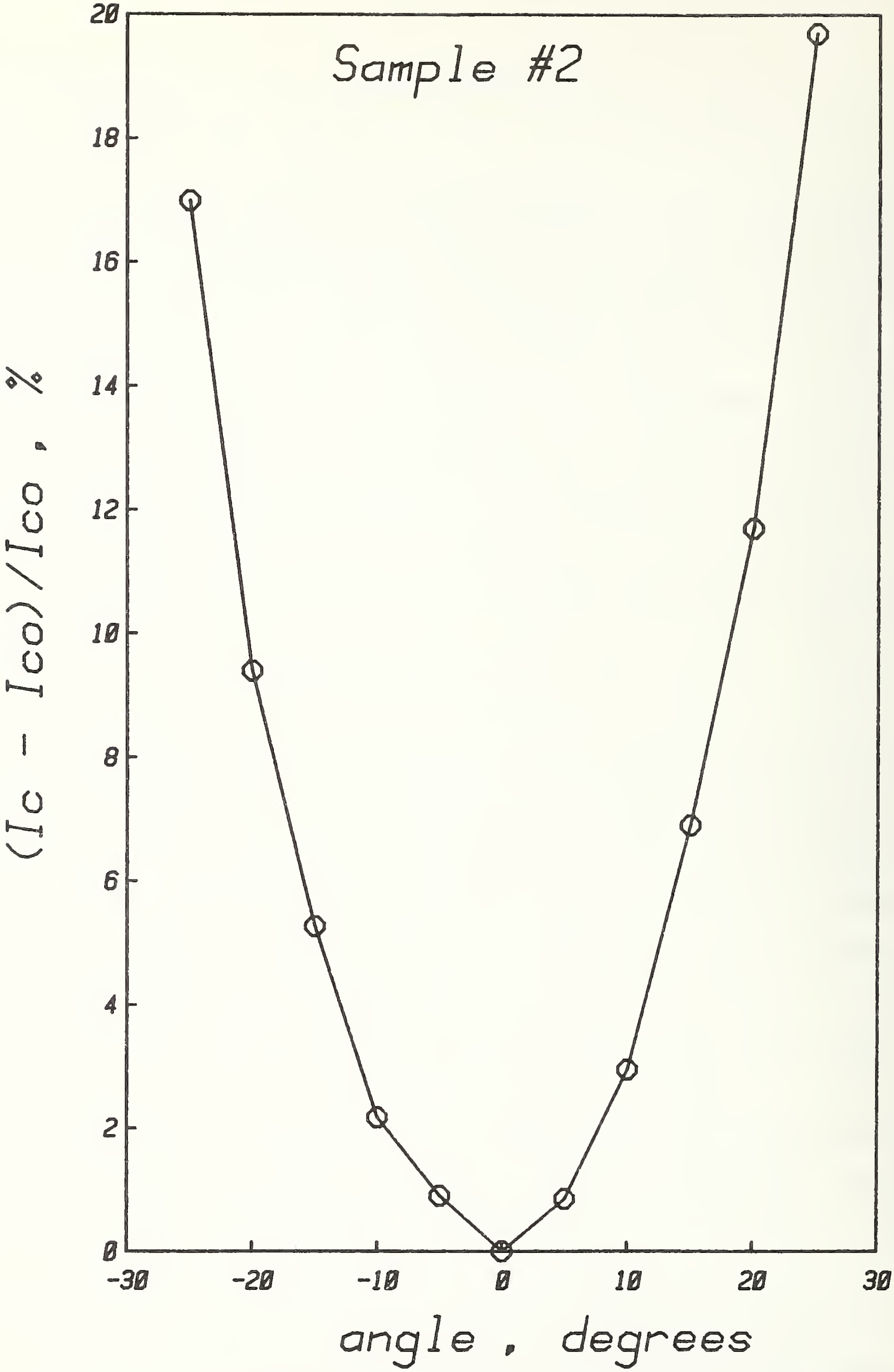

Fig. 1. Typical normalized I_c as a function of angle around the zero angle for sample #2 at 1 μV/cm and 9 T.

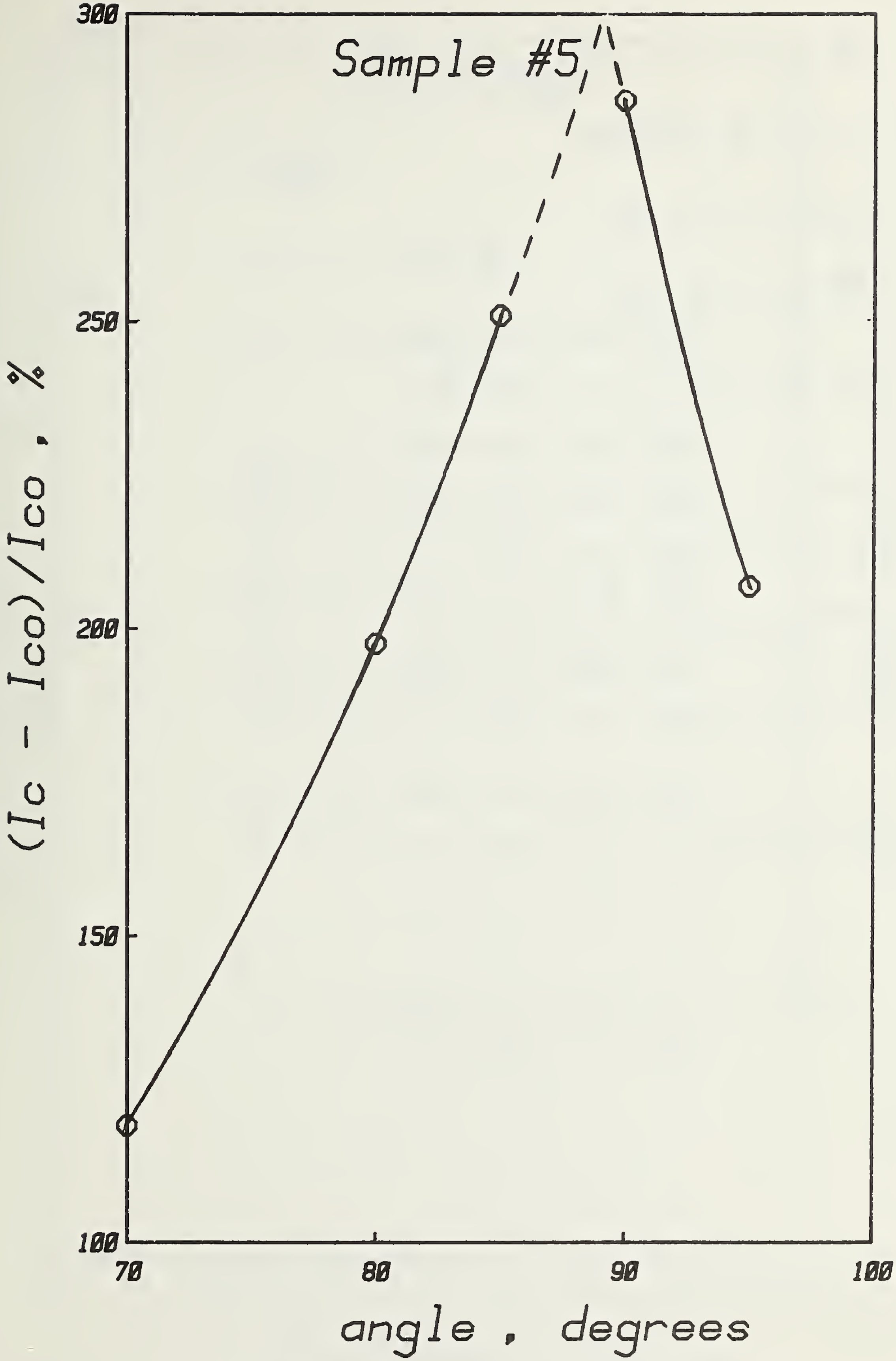

Fig. 2. Normalized I_c as a function of angle around the 90° angle for sample #5 at 10 μV/cm and 9 T.

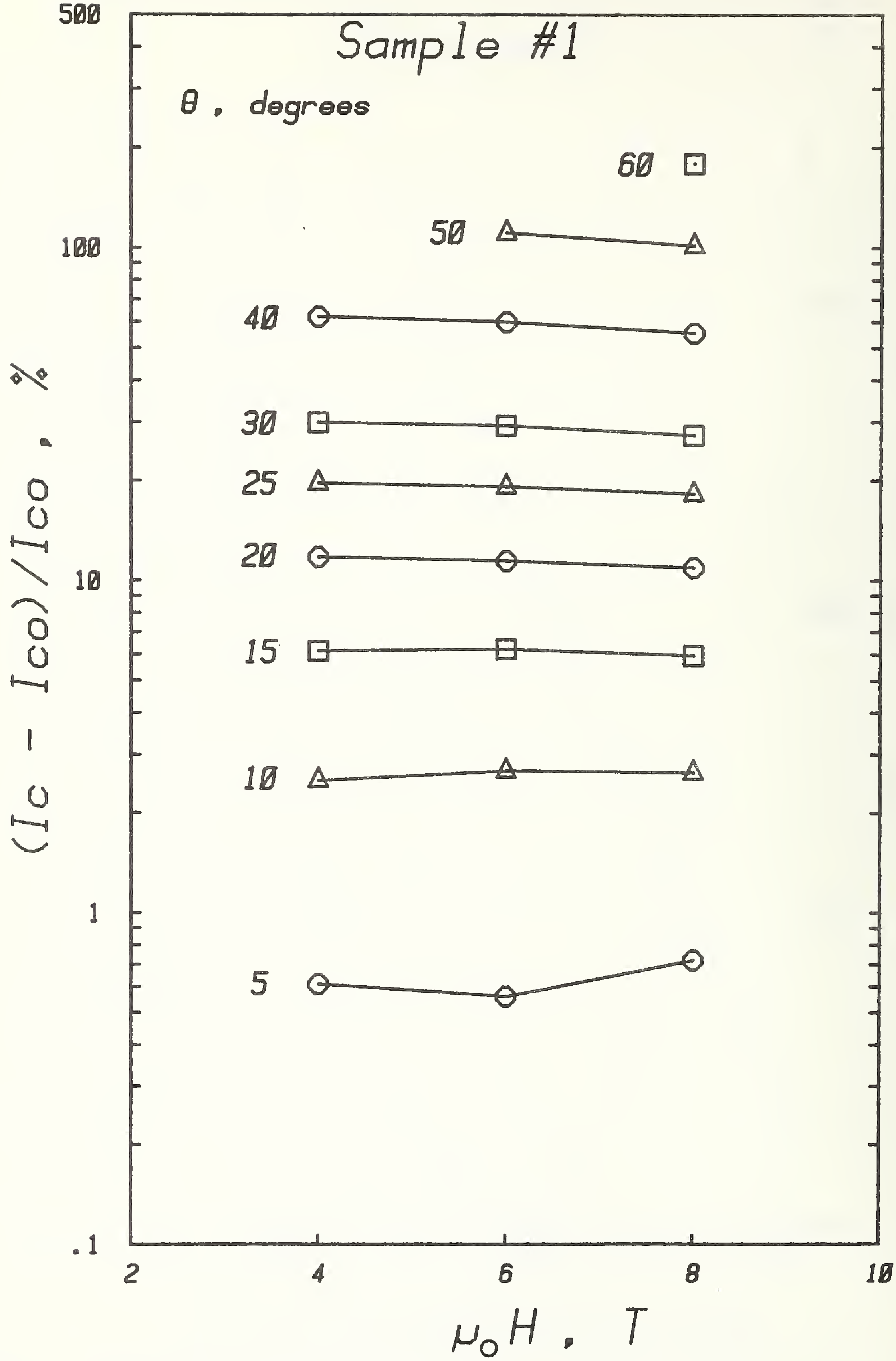

Fig. 3. Normalized I_c as a function of magnetic field at various angles for sample #1.

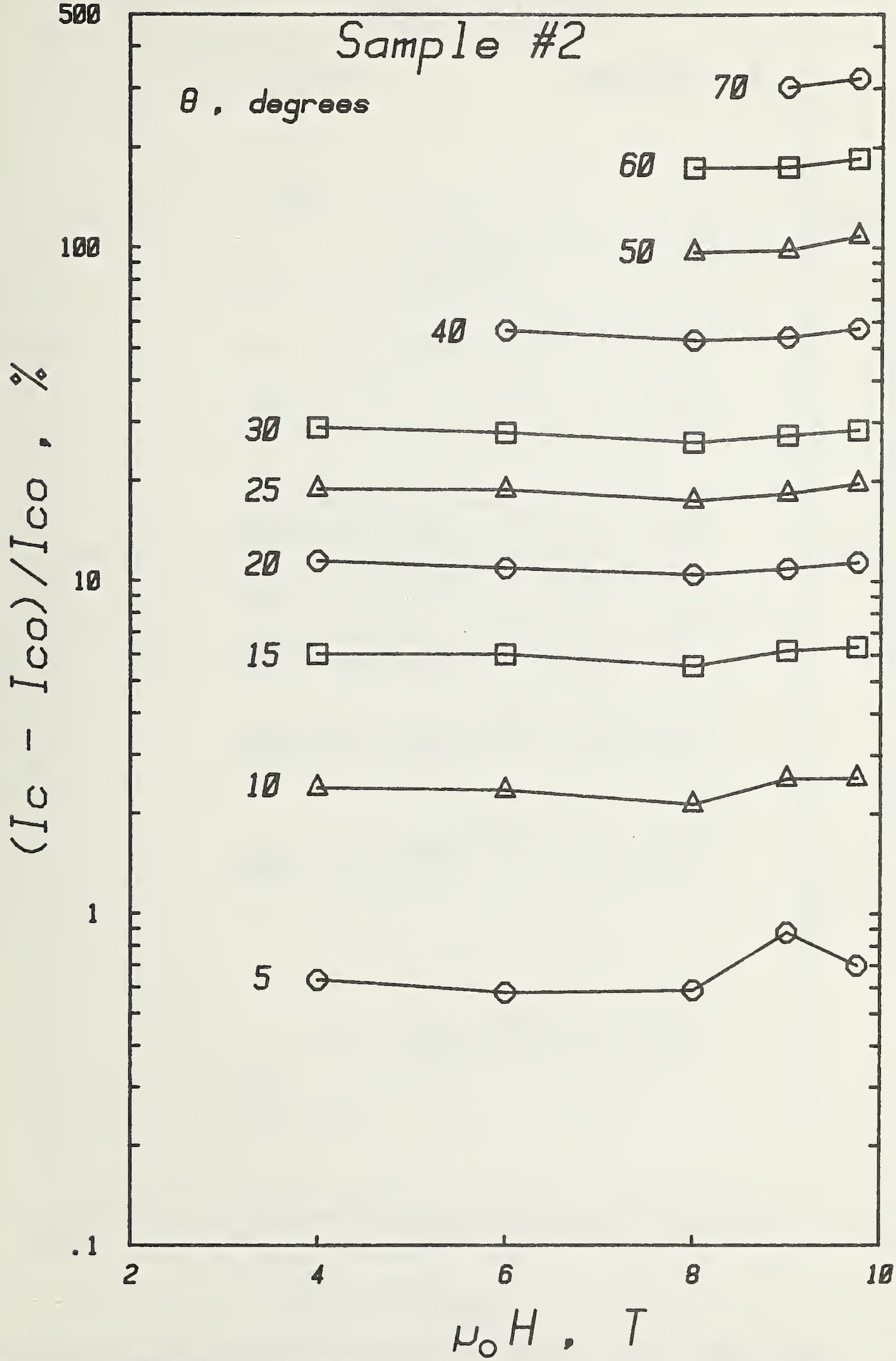

Fig. 4. Normalized I_c as a function of magnetic field at various angles for sample #2.

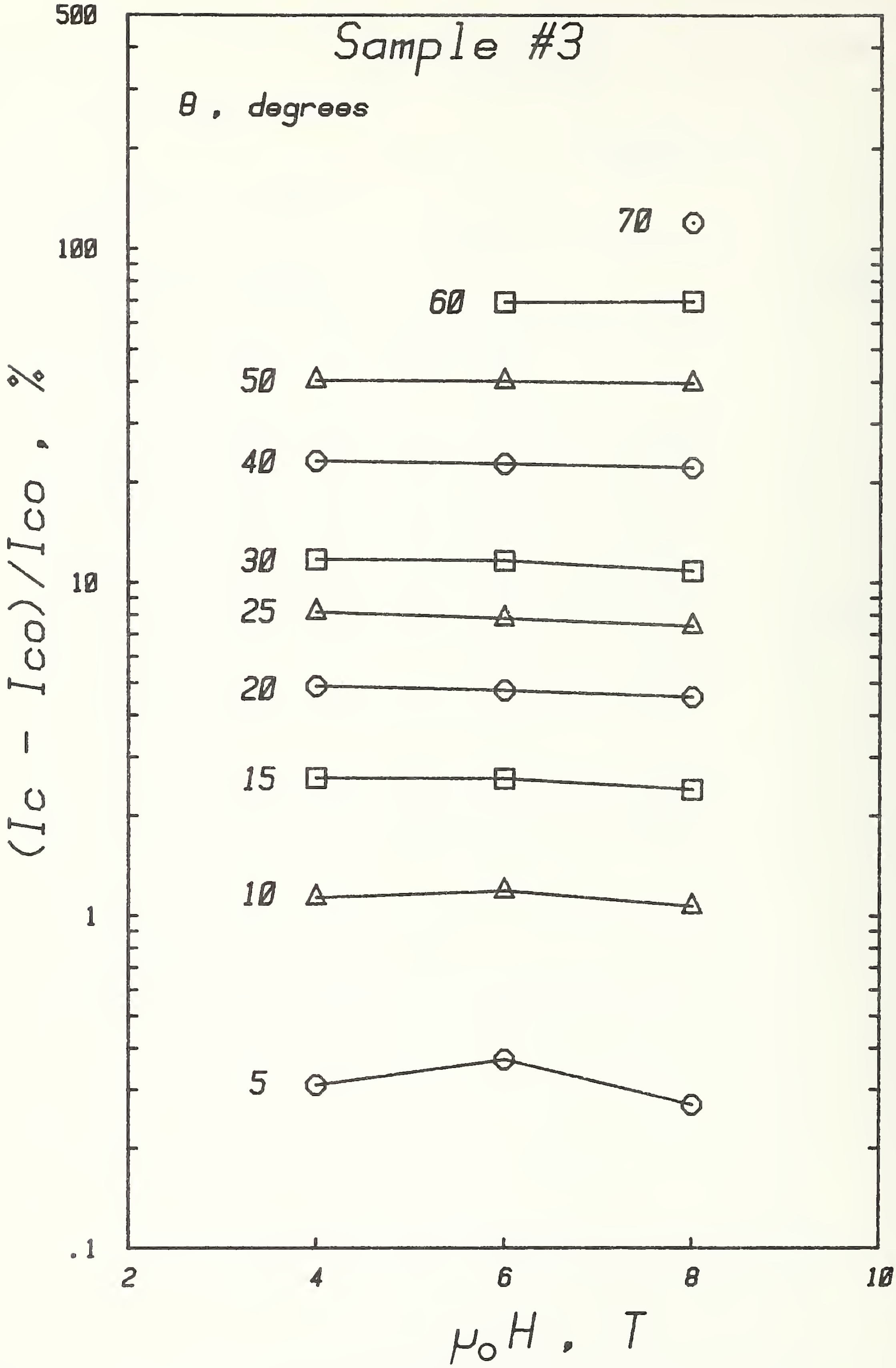

Fig. 5. Normalized I_c as a function of magnetic field at various angles for sample #3.

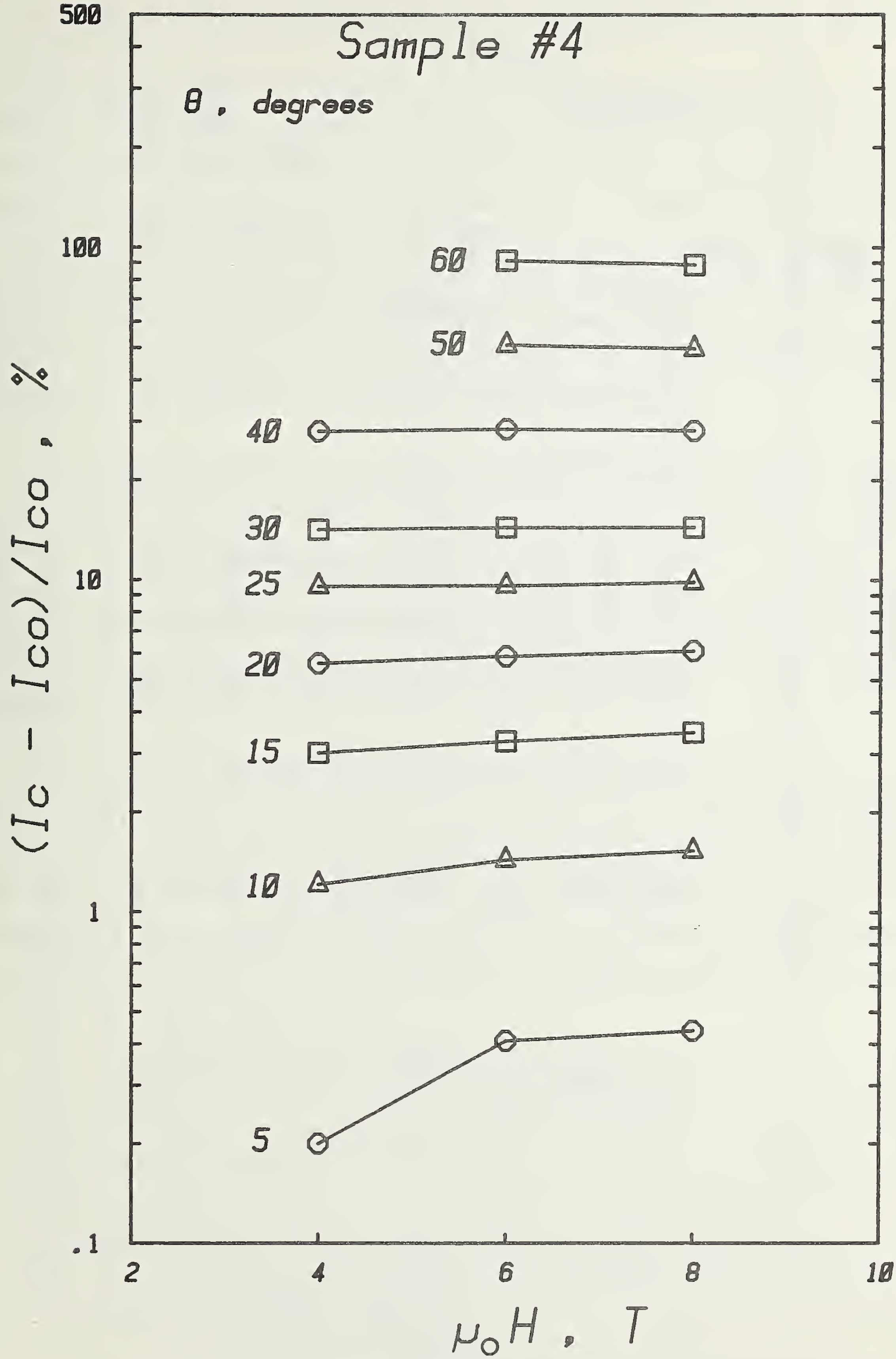

Fig. 6. Normalized I_c as a function of magnetic field at various angles for sample #4.

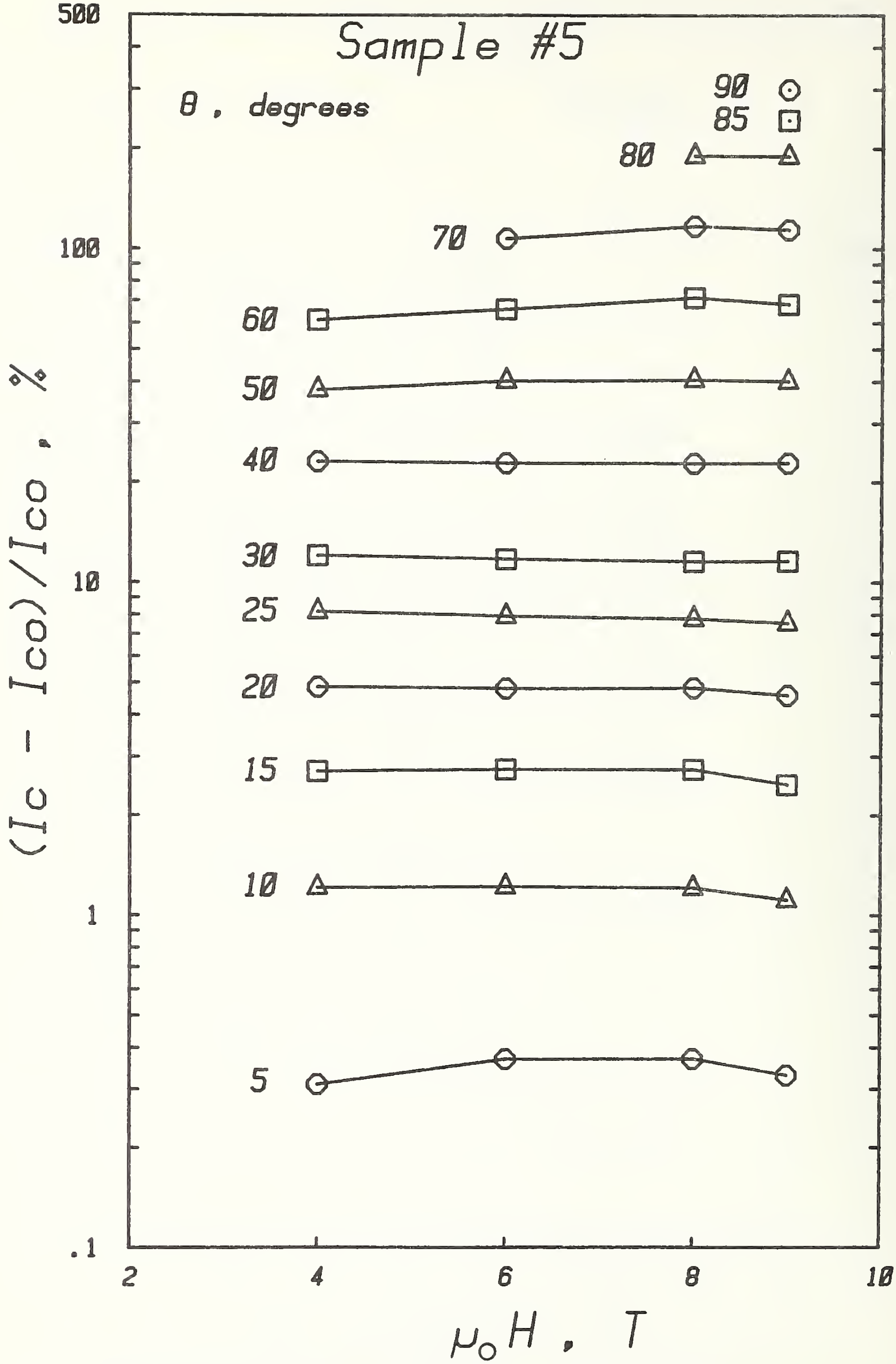

Fig. 7. Normalized I_c as a function of magnetic field at various angles for sample #5.

considering the range of angles, magnetic fields, and thus critical currents tested. The critical currents at the zero angle as a function of magnetic field for each sample are given in Table IV. Notice that I_c for sample #2 changed by a factor of 7.1 over the wide range of magnetic field tested. A further point not covered by this range of angles and magnetic fields is that this relation has to break down at low enough magnetic field and high enough angles since I_c in parallel field cannot be larger than I_c in zero field. This was not investigated because of the limited current capacity and the interest in the low angle and high magnetic field region.

The scaling of $I_c(\theta)$ with critical current criterion using the same kind of normalization as Eq. (1) is shown for two samples on Figs. 8 and 9. Similar data were obtained on the other samples. Notice the lack of significant dependence of the normalized I_c on the criterion. The value of I_{co} for each of these criteria are given in Table V. These data indicate that the shape of the voltage-current curve must not change much with angle even though I_c is changing significantly.

The shape of the normalized I_c as a function of angle for each of the five samples is shown by a full log plot on Fig. 10. All of these data were at 8 T and the criterion listed on Table IV. Notice that the results from the two NbTi samples are about the same. Also, the results of the tested and untwisted MF Nb_3Sn samples are about the same. The shape of the normalized I_c as a function of angle for the three types of superconductors are very similar, but with different sensitivities.

The normalized I_c as a function of angle was measured up to 90° for two of the samples, MF NbTi and MF Nb_3Sn. These measurements could only be made at higher magnetic fields. The data for the MF NbTi and the MF Nb_3Sn are shown respectively on Fig. 11 at 9.75 T and on Fig. 12 at 9 T. One of the NbTi data points, the triangular symbol, was measured on a coil sample holder at 90°. The rest of the data were taken on the rotating device. Notice that the curve smoothly continues up to 90°.

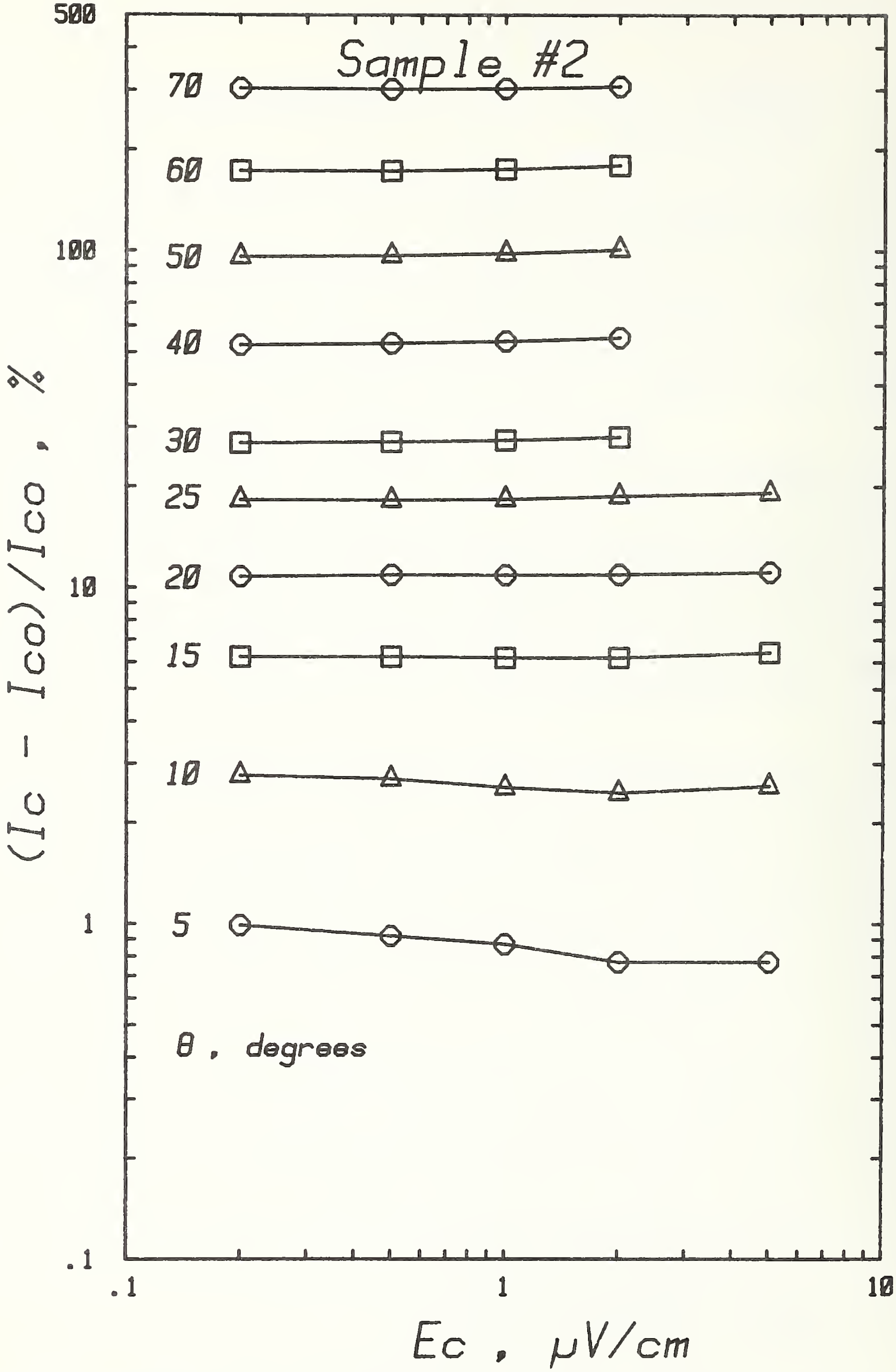

Fig. 8. Normalized I_c as a function of E_c at various angles and 9 T for sample #2.

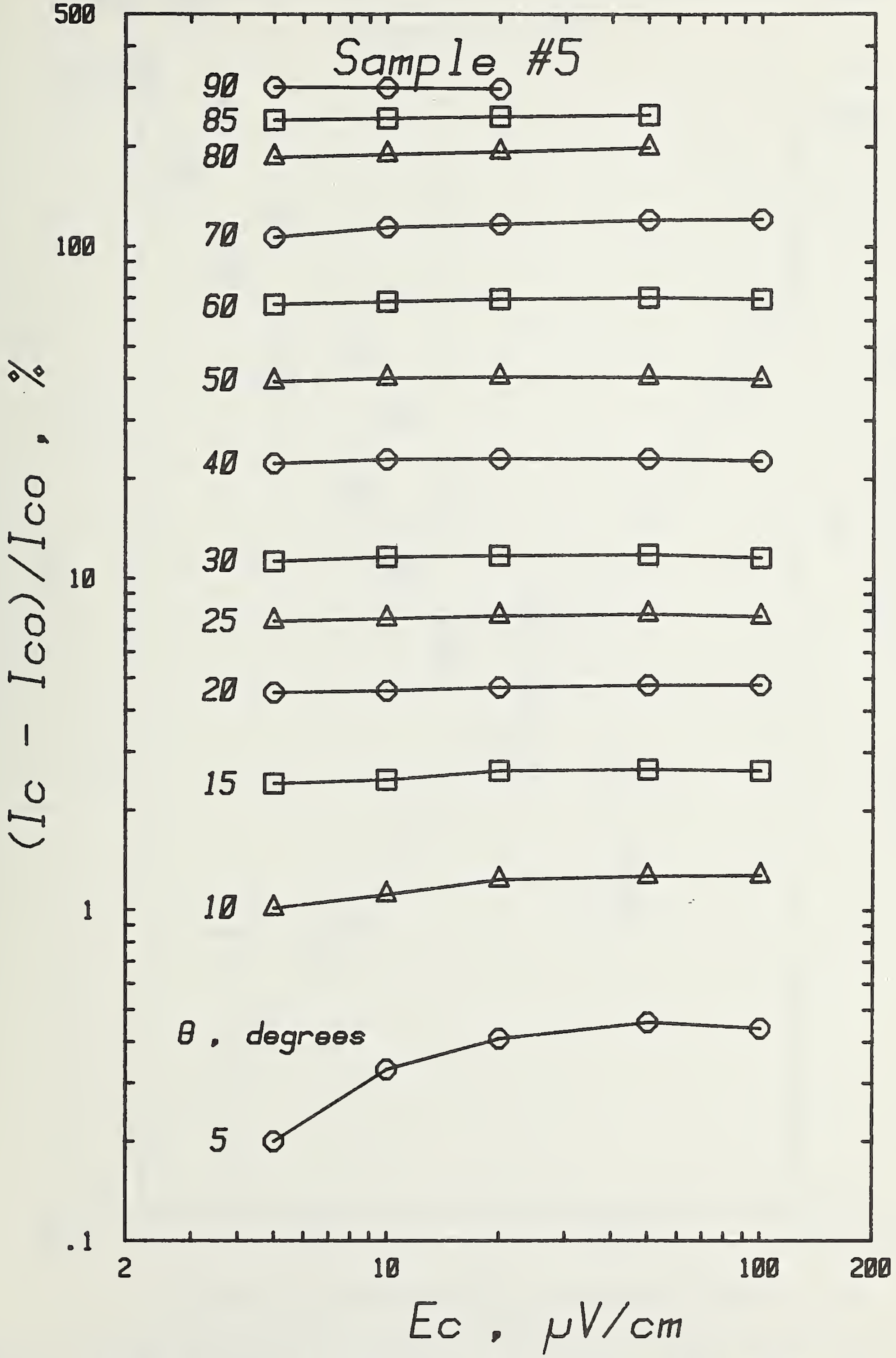

Fig. 9. Normalized I_c as a function of E_c at various angles and 9 T for sample #5.

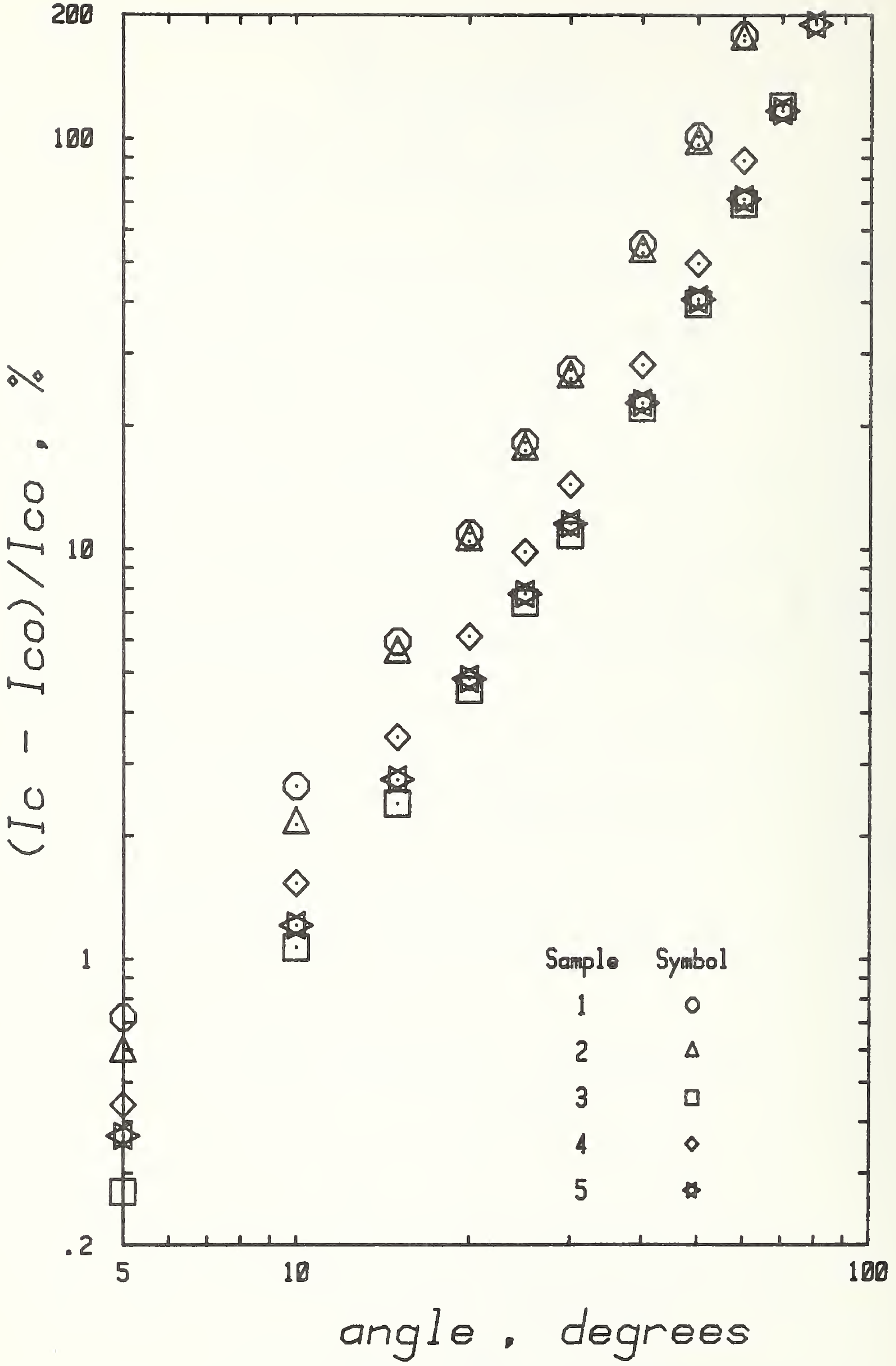

Fig. 10. Normalized I_c as a function of angle for all five samples at 8 T.

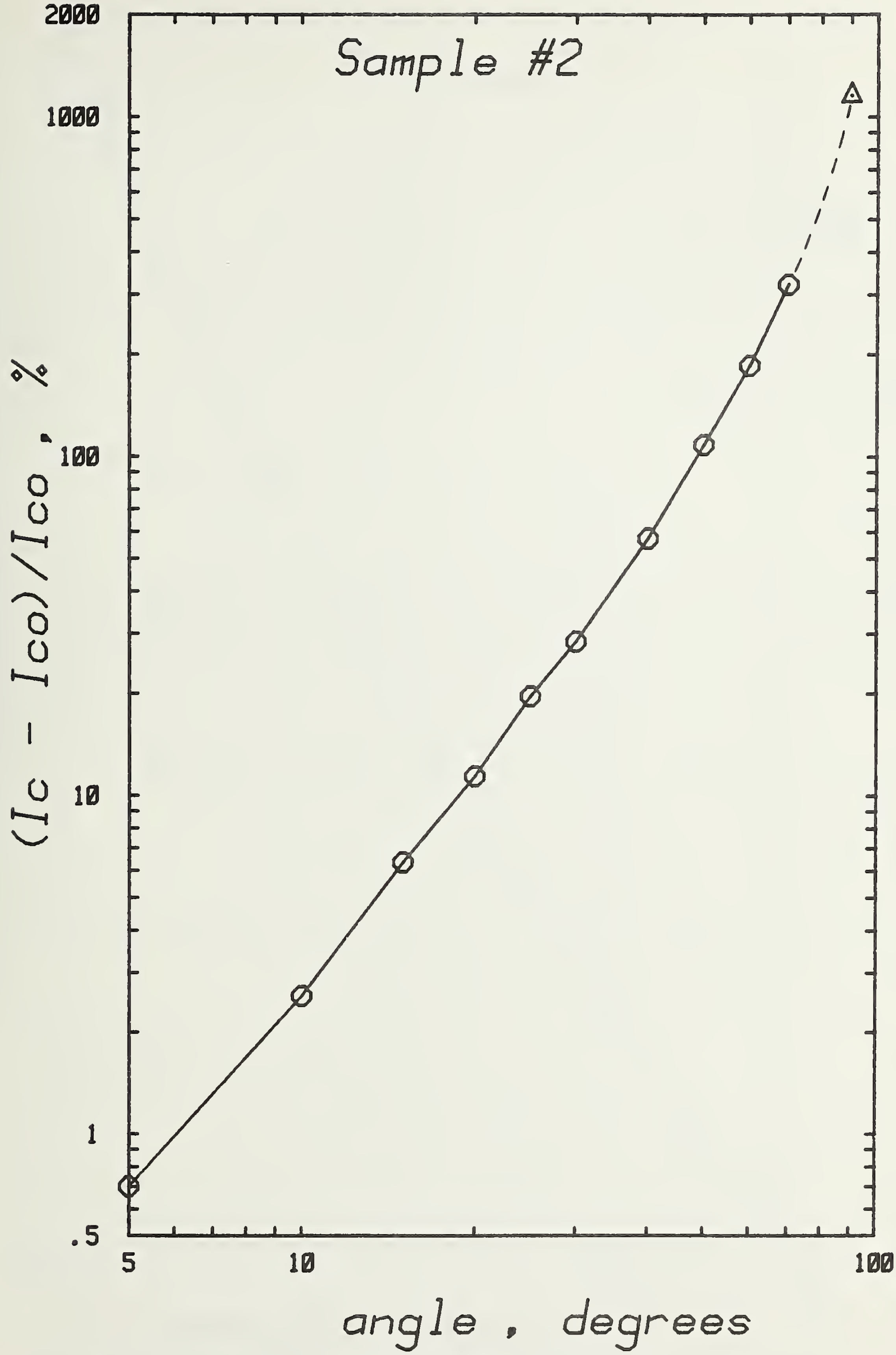

Fig. 11. Normalized I_c as a function of angle for sample #2 at 1 μV/cm and 9.75 T.

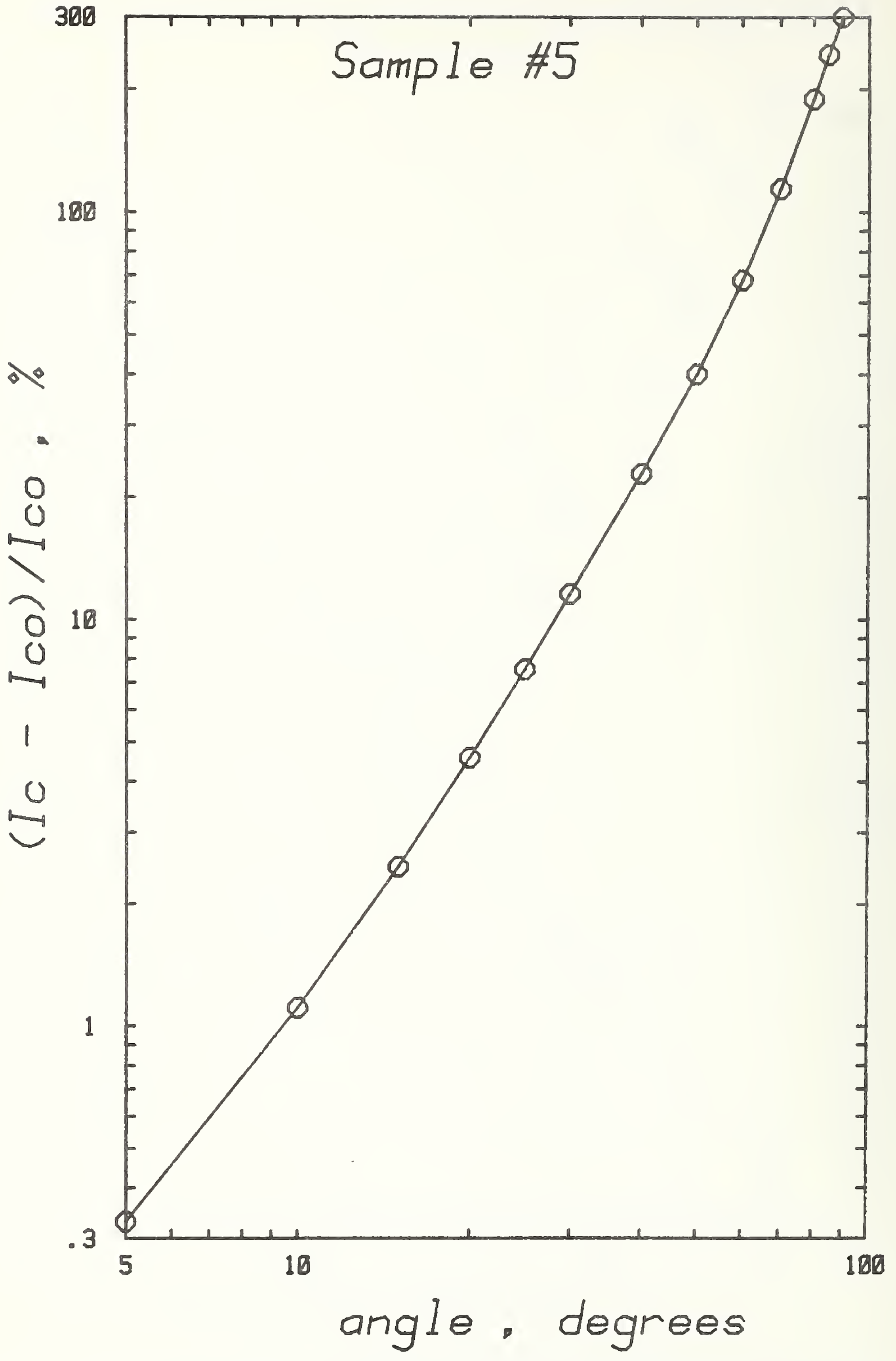

Fig. 12. Normalized I_c as a function of angle for sample #5 at 10 μV/cm and 9 T.

Table IV. I_c as a function of magnetic field

Sample Number	E_c, μV/cm	I_c, A at field, T				
		4	6	8	9	9.75
1	1.0	280.6	189.3	111.6		
2	1.0	348.9	226.8	127.4	81.46	49.03
3	50	312.9	205.2	141.6		
4	1.0	300.3	235.8	171.7		
5	50	325.8	214.8	148.6	124.1	

Table V. I_c as a function of E_c at 9 T

Sample #2					
E_c, μV/cm	0.2	0.5	1.0	2.0	5.0
I_c, A	77.40	79.53	81.46	83.39	85.48
Sample #5					
E_c, μV/cm	5	10	20	50	100
I_c, A	112.1	115.1	118.7	124.1	129.3

d. Conclusions

The normalization according to Eq. (1) works very well in scaling $I_c(\theta)$ with magnetic field and criterion. $I_c(\theta)$ for all of the samples tested had very similar shapes, but with different sensitivities. The results indicate that the sample axis and the applied magnetic field can be misoriented from perpendicular by as much as 7° with less than a 2% change in I_c. The high field data indicate that I_c in a parallel field for a MF NbTi and MF Nb_3Sn may be respectively as much as twelve times and four times larger than the I_c in a perpendicular field.

4.3 ac Losses

A relatively low level effort has continued to assess the measurement problems for ac losses. Although virtually lossless under dc conditions, superconductors do have finite losses when operated in an ac magnetic field, with ac current, or both. Earlier efforts showed that measurements by different techniques, although frequently giving wide disparity of results, can be shown to agree [6, 16]. It appears now that some of that agreement was fortuitous. The work in this area described below has been mostly supported by NBS.

There have been developed one caloric and several electronic methods of determining ac power losses. The caloric method utilizes a determination of the liquid helium boil-off rate as a measure of the additional power lost in a superconductor in ac conditions which necessarily shows up as heat. The method is straightforward and unambiguous but requires great care in apparatus design and is not very accurate below a few milliwatts. Several of the electronic methods involve either the measurement of a phase angle or the multiplication of current and voltage signals. Because the very large inductive component in most superconductors swamps the small resistive (power loss) component of the voltage signal, this requires very precise voltage phase and magnitude measurement is required. Magnetic techniques are also possible but have not been explored as yet.

The existing apparatus [16] was slightly modified to increase the caloric sensitivity and provide a larger, more definable sample volume, and comparisons were tried with the lock-in amplifier and analog multiplication techniques. It was quickly determined that even with an improved lock-in amplifier the zero-setting of the phase was not reproducible to the 0.03 degrees required as a minimum. The analog multiplication technique was tried with a "Brookhaven" wattmeter which NBS acquired for this study. With this device a "current" and a "voltage" signal from the superconducting sample are amplified and then multiplied together. The wattmeter is designed to have very low and calibratable phase shifts in each channel. After experiencing some difficulty in obtaining reproducible results, the characteristics of the wattmeter were studied.

Using a precise phase signal and meter available in another group of NBS, the phase shifts in the amplifier and multipliers were measured. Typical results are shown in Figure 13 for the voltage channel phase shift as a function of frequency. The clear minimum can be shifted in frequency over a wide range with proper calibration but must be done each time a new frequency is used. The minimum, although not precisely zero, presumably could be made the same in both channels to within 0.03 degrees.

Identical signals with a precisely known phase difference were also fed into the multiplier channels and the output versus phase angle measured. The output very nicely followed the expected cosine curve but on an expanded scale near the important 90° point the multiplier output showed significant non-zero contributions. The conclusion was that the wattmeter device could readily be used for comparative measurements but was not appropriate for research studies of ac losses in general.

With borrowed electronics a similar study was done on the multiplication technique but using digitized signals with a greatly enhanced accuracy. The phase shifts were measured and it was concluded to be a viable and accurate technique. Based on this, NBS has acquired the necessary digital processing electronics for further research. In addition, a new sample cryostat is being designed that will also permit magnetization studies. It will also provide a sample configuration more comparable to a theoretical model which is also being developed, and more thermal sensitivity for the caloric method.

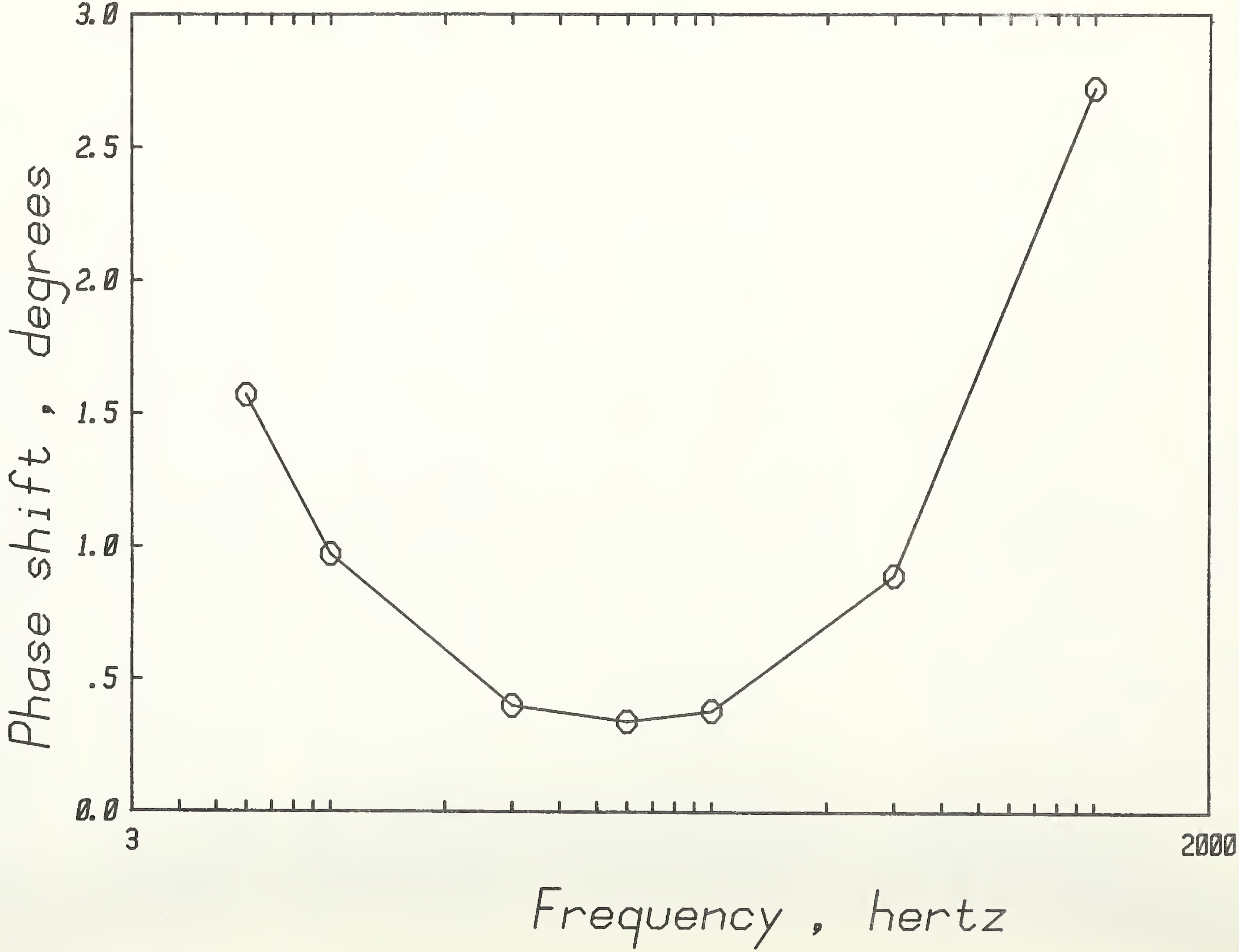

Fig. 13. Phase shift in amplifier section of wattmeter as a function of frequency.

5. CRITICAL CURRENT MEASUREMENTS: A COMPENDIUM OF EXPERIMENTAL RESULTS*†

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ABSTRACT

The results of a program to evaluate the measurement of the critical current of relatively small (<600 A) practical superconductors are presented. Experimental data showing the effect of various parameters on the measurement are given. Specific areas covered are: experimental design and sample mounting; electric field and resistivity criteria; temporal and spatial variations in the field and current; and temperature and strain effects. The goal of the presentation is to describe the critical current measurement process and its pitfalls in sufficient detail to serve as a guide for those relatively new to the field of practical superconductors.

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†References, Figures, and Tables in this section are numbered independently from the remainder of the report.

I. INTRODUCTION

Accurate measurement of the critical current, I_c, of practical superconductors is a subject of concern both technically and in the commerce associated with these materials. The measurement is not a simple one and it is not unusual to find that two critical current determinations for the same material disagree by large amounts, often on the order of 20-30%. In an attempt to explain the source of some of these discrepancies and to promote more uniform measurements, a cooperative standards program involving DoE, NBS, and ASTM was begun. Research was undertaken at NBS and by the U.S. wire manufacturers that would ultimately lead to an ASTM Standard for the measurement of critical currents below 600 A. The results of the program to date have been published[1,2] and a draft standard is now being evaluated by the ASTM membership. In the course of the program many measurements were made at NBS to evaluate the effect of various experimental parameters on the critical current determination. In this paper we present the results of these measurements and discuss their effect on the measured critical current.

Our objective here is to present adequate information so that a technically knowledgeable person can make an accurate measurement of the critical current of a commercial superconductor. This task involves the construction of a proper apparatus and the use of a correct measurement technique. The effect of the most important parameters (e.g. field orientation) on the results are treated in detail in separate sections; usually with data showing the result of variations in the parameter on the measurement.

We deal here only with practical superconductors, usually multifilamentary niobium-titanium (NbTi) or niobium-tin (Nb_3Sn) wire with a copper matrix, although Nb_3Sn tape conductor is mentioned occasionally. The general construction is shown in Fig. 1 and a cross section of a complex conductor in Fig. 2. Most practical conductors are not round (and sometimes not monolithic) and this leads to a whole new set of field orientation effects. Most of what we have to say will, of course, apply to any superconductor, but some of the topics (e.g. matching of thermal contraction) will require reevaluation for conductors of significantly different composition from those investigated here. Also it is important to realize that commercial superconductors are subject to significant variability in their properties due to variations both in basic materials and in processing from one wire lot to the next.[2] Thus, frequent measurements of critical current are required in order to maintain

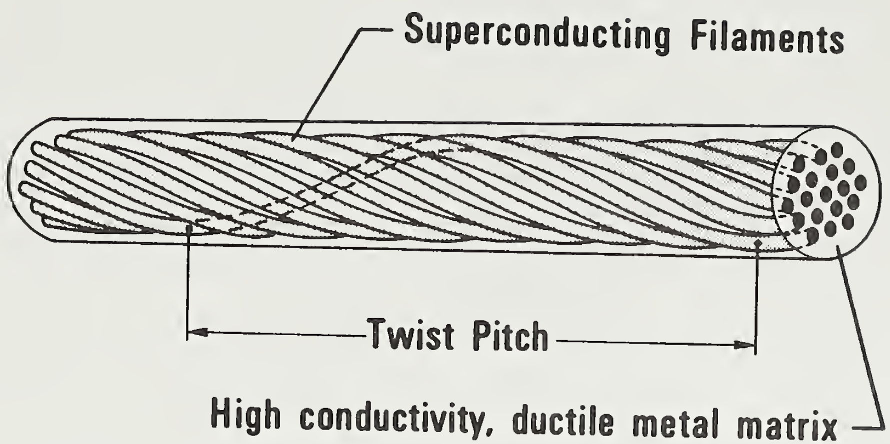
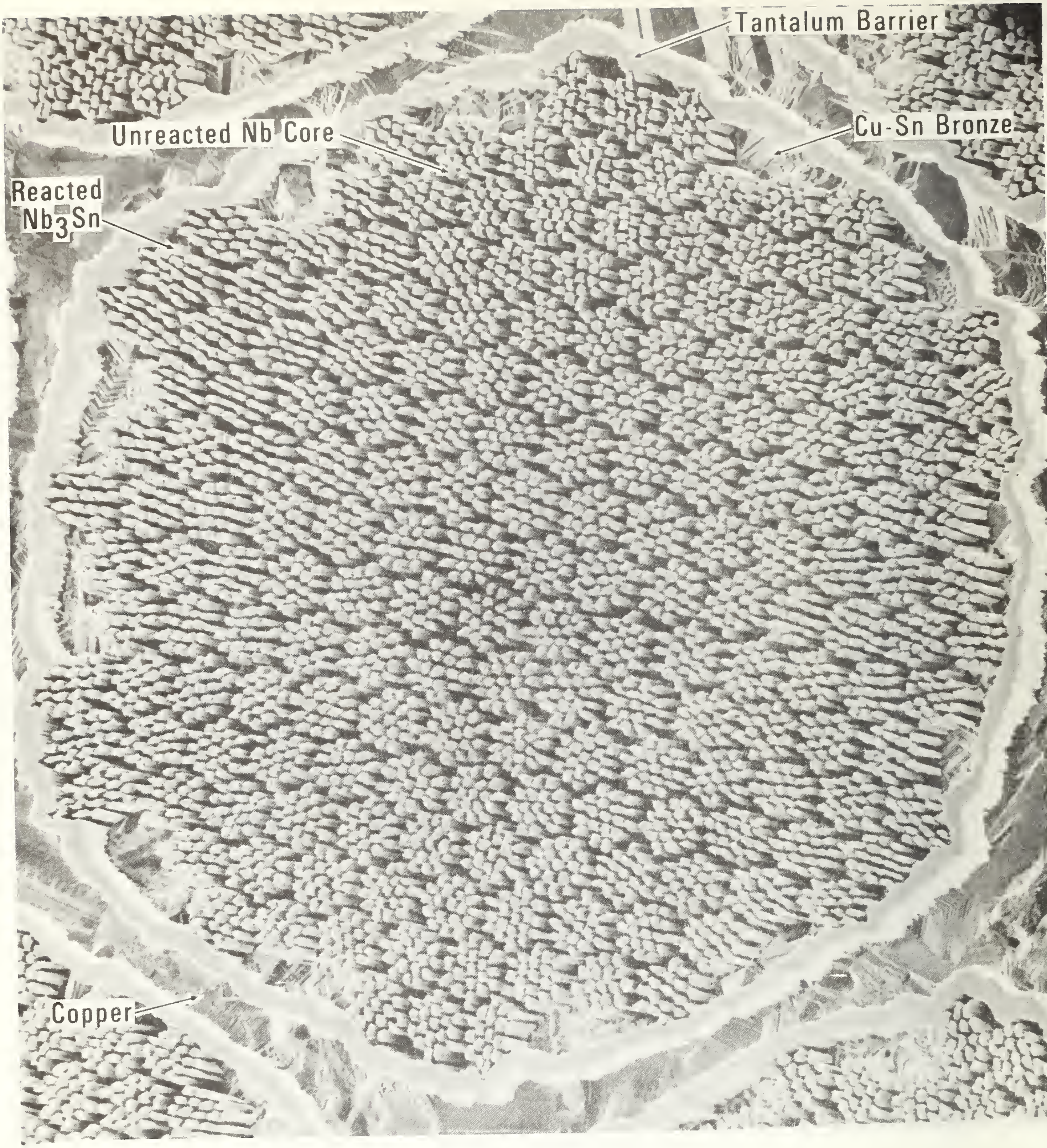


Fig. 1. Construction of a simple twisted multifilamentary superconductor. Typical of NbTi composite.



3553 (187x19) Filaments
5μm Filament Diameter

Fig. 2. A complex composite superconductor based on Nb_3Sn.

quality control and the measurement technique should reflect this by being as easy as possible to use.

The basic data from which the critical current of a practical superconductor is determined is a plot of voltage, V, as a function of current, I, the V-I characteristic. It is assumed that other parameters such as applied field, temperature, strain, and displacement are constant during this measurement. A typical real V-I characteristic is shown in Fig. 3. The curve should be reversible (taking into account any dI/dt voltage); irreversibility is an indication of potential problems such as sample heating. The most common types of sample holders and magnets are shown schematically in Fig. 4, the reasons for choosing one configuration over another is discussed in Section IV. The V-I characteristic of Fig. 3 shows one problem immediately -- a unique critical current value is difficult to define here. This problem is resolved pragmatically by the selection of a "critical current criterion," either a specific value of electric field, E_c (voltage per unit length), measured along the wire or an effective resistivity (a line of some specific slope, E/J, in Ω·cm where J is the current density). The philosophy of the selection process and its effect on the results is discussed at length in Section V. Further problems arise in that the low current part of the curve in Fig. 3 is actually showing a phenomena, known as current transfer, that is determined by the sample mounting and/or measurement configuration and is not intrinsic to the wire. It arises as currents flow through the resistive matrix between superconducting filaments in response to changing conditions (see Section V). Its presence does not necessarily degrade the accuracy of the measurement, but it may. The high current portion of the curve does represent an intrinsic property of the superconductor, the flux flow voltage, that arises from the motion of flux vortices across the superconductor. There is an empirical relationship that shows the voltage in this region to be proportional to some power of the current; more about that later.

Another aspect of practical conductors that needs mentioning is their stability, the amount of disturbance, either mechanical or thermal, that the conductor will tolerate before thermal runaway (or quench) occurs. This property is controlled by the addition of relatively pure metal, most often copper, to the conductor composite. More copper results in greater stability, but a lowered overall current density for the conductor which is frequently undesirable in magnets. Superconductor stability is a complex topic, but one

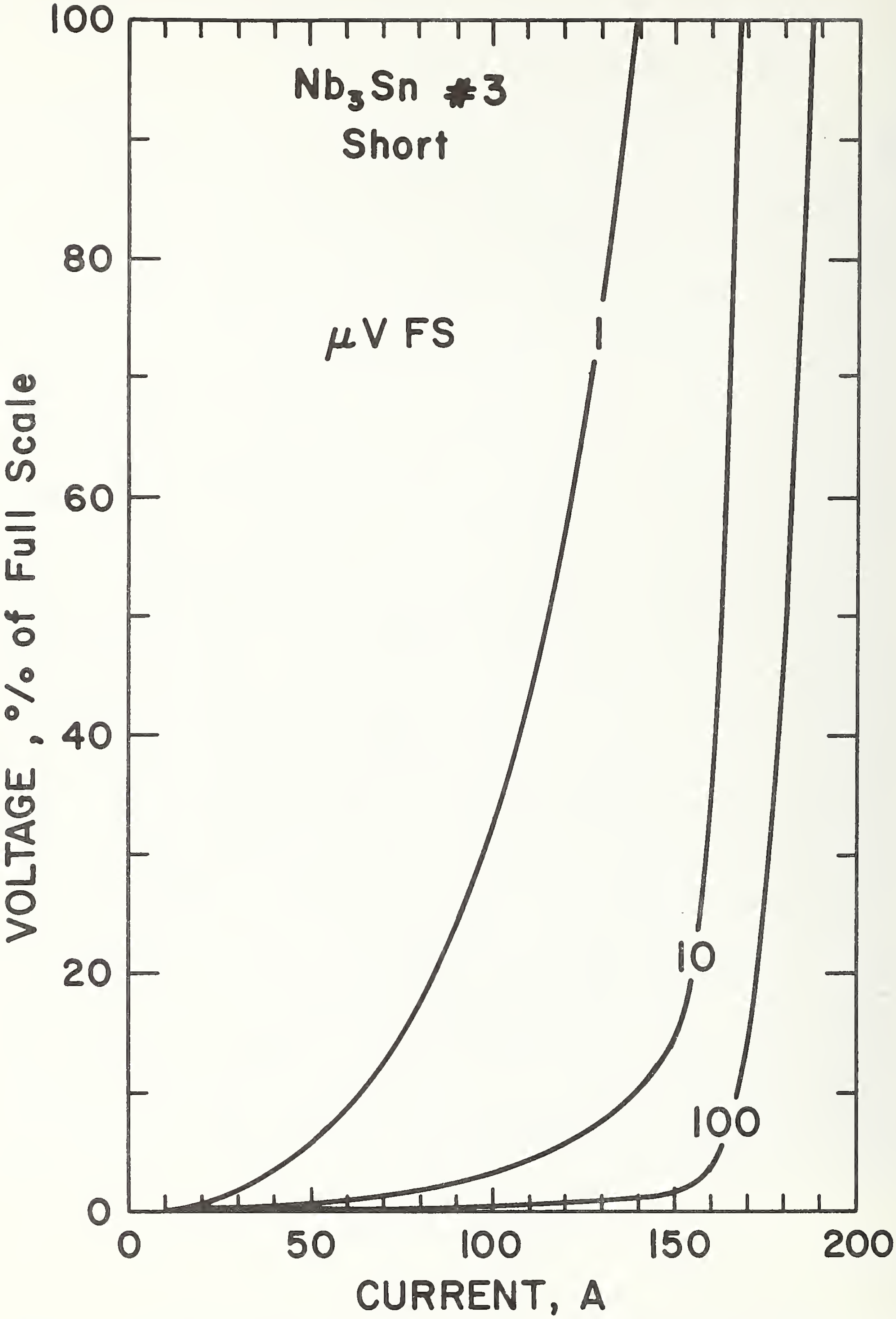


Fig. 3. Typical V-I characteristic for a commercial superconductor (multi-filamentary Nb_3Sn at 7 T). The curves show the structure of the curve at different voltage detection levels.

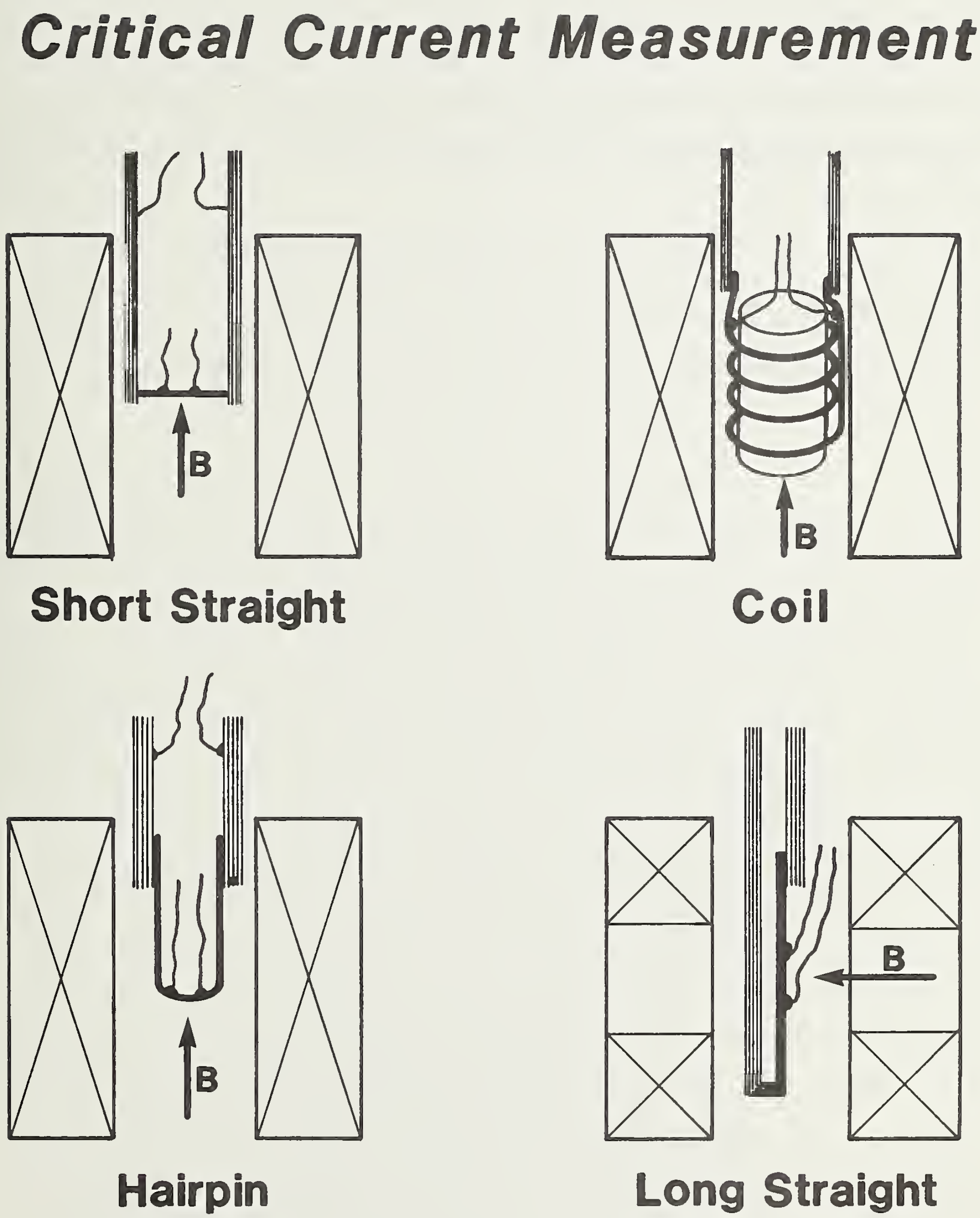


Fig. 4. Common sample holders and configurations used for critical current determination.

that has been frequently discussed in the literature.[3] The degree of stability of a wire should not greatly affect the measured critical current, but the actual experiment is more difficult to perform on marginally stabilized wires.

The rest of the paper is divided into five major sections. Section II treats the design of our apparatus, and Section III the choice of materials for the test program. In Section IV we discuss the effect of various parameters on the design of critical current experiments. Section V treats the experimental measurements and their interpretation. The results are summarized in Section VI.

II. APPARATUS

There is an important distinction to be made immediately. In this section we describe our apparatus constructed for the rather complex and sensitive experiments needed to evaluate various aspects of critical current measurement. In later sections we will be discussing the design of experimental systems that may well be less complex than ours. In general, we feel that any system that takes into account the applicable constraints of the later sections will be adequate for critical current measurements with an inaccuracy of ±5%.

A schematic diagram of our apparatus is shown in Fig. 5. Each of the parts is discussed in more detail below. Regardless of the specific configuration chosen, however, the system will measure the appropriate critical current to better than ±5% and reproduce a given measurement to better than 0.5%.

Sample Holders

Sample holders of each of the types shown in Fig. 4 were constructed, since one of our goals was to determine the limits of useful application for each type. In addition, numerous holders representing modifications of these were made for specific tests. Some examples are: coils with variable turns-per-centimeter to evaluate field angle effects and a rotating table system for the same purpose; flat bottom hairpin holder to evaluate the effect of small radius of curvature; various configurations of the short straight current leads, used in studying current injection effects; and holders that allow placement of voltage taps on opposite sides of the sample while still maintaining support against the Lorentz force. In each holder, except those designed to measure orientation effects, the applied magnetic field is essentially perpendicular to the sample axis, at least between the voltage taps. This is the orientation in which the minimum critical current will be measured and, thus, represents the limiting case for most applications.

Nearly all of the holders are made from fiberglass-epoxy matched to the sample for relative thermal contraction as discussed below. Several of them are shown in Fig. 6. High current NbTi bus bar (>700 A at 8 T) was used for the current contacts. These were epoxied into grooves in the sample holder with a high temperature version of a commercial filled epoxy. This technique allows repeated soldering of samples without loosening of the bus bar.

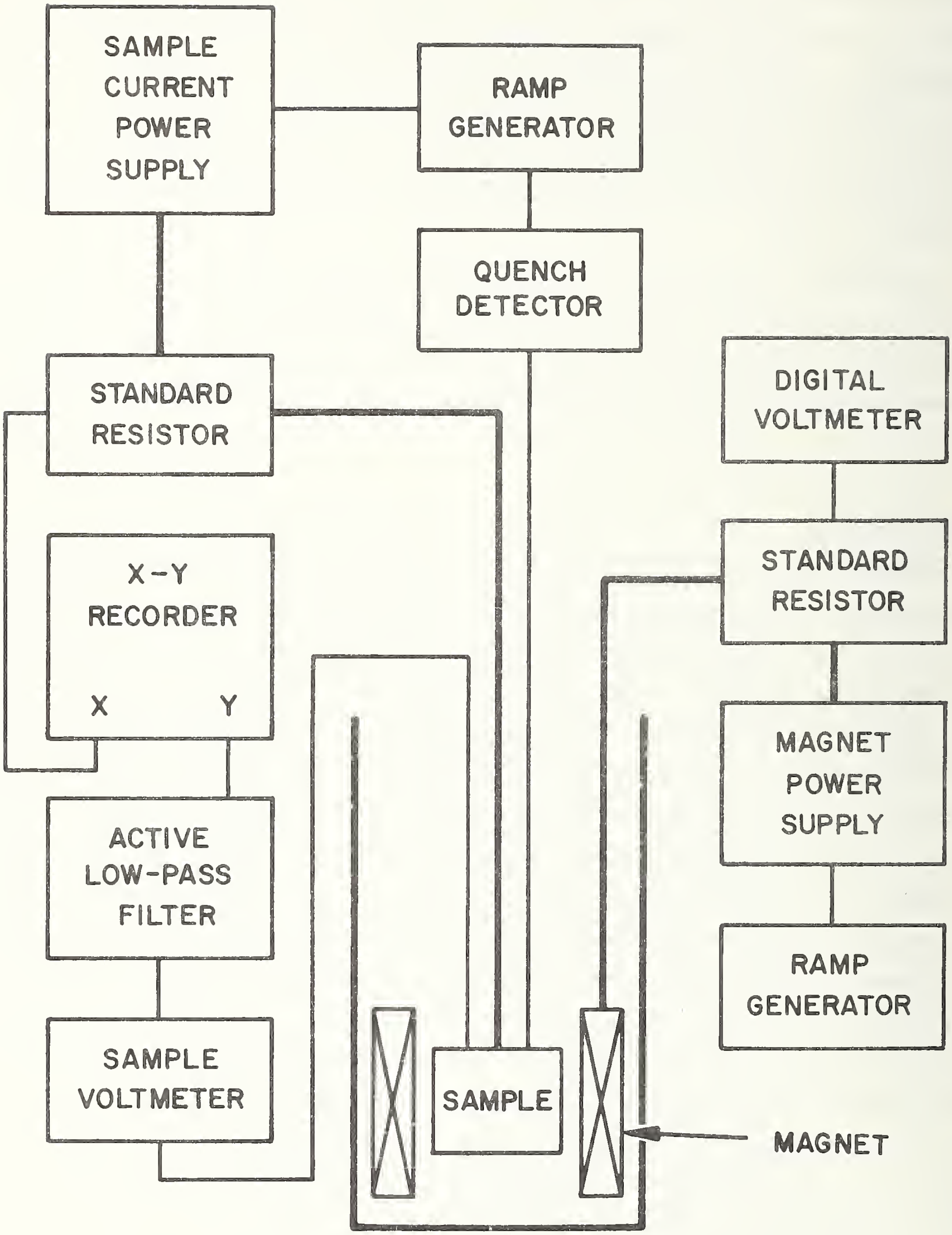


Fig. 5. Electrical systems for critical current measurement.

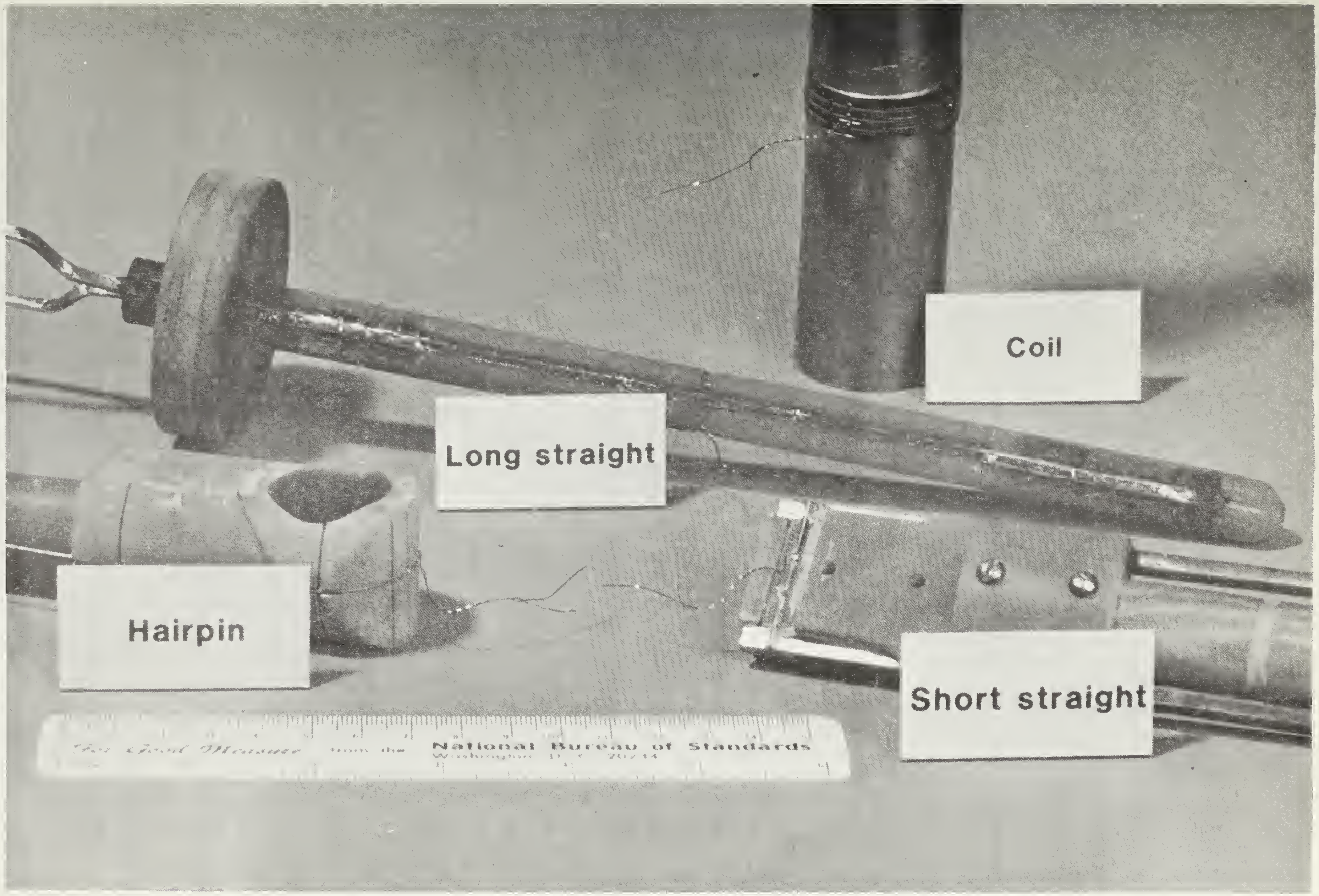


Fig. 6. Actual sample holders of the types shown in the drawing of Fig. 4.

Sample Voltage Detection and Current Supply

As shown in Fig. 5, the sample voltage is read by an analog nanovoltmeter and, after filtering, is plotted on the Y axis of an X-Y recorder (some early comparisons were made between this system and a digital multimeter with an analog output). The input cord of the nanovoltmeter has copper clips that are manually clipped to the appropriate set of terminals on the wire bundle from the sample holder, which may contain as many as sixteen wires. This is the only junction between the sample and the nanovoltmeter input. Isothermal conditions were maintained by putting small bags of lead shot under and on top of the junction.

The sample power supply for most measurements was a series-regulated 600 A battery driven by a commercial ramp generator. For comparison studies and the evaluation of ripple and noise, a 600 A silicon-controlled rectifier (SCR) regulated supply was used. In each case standard current shunts (±0.25%) were used to measure the current and/or drive the Y axis of the recorder. Current leads into the dewar were commercial 600 A vapor-cooled leads.

The most sensitive of the possible configurations, the nanovoltmeter and battery power supply, allows the measurement of voltages as low as ten nanovolts. This is a much greater sensitivity than required for conventional critical current measurements, with the possible exception of the evaluation of wire used in magnets for nuclear magnetic resonance (NMR) measurements.

The desire that the V-I curve be reversible for all measurements on all samples requires a quench-protect circuit. The circuit diagram of our quench protect (adopted from a Los Alamos National Laboratory design) is shown in Fig. 7. The voltage across the entire sample at the current bus bars is detected and used to shut down the current ramp. The level at which this shutdown occurs is adjustable by means of a front-panel dial. This circuit is not absolutely necessary. Especially in the case where many measurements are to be made on similar wires an experienced operator can easily prevent thermal runaway after a few samples have been quenched.

Magnet Systems

Both types of magnets shown in Fig. 4 were used in these experiments. The simple solenoid was a 10 tesla magnet with a 3.8 cm bore. The split-pair magnet used for the long straight configuration measurement had a maximum field of 7 tesla and a radial access port of 1.5 cm (5 cm bore). Both magnets

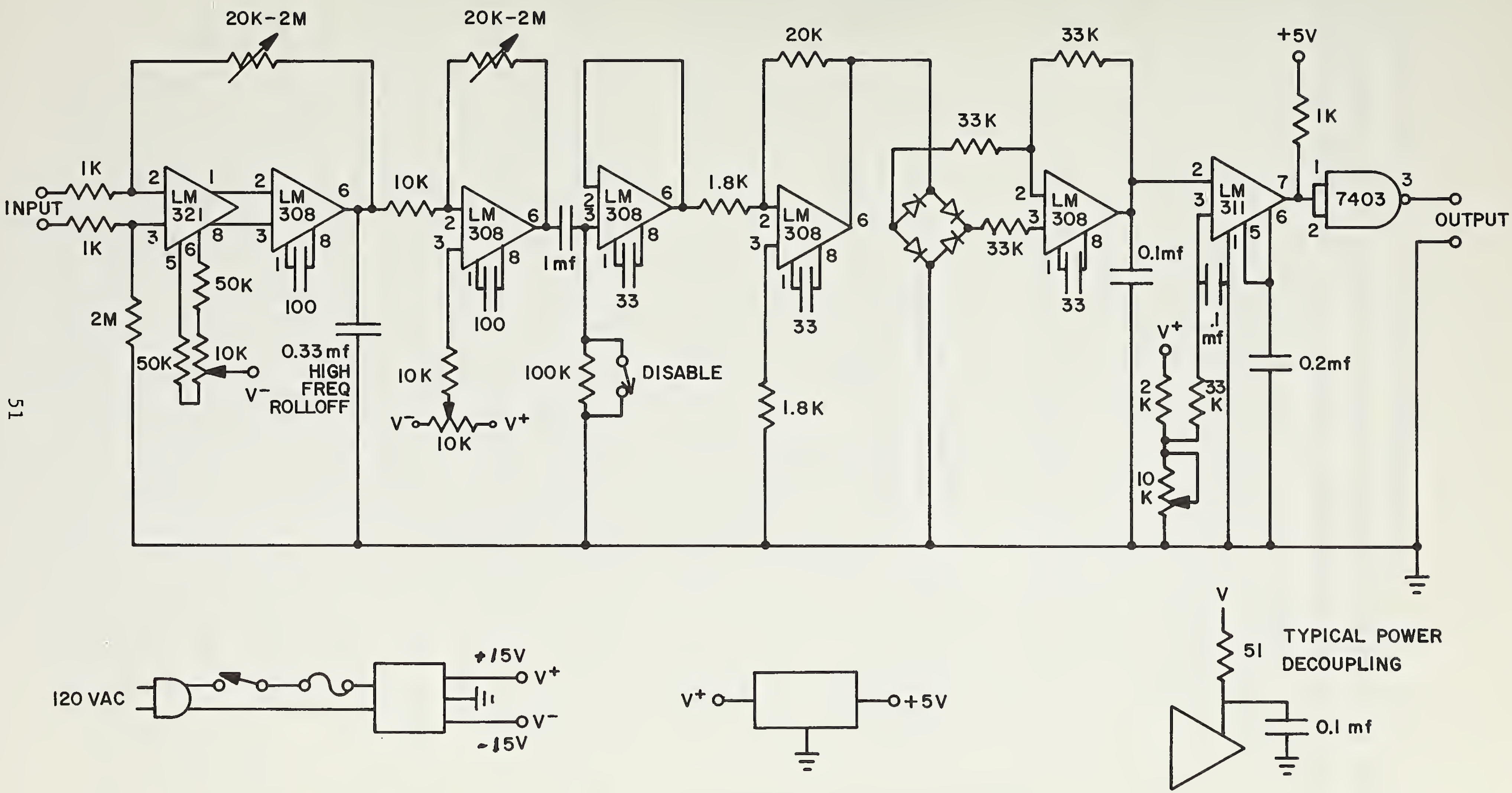


Fig. 7. Circuit diagram for a quench protection system. The resistors are marked with units of ohms and the capacitors with units of pico-farads unless otherwise noted.

have been calibrated to a field accuracy of ±0.2% and a reproducibility of ±0.1%. At very low fields trapped flux could degrade these numbers significantly, but none of the measurements reported here involve that field region.

III. MATERIALS

As mentioned earlier, one of the goals of the research described here was to develop supporting data for a "standard test method" for general laboratory use in the measurement of critical current. In this endeavor we limited our consideration to commercial superconductors with high field critical currents less than about 600 A, since this represents a practical limit for many laboratories. The materials used for our tests are described in Table 1. Sample numbers in the text and figures refer to this table.

Table 1. Critical Current Test Materials

Sample Number	Type	Dimensions (mm)	Number of filaments	Twist (cm^{-1})	Copper to non-copper ratio	Approximate Critical Current at 8 T, 4 K. (A)
1	Rectangular NbTi	0.53 x 0.68	180	0.79	1.8	114
2	Round NbTi	0.64	180	0.79	1.8	128
3	Round Nb_3Sn	0.70	2869	0	1.7	132
4	Tape Nb_3Sn	0.2 x 2.3	----	----	1.6	172

The first wire listed in the table is one that has been used for numerous experiments at NBS over the years. The second wire is similar to the first except it is round. This wire was added to the group when the effect of the aspect ratio of rectangular wires discussed below was observed. The multifilamentary Nb_3Sn is a conventional wire that we react after forming; note that the filaments are untwisted. The lack of a twist pitch helps considerably in understanding the intricacies of current transfer along and across the wire as discussed below. The tape conductor is most helpful as a "worst case" sample in the evaluation of field orientation and current ripple effects.

Many lengths of each of these conductors were used throughout the tests reported here. Thus, as already mentioned, some sample-to-sample variation in properties is to be expected. Our experience indicates that, with careful sample selection, this should not result in more than about a 2% variation in critical current among samples of a given material as used here. This source of uncertainty could be minimized by use of a carefully characterized standard reference material and this possibility is now being explored at

IV. EXPERIMENT DESIGN

This section and the following one present the bulk of our data on the various factors that influence the correct determination of critical current. In each instance we discuss the implications of the data for the design and operation of an experimental apparatus. The general details of cryogenic apparatus construction are not treated here, but excellent texts on the subject are available.[4]

In this section we present data related to the design and construction of the experimental apparatus. It is probably possible to construct a "perfect" apparatus for the determination of I_c, but the restrictions of the real world make this attainment unlikely. Most of us must take into account the limitations of space, existing equipment, time, and money. With this in mind, we have tried to present a design philosophy that allows choices to accommodate such restrictions while still maintaining the overall measurement accuracy. At the least, we hope that the data presented will indicate the consequences of various design choices.

Sample Holders

The major sample holder types are shown in Fig. 4. Table 2 gives a comparison of the various types. The terms used have already been introduced, but they will also be discussed in detail below. It should be stressed that,

Table 2. Sample Holder Comparisons

Sample geometry	Advantages	Disadvantages
Short straight	simple geometry solenoidal magnet	high contact heating high current transfer insensitive criteria
Long straight	low contact heating moderate criteria simple geometry	some current transfer split-pair magnet
Hairpin	low contact heating moderate criteria solenoidal magnet	some current transfer moderate geometry
Coil	low contact heating low current transfer sensitive criteria solenoidal magnet	complicated geometry

in some circumstances, the effects listed as disadvantages may, in fact, preclude the use of that holder for measurements on a specific material. In all cases the sample should be fit closely to the holder to avoid buckling in the field, this is especially important for the coil geometry. The use of small amounts of varnish or grease to hold the sample in place is usually acceptable, but see the comments below on heating.

Typical V-I data taken with the various holders are shown in Fig. 8. The plot is made on a full-log grid to illustrate that the curve usually has two regions that must be considered. The high current behavior is representative of flux flow and is intrinsic to the superconductor. The data in the lower current region illustrate the varying role of current transfer in each design. This current transfer voltage must be subtracted in some manner in order to arrive at the intrinsic V-I curve from which I_c is determined. It is obvious from the figure that this problem becomes more acute as the electric field criterion decreases. Table 3 and Fig. 9 illustrate how the critical current determination at various fields and criteria is affected by sample holder type. A current transfer correction has been made to these data. Notice (see Fig. 8 and Table 3b) that, when the current transfer voltage is the same size or larger than the criterion used, the possibility exists of over- or under-estimating the current transfer part which may lead to large errors.

Clearly the choice of a sample holder requires some serious thought. Similarly, many of the problems vanish when a proper choice is made. It should be noted that most data presented here are for Nb_3Sn -- the situation is generally much less severe for NbTi, as shown in Table 3, because the current transfer voltage is generally lower. However, at very low criteria ($\sim$10 nV/cm), the possibility of error from this source must be considered as can be seen in the table.

Voltage and Current

The two problems to be resolved with regard to voltage and current leads are: how to get current into the sample and properly distributed among the superconducting filaments in as short a distance as possible; and, how to arrange the voltage taps so as to make the most meaningful measurement. Both of these problems are far more complex with a multifilamentary superconductor composite than they would be with, say, a simple copper wire. Again, the complexity is greatest for the Nb_3Sn conductors.

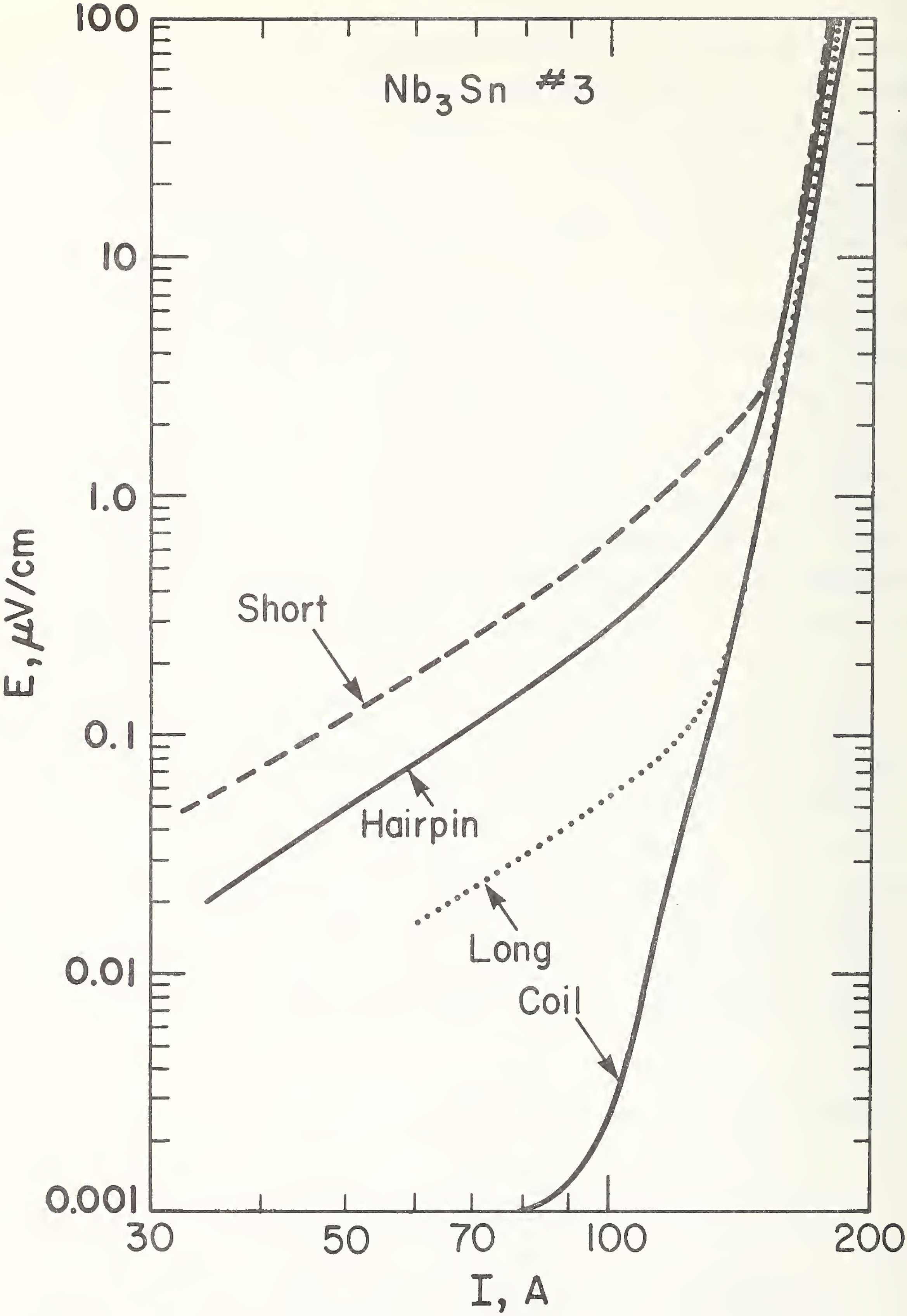


Fig. 8. Full log plot of representative I-V characteristics (multifilamentary Nb_3Sn at 7 T) for different sample holders.

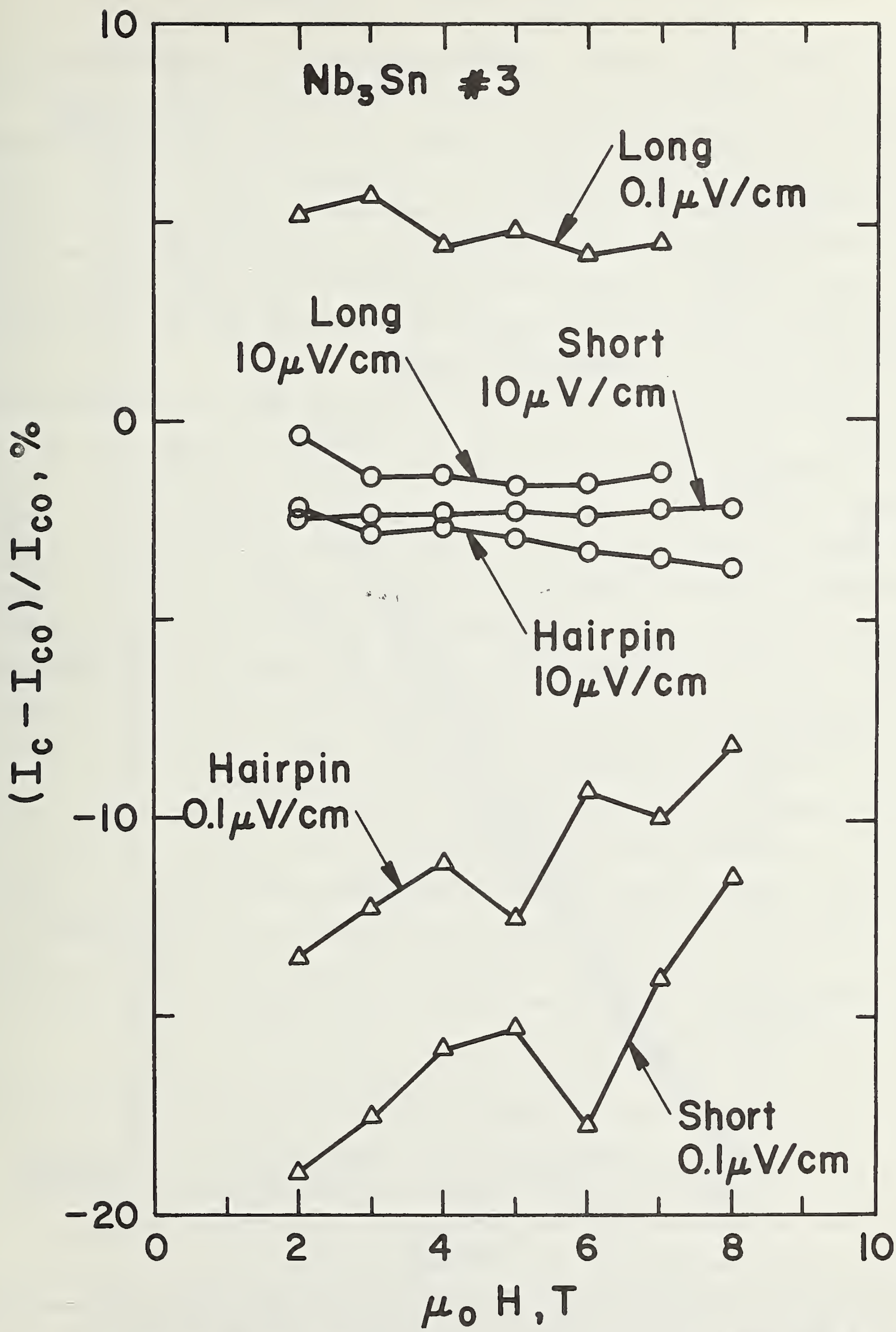


Fig. 9. The percentage change in I_c observed for a Nb_3Sn sample (# 3) with different sample holders as a function of magnetic field. The base data that defines zero is that from the coil sample, I_{co}. Results are shown for two values of the electric field criterion.

The large sample currents used in these tests are usually brought into the cryostat by means of commercial helium-vapor-cooled leads. Current is monitored by a conventional, low-resistance, series shunt at room temperature. In the cryostat, the leads connect to a superconducting current bus of much higher capacity than the samples (I_c at least double). Monolithic rectangular NbTi conductor is handy for this purpose unless flexible leads are needed, in which case a bundle of smaller wires is appropriate. In most geometries, an added measure of protection is achieved because the current bus is parallel to the magnetic field in the high field region.

Transfer of the current from the bus into the sample is a complex process involving: the length and resistance of the joint;[5] the size, distribution, and twist pitch of the sample filaments;[6] and the details of current transfer between the filaments of the sample.[7] Large voltages can arise due to these mechanisms that may overwhelm the intrinsic V-I data. In the papers cited, a large amount of data is presented on each of these topics. It can be summarized by saying that a perfectly adequate situation will be achieved if the current contact length is at least ten times the maximum transverse dimension of the sample. For conductors with twisted filaments this contact length should also be greater than one twist pitch. These requirements are easily met for all sample configurations except the short straight. There it is usually possible to bend the sample into a "flat-bottom hairpin" shape (or, in the case of multifilamentary Nb_3Sn, to react to this shape) such that a reasonable length lies along the bus bars. This approach helps to an extent.[6] It is important that none of the free wire between the bus bars be bent, i.e., the entire bend region should be soldered to the bar (except for a multifilamentary Nb_3Sn sample that has been reacted to this shape or if the bend of a NbTi sample is not too severe).

Even with reasonable current contact lengths, if the voltage taps are too close to the contact, large voltages related to the current transfer may be seen. The situation is significantly worse when marginal current contact lengths are used. The data shown in Fig. 10, taken on a coil sample of our Nb_3Sn wire, illustrate all of the above points. These data were obtained by making a set of measurements of the voltage between adjacent taps on the sample and then cutting the sample in the current contact region and repeating the measurements. The value used for the distance, x, of the pair of voltage taps from the current contact was obtained by an iterative process that takes

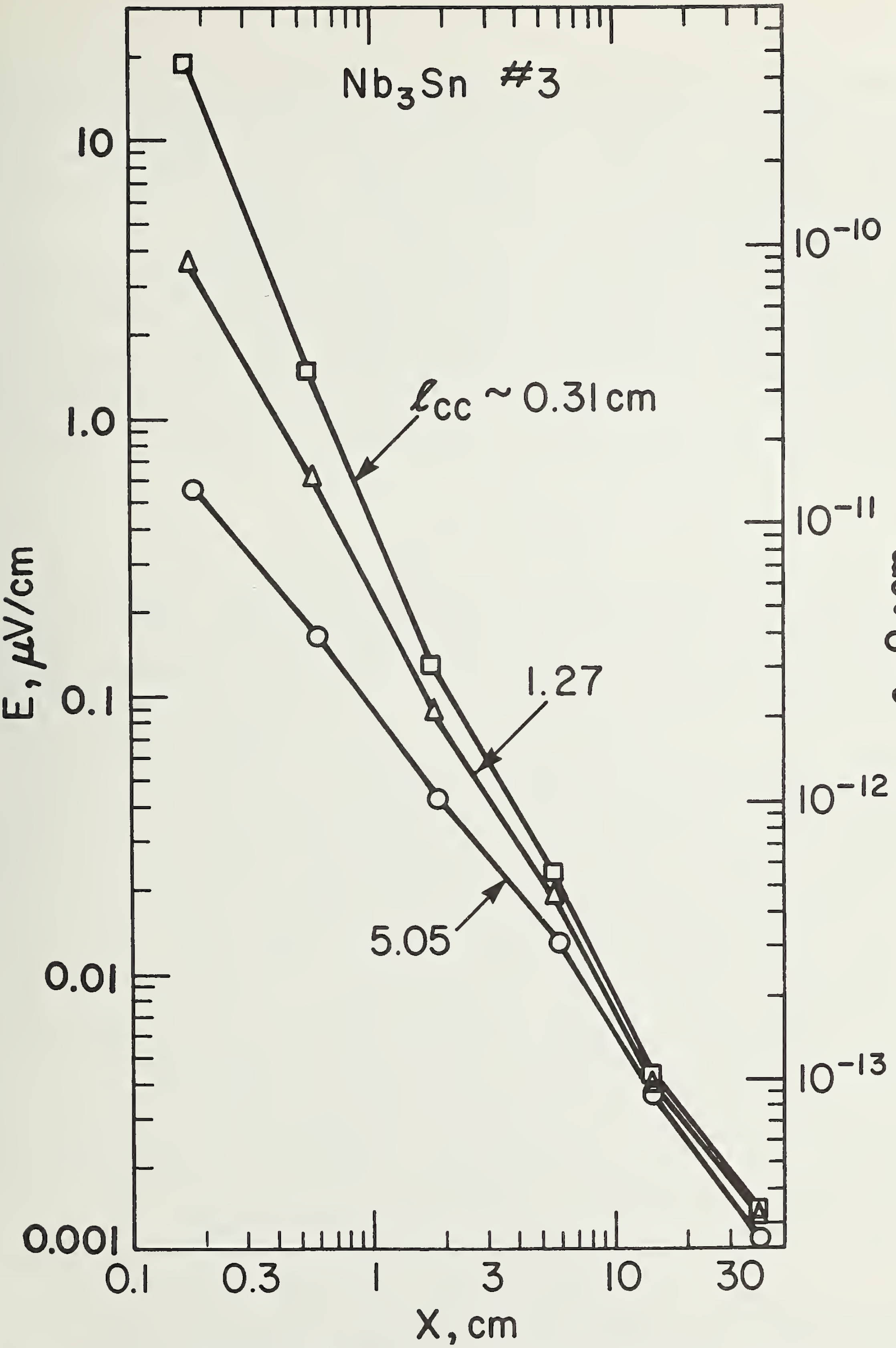


Fig. 10. Full log plot of the electric field (or effective resistivity) due to current transfer as measured at various distances, x, from the current contact. Each curve shows data for a different length current contact, ℓ_{cc}, between the sample and the bus bar. The wire is multifilamentary Nb_3Sn measured at 4 T and 160 A (note the intrinsic I_c at 1 nV/cm is ∿186 A).

into account the electric field as a function of position. The points on the plot at the largest x were taken on voltage taps positioned around the center of the coil sample. In general the data indicate that length of contact on the bus bar is not as effective in minimizing these voltages as is length of free sample beyond the contact before the first voltage tap.

The behavior illustrated by the data in Fig. 10 represents a complex aspect of practical superconductors that has been the subject of much study. A rule of thumb which will keep the current transfer voltages small in any arbitrary conductor is to make the free length between the current contact and the first voltage tap greater than the conductor's current transfer length,[7]

$$L = (0.1/n)^{1/2} (\rho_m/\rho^*)^{1/2} d \qquad (1)$$

Here ρ_m is the resistivity of the interfilament material, d the diameter of the filament region, n characterizes the sharpness of the superconductor's resistive transition (see below), and ρ^* is the resistivity equivalent to the criterion used to determine the critical current. For critical current measurements at a ρ^* of 10^{-11} Ω·cm, a free length 30 times the transverse dimension d will typically be more than adequate for Nb_3Sn:bronze conductors. The required length becomes greater as the critical-current criterion becomes more sensitive, however. Once again, the problems are minimal with NbTi:copper where the required length is typically 15 to 20 times less than for Nb_3Sn:bronze conductor. These general requirements on the free sample length are conservative. Free lengths shorter than the expression for L may well do the job, especially if the current contact is long, as shown in Fig. 10. Measurements made at low voltage levels may give strange results (including negative voltages) in the case of very short current injection contacts.[6]

Another aspect of the current transfer problem is that the redistribution of current among the filaments can occur near a change in magnitude or angle of the applied magnetic field as well as adjacent to a joint. This was observed in obtaining the data shown in Fig. 8. The long geometry is an example of the sample in a field gradient. The total length of sample #3 (Nb_3Sn) measured in this geometry was 22 cm (550 d), which put the ends of the sample in a very low field region (5 cm bore). A number of voltage taps were placed along the sample and a current transfer voltage was observed adjacent to the joint and in the bore region, however, there was a region (a few centimeters long) in between these two where the current transfer electric field was very small (less than a few nV/cm) even up to the I_c of the bore region. A profile of the current transfer electric field in the field gradient region indicated gradual increase of E with increasing field through this region, then a slight decrease in the bore region. This same kind of separation of these two causes was also observed in the hairpin sample where instead of a field gradient region there is a change in angle between the sample and the magnetic field. Both of these observations indicate that no matter how long the low or parallel field region is, there can be a current transfer voltage in a temporal or spatial field variation and in fact the high perpendicular field region is necessary to complete the distribution of the current among the filaments. This is another advantage that the flat-bottom hairpin has over the curved bottom hairpin. In all cases the removal of the current transfer voltage adjacent to the joints from the measurement region is advantageous. The rule of thumb result given above is still valid; however, its application to these aspects of current transfer is more complex because of their distributed nature.

Protection of the sample against burnout during a quench has already been discussed and a quench-protect circuit was shown in Fig. 7. When many samples with highly resistive matrix materials (CuNi is sometimes used) must be measured, a reasonable alternative or adjunct to such a circuit is the use of a resistive shunt in parallel with the sample, usually just soldered across the bus bars. The shunt, usually of copper with a residual resistivity ratio (RRR) $\sim$200, conducts very little of the current when the sample is superconducting and most of it when the sample is normal. In determining the actual current sharing between the sample and the shunt, the contact resistance of the various joints involved must be considered. It is not uncommon to solder the sample directly to the shunt. This practice is acceptable in most cases, but it should be realized that it can make an intrinsically unstable superconductor (i.e., filaments too large, filaments not twisted enough, or not enough stabilizer) appear to be stable -- a misleading result.

Voltage taps are usually soldered to the sample. Attachment to the bus bars is sometimes used for relatively crude measurements. Care should be taken to avoid creating stress concentration points. The measured voltage is most often used to calculate an electric field or resistivity which is then compared against a chosen criterion to define I_c. Proper use of these criteria requires attention to the concept of effective length. The problem is illustrated in Fig. 11. It arises when a part of the sample between the voltage taps is not in perpendicular field, a situation that is common for the hairpin geometry. As the sample approaches its critical current, the appropriate voltage develops on a-a. Dividing this voltage by the tap spacing, ℓ_{aa}, gives the (nearly) correct electric field. However, if the voltage measurement is made on tap sets bb or cc a value nearly the same as that on aa will be seen because the sample lengths in parallel field have not yet developed any voltage -- they are not yet near to their critical current. Thus an electric field calculation using data from the cc taps and the measured distance between them along the wire would give a misleading result -- a very low electric field. Thus, it is necessary to find an effective length that can be used in calculations. This can only be done by using a "standard" wire that has been measured by some other technique.

The problem persists in a less drastic form all the way around the curve of a round-bottom hairpin sample because of the changing orientation of the wire with respect to the applied field. For example, a measurement made with probes located at opposite ends of a diameter on a round-bottom sample holder had a true effective length of 35% of the actual distance along the wire. Note that this length is even smaller than the perpendicular projected length. The basic conclusion is that the round-bottom hairpin geometry is not one to use if precise data are needed, but can be adequate for comparisons.

Magnetic Field

Magnetic field is an expensive commodity and it is, thus, the parameter that usually determines the design details of the critical current measurement apparatus with regard to size and shape. Most high field laboratory magnets are simple solenoids with bore diameters of <10 cm for 8 tesla NbTi magnets and <5 cm for 10 tesla Nb_3Sn/NbTi compound magnets. The region of 1% field homogeneity is usually on the order of a few centimeters.

The major design problem related to field configuration, once the size of things is fixed, is the angle between the conductor and the field. There are two aspects to this problem: 1) the effect of a lack of perpendicularity between the sample axis and the field; and 2) for rectangular conductors, the effect of the angle of an accurately perpendicular field with respect to, say, the wide face of the sample.

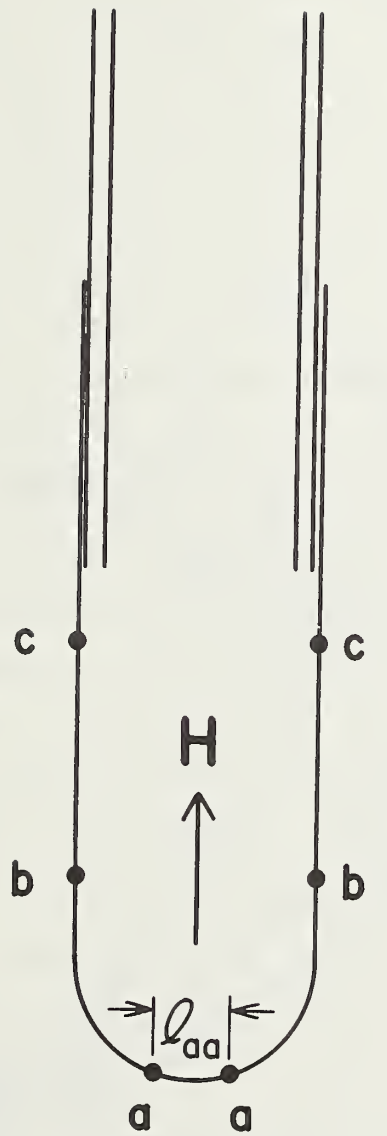


Fig. 11. Hairpin sample geometry to illustrate the concept of effective length (ℓ_{aa} = length between taps a and a).

The first of these concerns was investigated in two ways. First, a series of coil samples were prepared with winding pitches varying from 1 to 40°. Total sample lengths varied from 10 to 90 cm. The results of the critical current measurements with these samples are shown by the open circles in Fig. 12. A more complete series of measurements were made on all samples using a rotating table device that allows a single short (3.6 cm) sample to be rotated through a total angle of nearly 120° and the critical current measured at as many points as desired. These results are also shown in the figure. Two features are obvious: the sample can be misoriented by quite a bit without seriously degrading the measurement accuracy (at least 8° before a 2% increase in I_c occurs); and, beyond a certain point the critical current increases very rapidly with field angle. The data for all samples presented here was taken in a field of 8 T, but data taken in 4 and 6 T had a very similar angular dependence when normalized to $(I_c - I_{co})/I_{co}$ (where I_{co} is the critical current with the field perpendicular to the sample axis) which suggests this magnetic field scaling for each sample. This magnetic field scaling was also observed for sample 2 (NbTi) at 9 and 9.75 T (note that I_{co} = 349 A at 4 T and I_{co} = 49 A at 9.75 T). Also, there was very little change in these curves over a wide range of critical current criteria for each of these samples. In addition, different types of NbTi conductor give similar behavior. The behavior of the multifilamentary Nb_3Sn is somewhat different, but the effect is similar to that for the Nb_3Sn tape. A twisted multifilamentary Nb_3Sn sample (prepared by twisting a length of sample 3 prior to its reaction) was also measured and its angular dependence of I_c was very similar to the untwisted sample. For each of the rectangular conductors, the field is parallel to the wide face during this measurement. If one attempts to explain the observed angular dependence, the first guess at the shape would be $I_c/I_{co} = 1/\cos\Theta$ considering the perpendicular projection of the applied field. The NbTi I_c's increased faster with angle than this and the Nb_3Sn I_c's increased more slowly. Figure 13 is a full-log plot of the data showing the large angle (conductor and field closer to parallel) data as well. The leads to the rotating table device limited the measurement to currents less than about 400 A, but higher field data on the twisted multifilamentary Nb_3Sn sample and sample 2 indicated that the curves on Fig. 13 can be extrapolated to 90°.

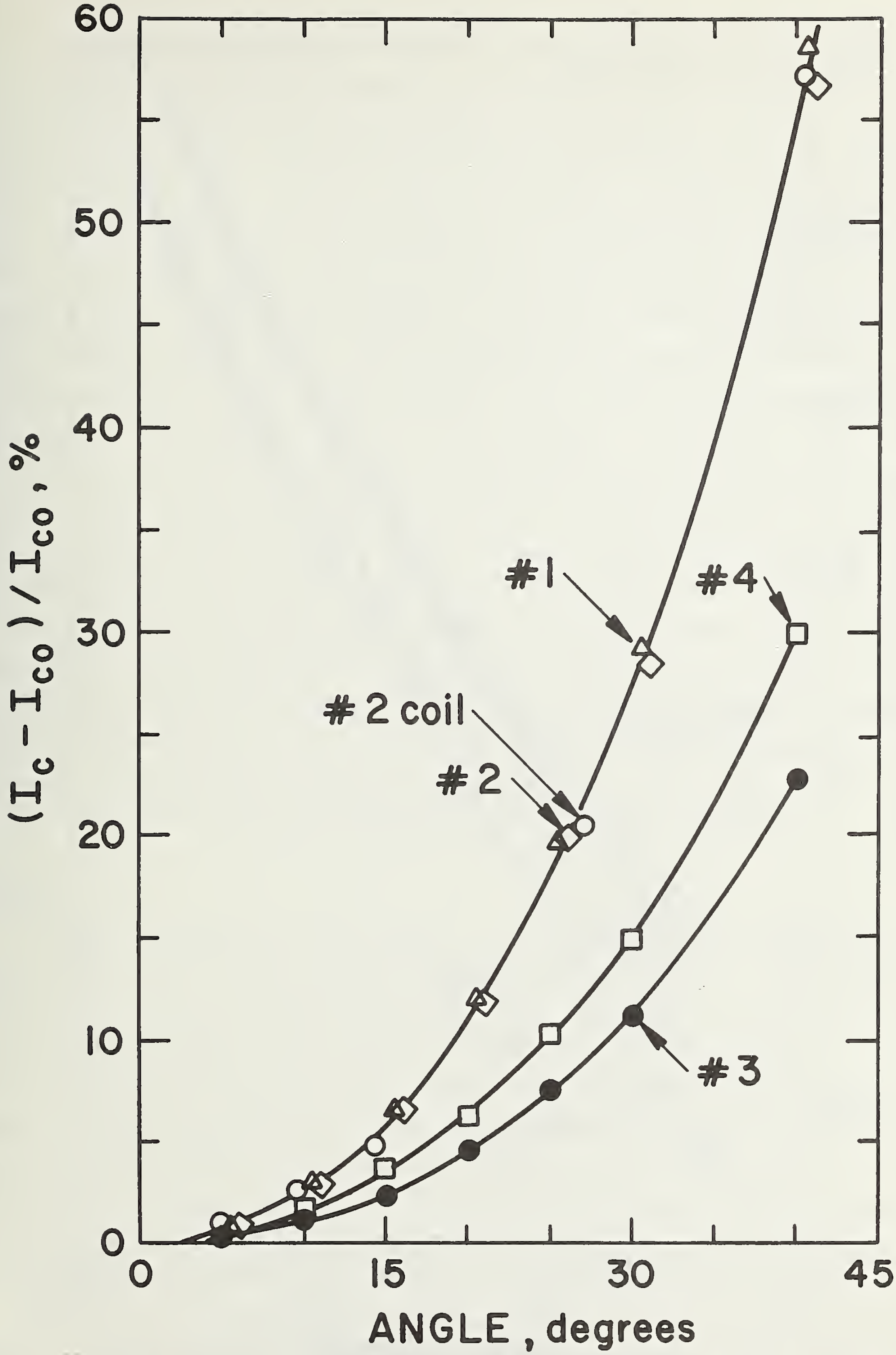


Fig. 12. The effect of angle between the conductor axis and the applied field on the critical current determination. The angle is zero when the conductor axis is perpendicular to the applied field. I_{co} is the critical current at the zero angle. Data shown were taken with variable pitch coils (marked coil) and with a short-sample rotating table device. The numbered samples are described in Table 1.

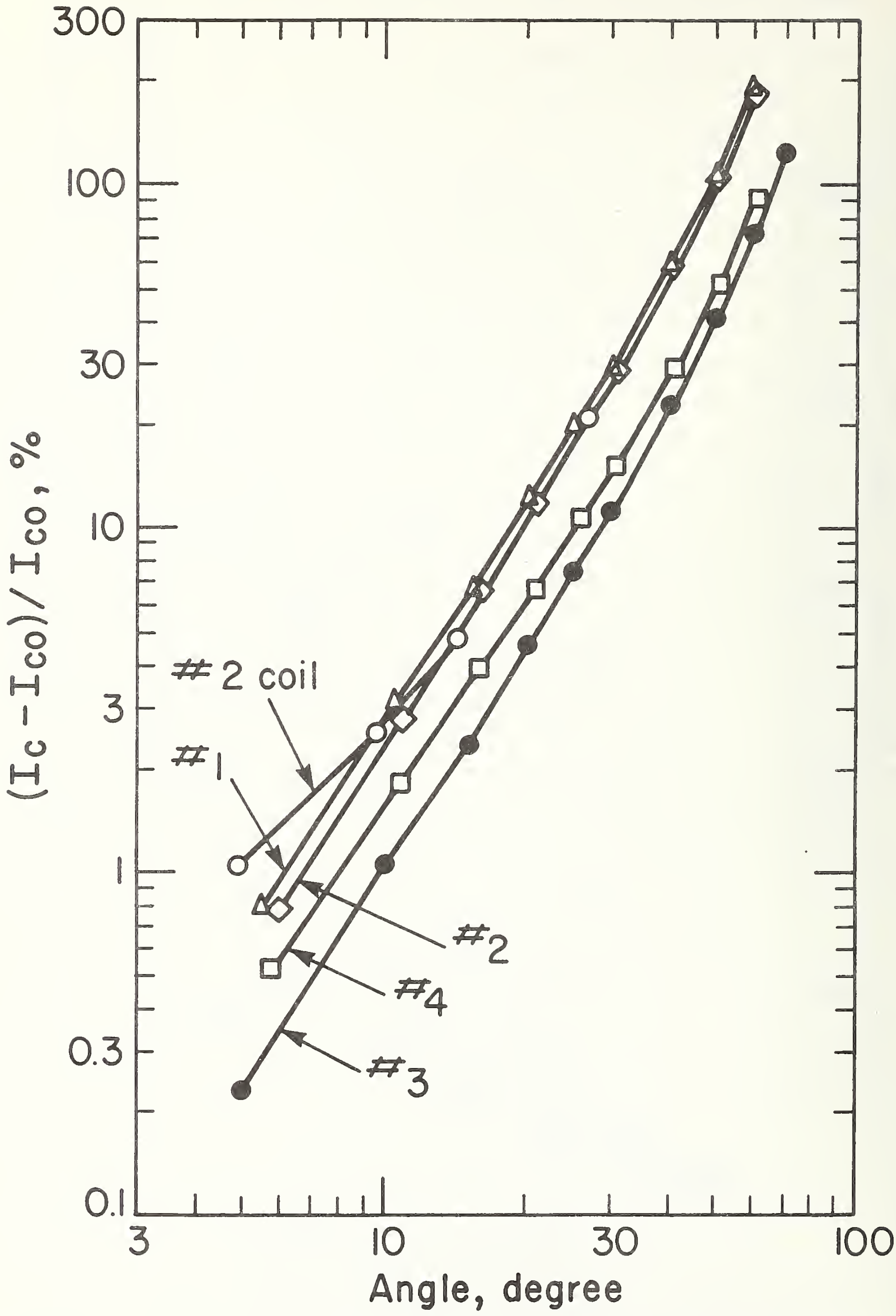


Fig. 13. Full log plot of data shown on Fig. 12, including some larger angle data. I_{co} is the critical current at the zero angle.

The effect of field orientation with respect to the faces of the rectangular conductors was investigated using a long straight sample in the radial-access magnet. The field is always normal to the conductor axis in these tests. The results are shown in Fig. 14 where I_{co} is the critical current with the field parallel to the wide face of the conductor. Measurements at 3 and 7 T (7 T data shown in Fig. 14) indicated that $(I_c - I_{co})/I_{co}$ was a good magnetic field scaling of this effect. There are several interesting features here. The most important from the standpoint of experimental design is that moderate care in positioning the sample will result in good data when the measurement configuration has the field parallel to the wide face. This configuration is the one most commonly encountered in the high field region of simple magnet windings. On the other hand, the configuration that has the field normal to the wide face has a stronger angular dependence for the critical current and, thus, measurements in this position will require significantly more care in sample orientation. The figure shows another interesting effect in that the angular dependence of the critical current of the tape conductor is opposite to that of the rectangular multifilamentary conductor. This is probably due to a difference in the pinning mechanism of these two types of superconductors. This topic of aspect ratio and its effect on I_c is a very interesting one and is currently under study at NBS.

Strain

Proper assessment of the sources and effects of strain on the sample is one of the most critical aspects of experimental design. The problem is complicated because sample strain may arise from many sources including: differential thermal contraction of the apparatus, both static and dynamic (due to different cooling rates); sample mounting; and Lorentz force. In addition, the complex nature of the composite conductor makes detailed evaluation of the strain in the twisted filaments quite difficult. A recent comprehensive review of this topic has been published by Ekin[8] and should be consulted for details on the effects of strain within the superconducting composite.

An important feature of strain effects is the extreme difference between NbTi and Nb_3Sn. Niobium-titanium conductors are generally very strain tolerant. Their critical current is not degraded significantly (1%) until the overall tensile strain reaches ∿0.5%. Further straining to 2% gives only a

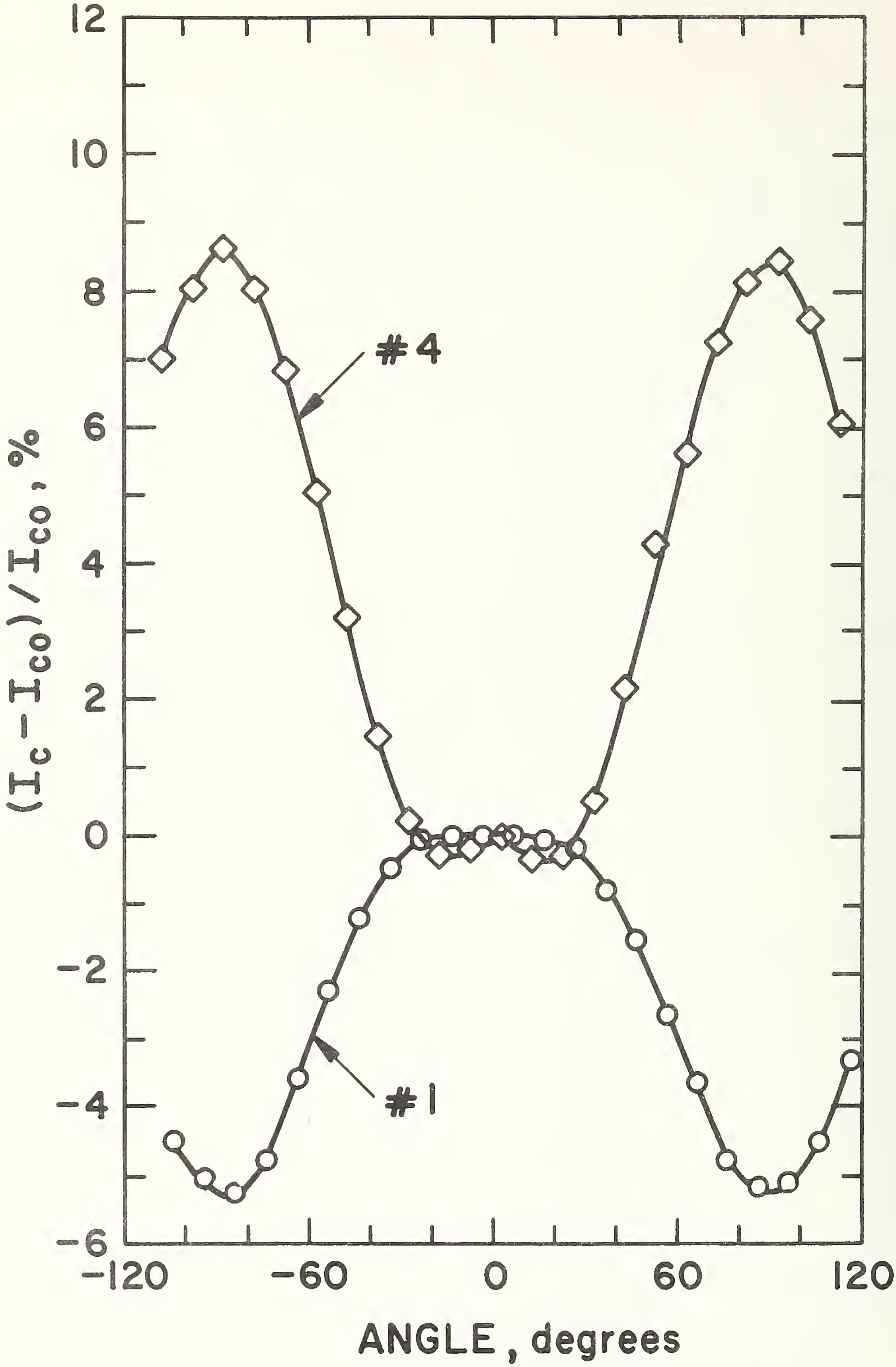


Fig. 14. Dependence of I_c on rotational angle of field around the conductor axis for rectangular conductors at 7 T. The zero angle is defined where the field is parallel to the wide face of the conductor and I_{co} is the critical current at the zero angle.

10% degradation of I_c.[8] Niobium-tin, on the other hand, is very sensitive to strain as illustrated by Fig. 15 from the review just mentioned. The intrinsic strain is that existing in the Nb_3Sn itself and may have components from the conductor matrix material. Thus, a particular sample may lie on either side of the peak when under no external stress. In any event, it is clear that strains as small as 0.2% may result in significant changes in I_c. One practical result is that samples of Nb_3Sn conductor must usually be formed to the shape required for the test before they are given the final reaction heat treatment to form the intermetallic compound (to avoid introducing bending strain).

Another aspect of the strain dependence of critical current that is important for measurements and applications near the upper critical field is that the strain dependence becomes a strong function of magnetic field. This occurs for both NbTi and Nb_3Sn, but is probably only significant at reasonable strain values for the latter. Data illustrating this effect is shown in Fig. 16 from recent measurements by Ekin.[9] Recent theoretical and experimental work[9,10] has led to a mathematical description of this "strain-scaling" behavior and these papers should be consulted if measurements at high fields (above about 10 T) are contemplated.

Strains induced by differential thermal contraction of the sample holder with respect to the sample may be large because the holder is most often a nonmetallic and these materials contract much more on cooling than do the metals. The two most common solutions are to make a metallic sample holder or to use a nonmetallic composite, usually epoxy-fiberglass. The former approach is not recommended because of the problems associated with electrical insulation. The fiberglass-epoxy materials, especially NEMA G-10, are useful if proper attention is paid to the large thermal expansion anisotropy. Typical data taken in our laboratory[11] are shown in Fig. 17 for both G10 and G11 fiberglass-epoxy as well as the much less expensive (and less well characterized) cotton phenolic. Data are also given in the reference for both NbTi and Nb_3Sn commercial multifilamentary conductors. They fall within the range of the "warp direction" curves. Thus, for example, the best way to make the bottom segment of a round-bottom hairpin is by using a piece of rolled-cloth fiberglass-epoxy tube with its axis normal to the centerline of the apparatus.

Attachment of bus bars and such to these nonmetallic holders is easily accomplished with filled epoxies that also match the thermal expansion

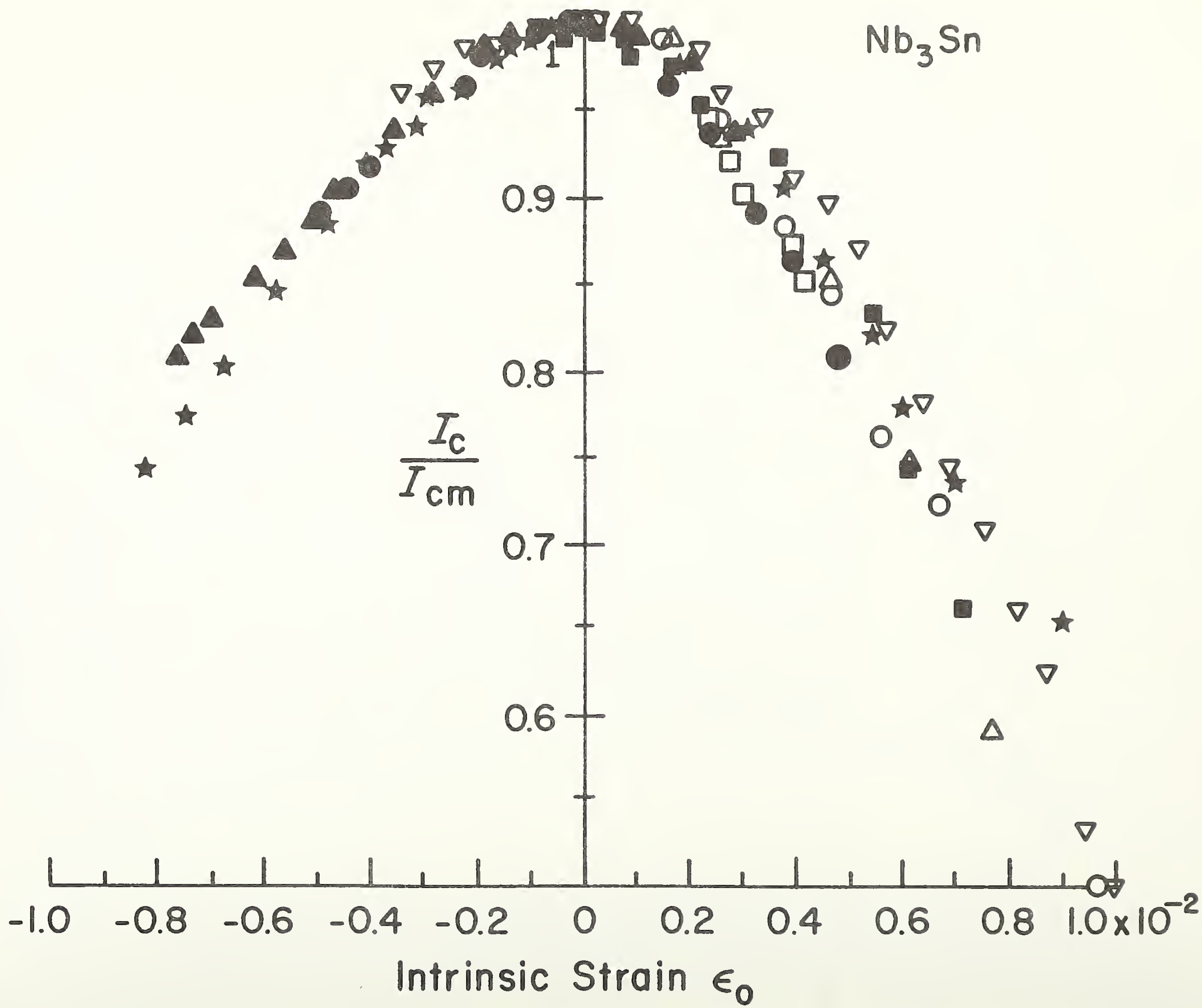


Fig. 15. Effect of intrinsic strain on the critical current of commercial multifilamentary Nb_3Sn. From reference 8. I_{cm} is the maximum critical current.

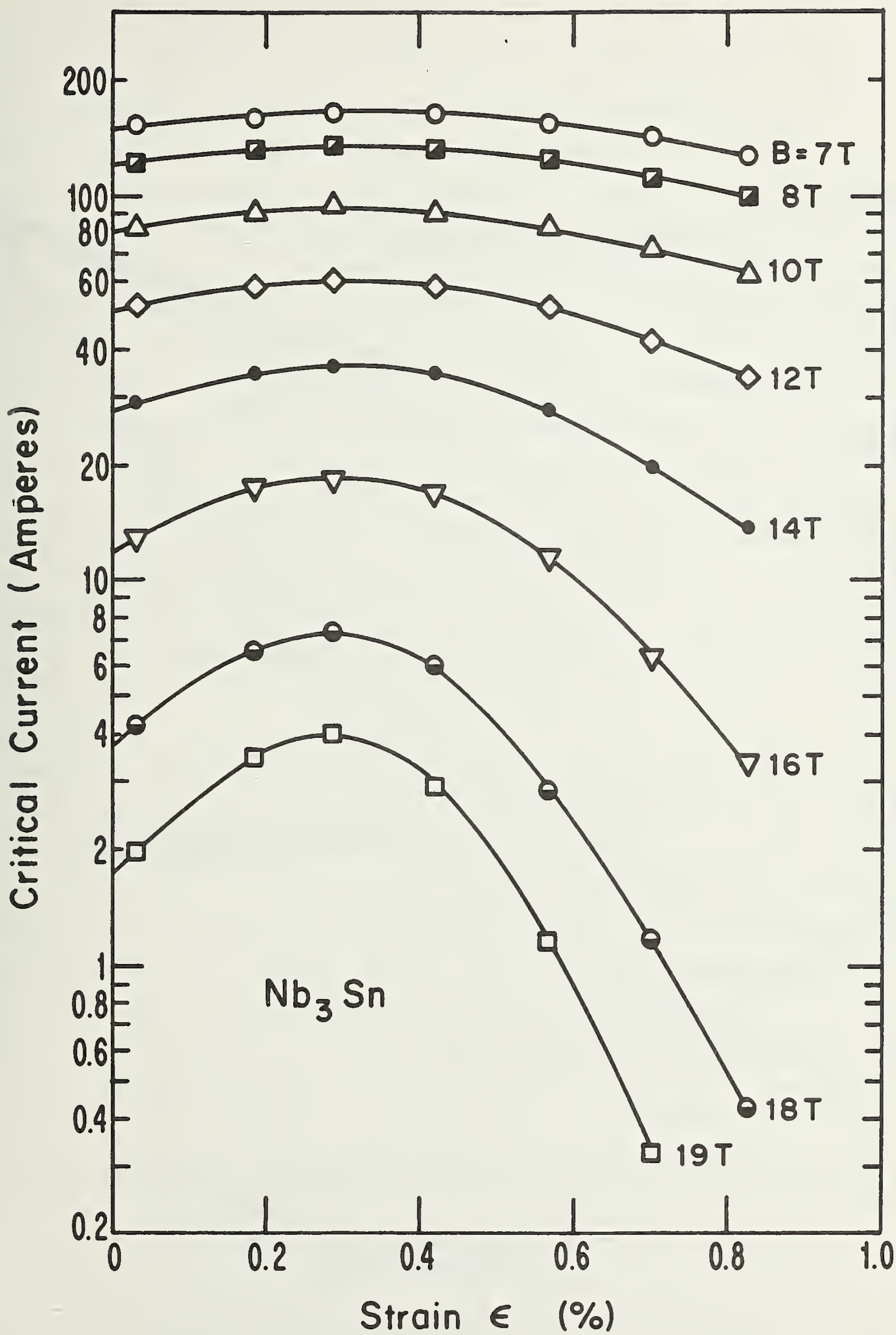


Fig. 16. Observed change in the effect of strain on the critical current of Nb_3Sn conductor at fields near the upper critical field. From reference 9.

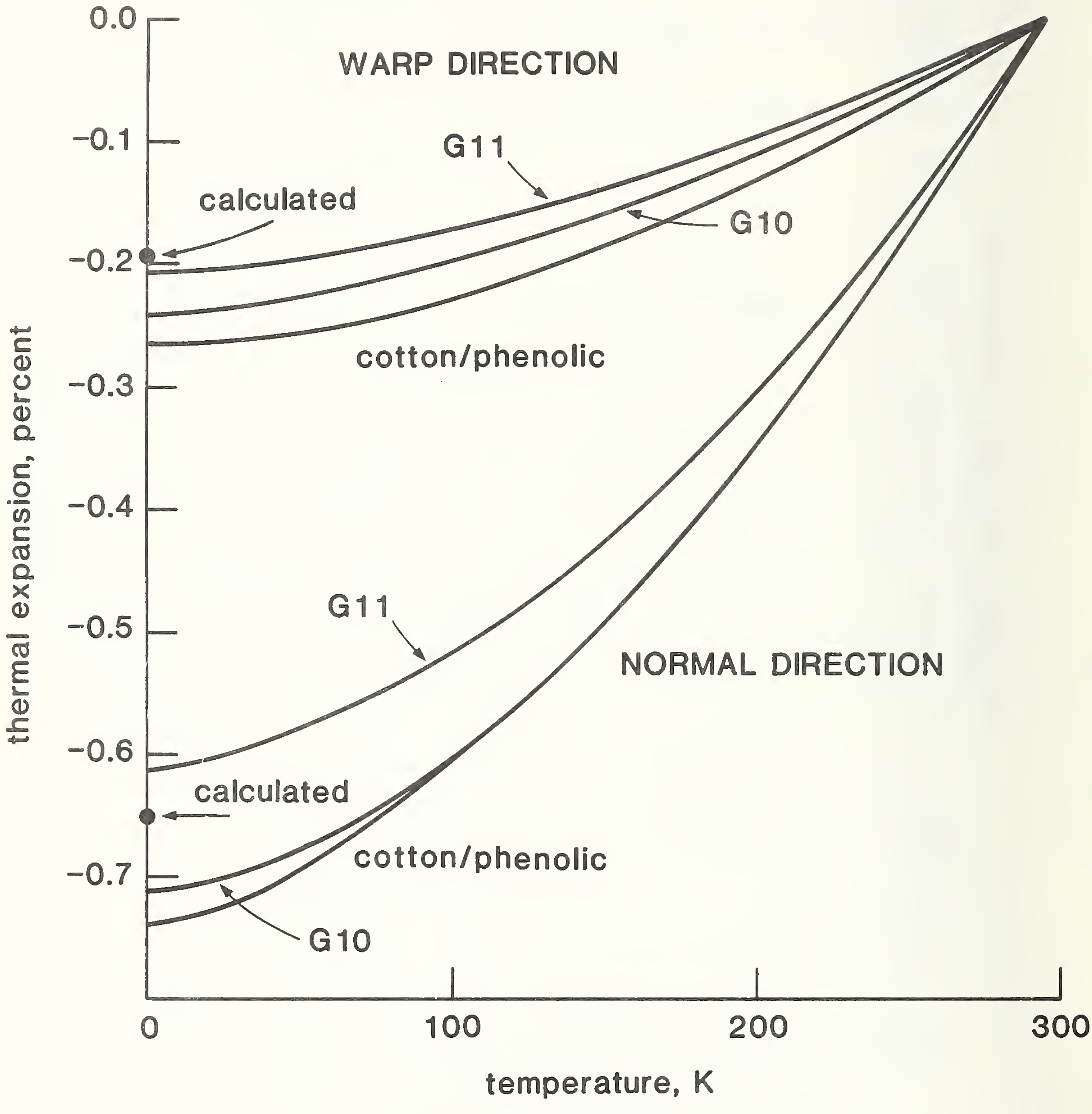


Fig. 17. Thermal contraction of nonmetallics used in sample holder construction. From reference 11.

reasonably well. Both the fiberglass-epoxy and the filled epoxies can withstand the heating required for making soft solder joints. An insulating electrical varnish soluble in alcohol-toluene is used for holding down voltage leads and other low stress, nonpermanent applications.

The Lorentz force is a serious source of strain because of the high currents and fields involved in critical current testing. The force on a conductor carrying 600 A in a 10 T field is 60 kg per centimeter of length. Also, because of the form of the dependence of I_c on H, this force reaches its maximum at relatively low fields for practical conductors. The problem is usually solved by laying the test sample in a fairly tight-fitting groove in the holder and orienting the sample with respect to the field so that the force is directed into the holder. There are experiments, such as rotation tests in the long straight geometry, where this solution cannot be used. In that case either a special holder is needed or one must use varnish or grease to hold the sample in place and the contraction precautions observed. This solution also has the potential of restricting the transfer of heat from the sample to the bath resulting in the self-heating effects described below.

Temperature

There are numerous ways by which heat can be introduced into the test specimen. Some of them have already been mentioned, such as contact heating, heating due to current transfer between filaments, and the intrinsic heating that occurs near I_c. In addition, rapidly varying the sample current or the magnetic field can introduce eddy current heating. The specific heat of all common materials is extremely low at liquid helium temperature and, thus, a small energy input can result in a large temperature excursion. The use of varnish and/or grease on the test sample for mechanical stability may result in lowered thermal stability as mentioned above. Reasonable care in making joints is generally all that is required for preventing thermal runaway.

There is a more subtle thermal effect that is more common. In this case, the V-I data are still "normal" in appearance and behavior, but the value of I_c is reduced by 1-4% depending on the criterion used (greatest reduction for high criteria) and on the magnetic field (greatest reduction for lower fields). Detection of this situation requires a careful examination of the V-I curve in the flux flow region. As we will see shortly, the voltage there is approximately proportional to I^n. Values of n cover a wide range in general, but for a given material n is reasonably constant. When the heating effect occurs, the value of n changes dramatically, becuase I_c is a function of temperature, which in turn is a function of where the sample is on the V-I curve. A typical example from our Nb_3Sn data: n = 23 for a normal run, but for a run with a relatively light coat of grease on the wire n $\geq$ 30 at the higher electric fields (within a factor of 5 of quench). A practical technique for avoiding this problem is to determine the sample voltage at quench and use a criterion that is well below that (factor of 5 or 10).

V. EXPERIMENT EXECUTION AND DATA ANALYSIS

The successful execution of a critical current measurement requires consideration of a number of points that do not exist in conventional resistivity work. Not the least of these is the definition of critical current. This is not a philosophical question, but a rather practical one involving the choice of an appropriate criterion of electric field or resistivity. Similarly, the voltages caused by currents travelling through the nonsuperconducting matrix must be treated with care in the data analysis. These problems and numerous other, more mundane ones are the subject of this section.

V-I Curve Measurement

The sample voltmeter shown in Fig. 5 may be either digital or analog. We have used both. The analog meter is a commercial nanovoltmeter. If a battery power supply is used for sample current, the noise level is down to ∿2 nV and this combination provides the greatest sensitivity. However, when an SCR regulated power supply is used, the SCR switching noise reduces the sensitivity of the nanovoltmeter to ∿100 nV. In this case it offers no advantage over the digital voltmeter. Our measurements of I_c using the two meters (with the SCR current supply) agreed to within 0.5%.

The choice of a criterion to define the point on the V-I curve where the critical current is reached is most often determined by the potential application of the conductor. Large, high field conductors may use relatively high criteria, while conductors for NMR magnets may require very low values.

The criterion may be stated in terms of either electric field or resistivity. The electric field criterion indicates the voltage drop per unit length of the superconductor in the flux-flow state at the critical current. Typical values range from 0.1 to 10 μV/cm for conductors with critical currents of less than 600 amperes. The resistivity criterion refers to the effective resistivity of the superconductor in the flux-flow state, i.e., the voltage drop per unit length divided by the current per unit area. Typical values for the resistivity criterion range from 10^{-12} to 10^{-10} Ω·cm using the total cross-sectional area of the conductor. One problem with the resistivity criterion is deciding what cross-sectional area to use to calculate the resistivity. The case of a NbTi conductor is fairly simple, either the total area of the conductor, or that of the NbTi alone is used. For a Nb_3Sn conductor the area used may be: the total area of the conductor; the non-copper area (which may include the area of the diffusion barrier, bronze, Nb, and Nb_3Sn); the area of the Nb and Nb_3Sn; or the area of the Nb_3Sn alone. The determination of some of these areas involves extensive metallography and statistical techniques, which means it is difficult and very time consuming. For our multifilamentary Nb_3Sn superconductor, the total cross-sectional area is about 14 times that of just the Nb and Nb_3Sn. The critical current values determined at 7 tesla using a resistivity criterion of 10^{-11} Ω·cm and these two areas differ by about 19%.

We choose to use the electric field criterion. It does not penalize highly stabilized conductors and it can easily be converted into an equivalent resistivity criterion using the total cross-sectional area of the conductor. One should note that a given electric field criterion does not correspond to the same resistivity criterion at all values of magnetic field. At high fields a given E_c corresponds to a larger value of resistivity than at low fields. This could be a problem very near to the upper critical field, H_{c2} (because every conductor will show a finite critical current for any value of E_c), but most practical applications are restricted to upper fields of 0.8 H_{c2} or less.

The effect of choice of criterion on the value measured for the critical current is shown in Fig. 18 for NbTi and in Fig. 19 for Nb_3Sn. These plots illustrate how I_c scales with criteria and magnetic field where I_{co} is the critical current at 0.1 μV/cm for NbTi and 1 μV/cm for Nb_3Sn. The irregular shape of the curves at the lower criteria reflect the uncertainty of those values. These data were taken using a coil sample in order to minimize the current transfer voltages that must be subtracted out at the lower criteria. Clearly, there is a systematic variation with criterion as one would expect from the shape of the V-I curve. For both conductors there is only a slight dependence on field for values likely to be encountered in a reasonable test (use of NbTi at fields >8 T is not common at 4 K, nor is the use of criteria <10 nV/cm).

The behavior shown in the figures is another manifestation of the power law dependence

$$E \propto I^n \qquad (2)$$

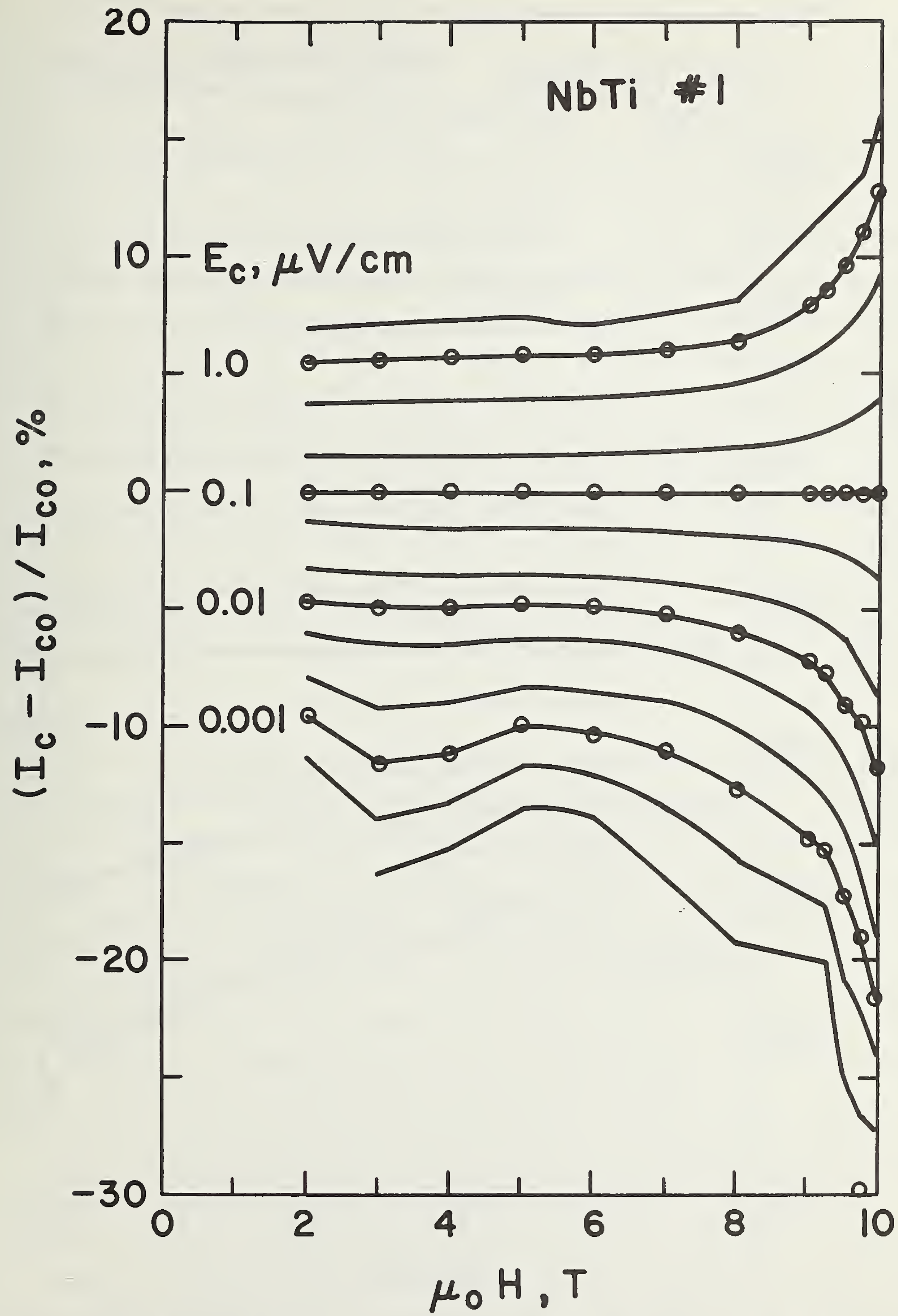


Fig. 18. Dependence on the critical current of NbTi conductor (# 1) on magnetic field for various electric field criteria (1, 2, 5 sequence). The vertical axis is normalized to I_c at 0.1 μV/cm, I_{co}.

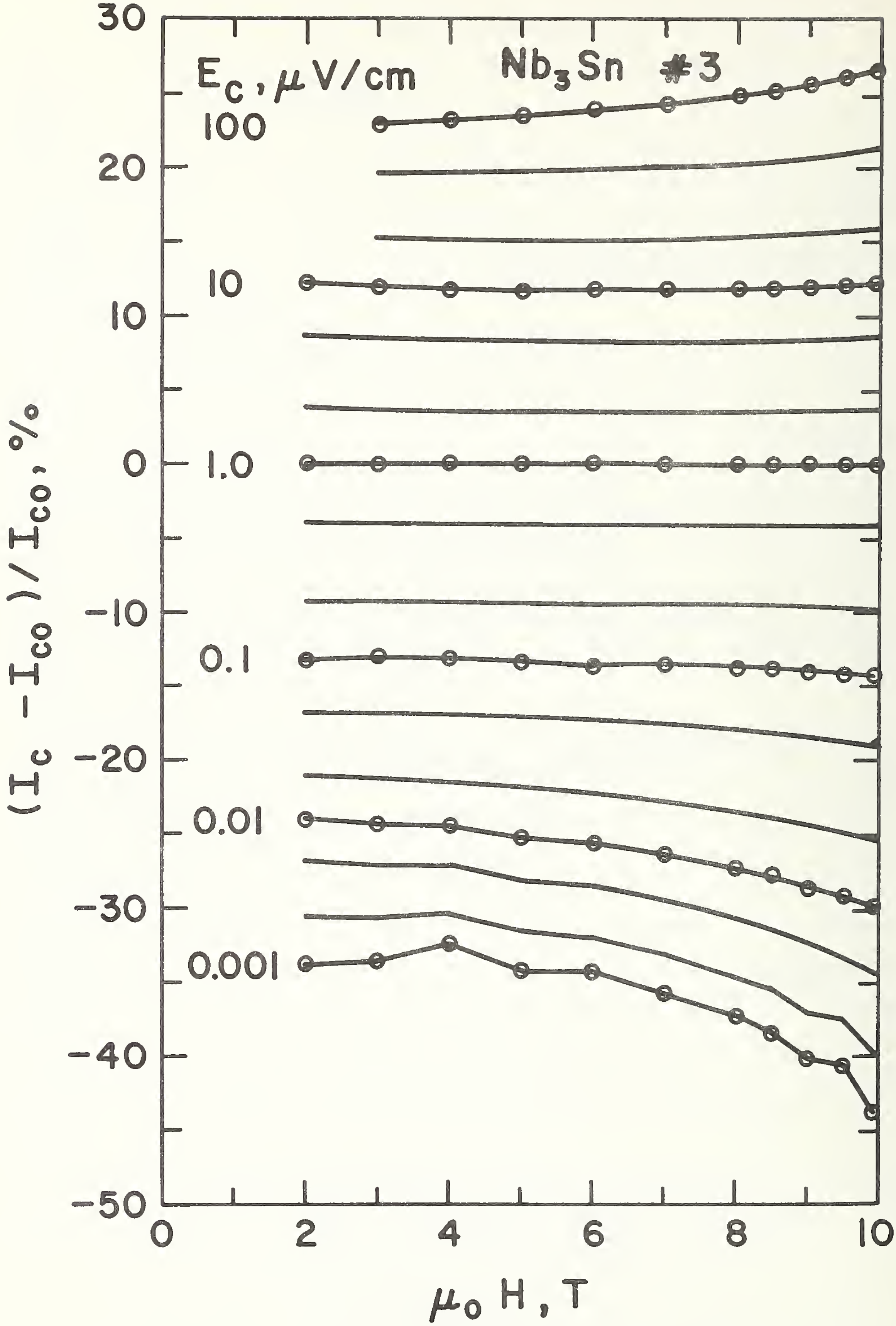


Fig. 19. Dependence of the critical current of Nb_3Sn conductor (# 3) on magnetic field for various electric field criteria (1, 2, 5 sequence). The vertical axis is normalized to I_c at 1.0 μV/cm, I_{co}.

in the flux flow region that was mentioned earlier. The sharper the transition (large n), the smaller the effect of choice of criterion on the critical current value obtained. Evaluation of n is not a critical part of a normal experiment, but knowledge of its expected behavior is helpful in analyzing problems, such as sample heating. In addition, a well-characterized n of a particular sample could be used to extrapolate to a lower criterion than can be achieved in another measurement. Selected data from our samples are given in Table 4. Very similar values of n will be obtained if one uses critical current data based on a resistivity criteria. The NbTi data (sample #1) are plotted in Fig. 20. The uncertainty in the value of I_c at the lower criteria cause the irregular shape of n calculated using those values. The conclusion to be drawn here is that each material has a value of n associated with it that depends somewhat on the criterion chosen and on the magnetic field. The value decreases, usually slightly, with increasing field. Values of n generally lie between 20 and 100. Variations of 10 to 20% in the value of n do not reflect significant change in the shape of the V-I curve. Significantly higher or lower ones nearly always indicate a problem in the measurement.

Current

The usual measurement technique involves establishing a constant magnetic field and ramping the sample current to trace out the V-I curve. Generally the ramp rate chosen is relatively slow (a few minutes to I_c), but even under these conditions voltages may be induced in the leads to the sample voltage taps during sensitive measurements. The technique for evaluating the magnitude of this effect is to stop part way up the V-I curve and start the current decreasing at the same rate for a few amperes. The (usually small) loop traced out measures the dI/dt signal. The effect can be minimized by carefully twisting all voltage lead pairs and providing minimum area at the sample itself. This latter consideration is especially important in the inductive coil geometry, where the voltage leads should be co-wound with the sample.

Ripple or SCR spikes on the current supply can make measurements at very low criteria impossible, as we discussed in the last section. At more reasonable criteria, however, these disturbances have no significant effect on the results, as shown in Fig. 21, which compares data taken with a zero-ripple battery supply to those with a commercial 600 A SCR supply. The agreement between these two was within the precision of the measurement (±0.2%) except

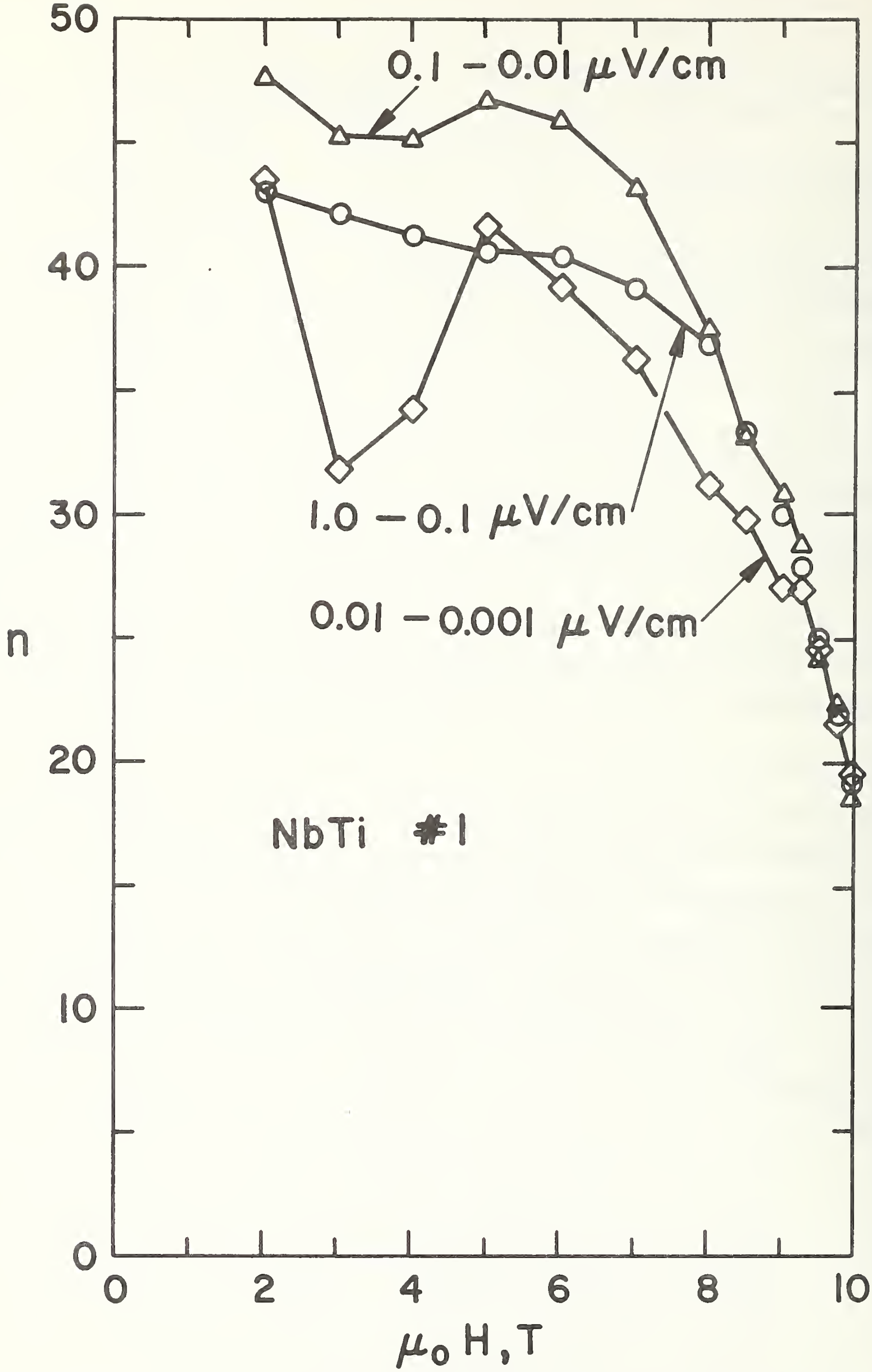


Fig. 20. Behavior of the exponent, n, as a function of magnetic field for various ranges of the electric field criterion. The sample is NbTi (# 1) in a coil configuration.

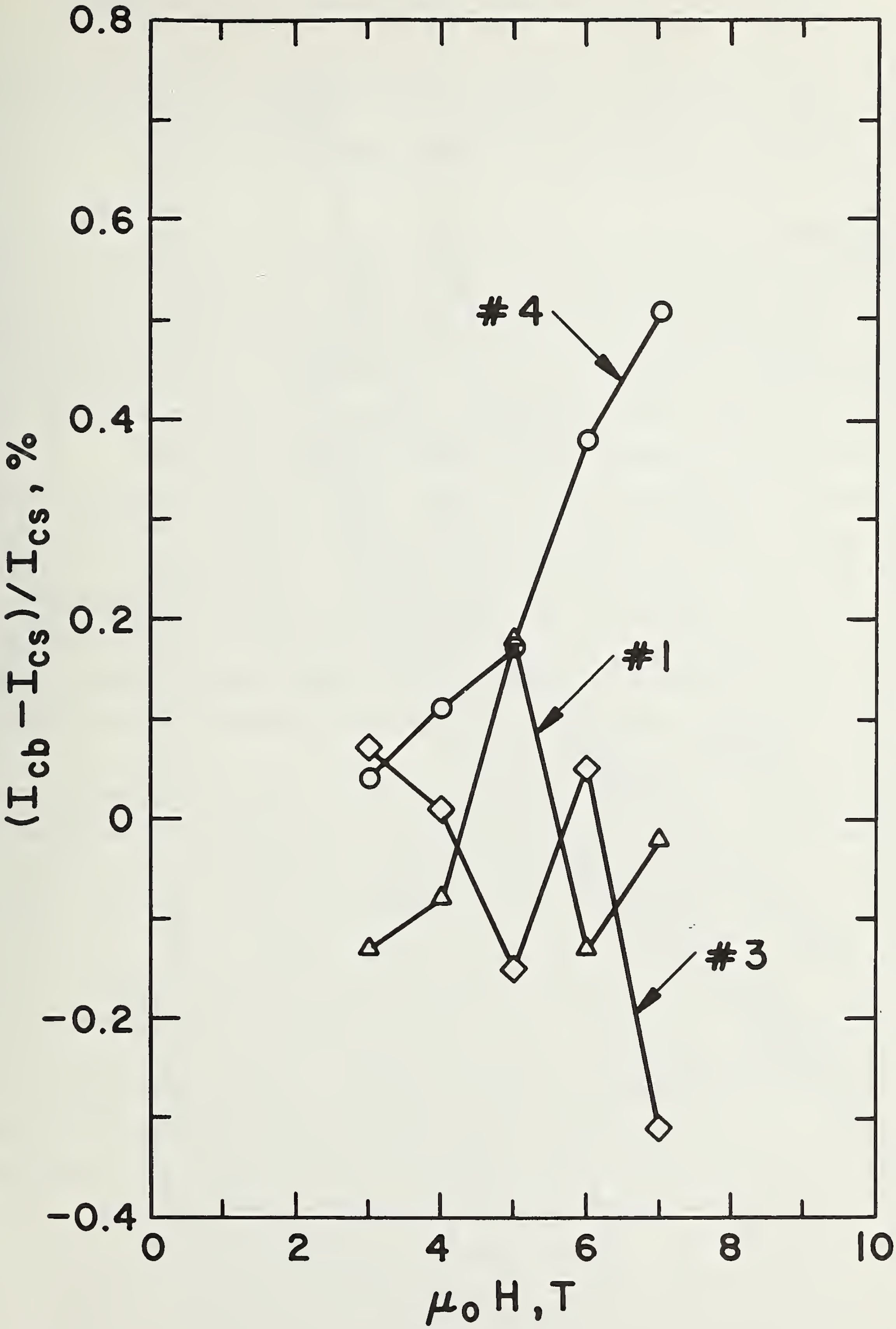


Fig. 21. Relative critical current values determined using a battery power supply (I_{cb}) and an SCR regulated one (I_{cs}). Samples are identified in Table I.

for the Nb_3Sn tape sample. The Nb_3Sn tape was expected to be the worst case in this comparison because of the higher ac loss of this type of sample and it may be showing this effect, but it was only 0.5% at 7 T.

Magnetic Field

There are sources of extraneous signals related to time variation of the magnetic field such as ripple and drift of the magnet supply. These are rarely a serious problem in a conventional measurement. The prescription for minimizing them is, as above, to create a minimum loop area in the various leads. Coil samples offer the greatest potential for problems here and, for very precise work, a noninductively wound sample may be required.

Because of the shape of the curve of critical current vs. magnetic field for practical conductors, small errors in field measurement can result in relatively large errors in the critical current. The dependence of I_c (E_c = 0.1 μV/cm) on magnetic field for our test samples is illustrated in Fig. 22. In preparation for a series of measurements the field and field profile of the magnet should be measured. The field should be known to ±1% and should not vary by more than that over the measurement region of the sample, i.e., between the voltage taps.

The concept of self field is often mentioned. This field is the one that is produced by the sample current. Figure 23 illustrates the self-field effect on a representative row (a-e) of twisted filaments in a conductor. Suppose that, if the filaments were not twisted, these five filaments could carry a total of 100 A (16, 18, 20, 22, and 24 A) with a flux-flow electric field of 1 μV/cm. If the filaments are twisted the critical current of each twisted filament will depend on its position relative to the magnetic field profile (greatly exaggerated to show this effect). Then current above 88 A will have to transfer through the normal matrix to redistribute among the filaments and an additional electric field will result depending on the twist length and current transfer characteristics of the conductor. The additional current transfer voltage will cause a reduction in the critical current for a given criterion, i.e., the total electric field will reach 1 μV/cm at a current less than 100 A. This is analogous to the bending strain effect where the spatial strain causes a spatially dependent current density. In conductors of the size considered here the magnitude of the self-field effect is small. Furthermore, the effect is similar in both the I_c measurement and in most

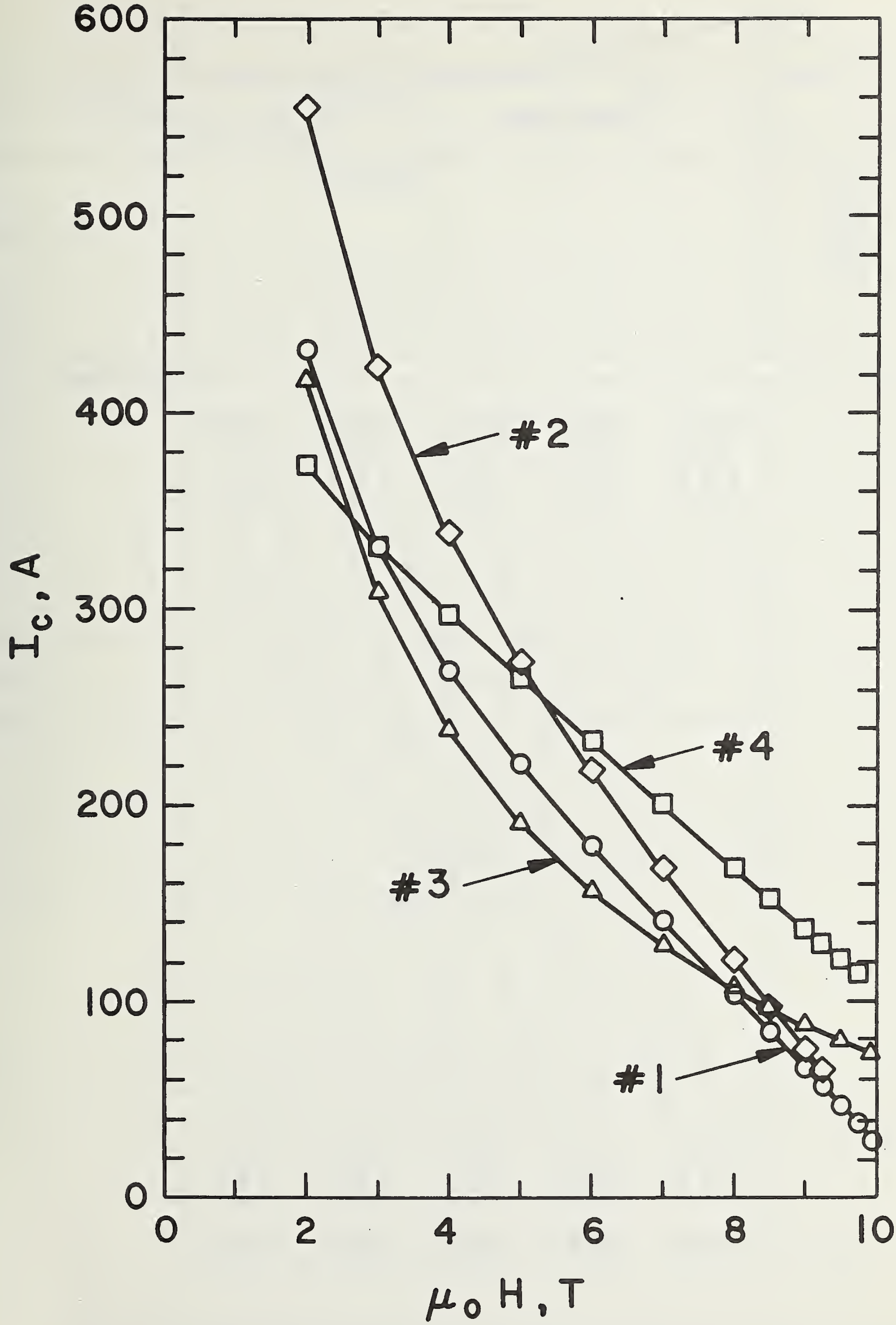


Fig. 22. Magnetic field dependence of the critical current for the samples of Table 1.

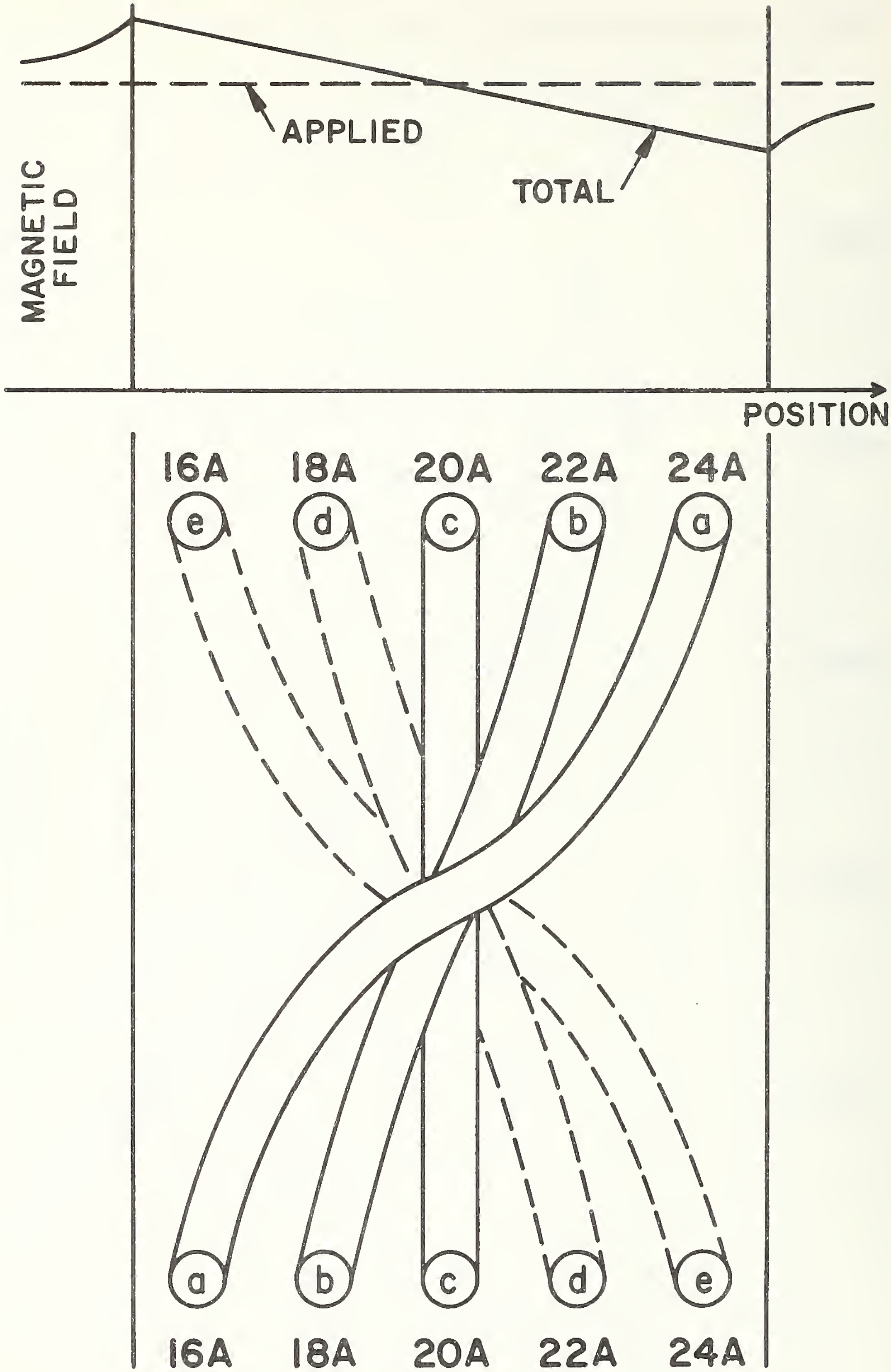


Fig. 23. Schematic of self-field effect showing a representative row of twisted filaments in a conductor, their critical currents and exaggerated field profile.

applications. In very large conductors made up of cabled and/or fully transposed strands in various cross-sectional shapes, the effect could be important when attempting to predict the behavior from that of a single strand.

Temperature

The effect of bath temperature on the critical current is one of the least well appreciated aspects of this type of measurement. It is our contention that a meaningful report of I_c data for commercial use requires a statement of the sample temperature to ±0.5%. Usually the assumption is made that the sample temperature is that of the bath and, in most cases, that seems to be adequate. The temperature of the liquid helium depends on the ambient pressure. The small additional pressure in the dewar caused by hydrostatic pressure and the use of vapor-cooled current leads is not usually significant ($\lesssim$ 10 mK) but could become so if the leads are partially blocked. Typical atmospheric pressure variations over the course of a year (typhoons, hurricanes, and tornados excluded) translate to bath temperature variations of about ±20 mK. To avoid problems it is recommended that the pressure in the dewar be monitored during the measurement. The bath temperature can then be determined from standard tables.[12]

Some justification is required for the above "hard line" on this subject. Extensive data have recently been presented on both NbTi and Nb_3Sn by two groups.[13,14] The basic result of these papers is that the critical current is observed to be related to the temperature by

$$I_c \propto (T_c^* - T) \quad (3)$$

where T_c^* is the bulk critical temperature at a given field. T_c^* is usually determined by extrapolating $I_c(T)$ (for temperatures near the temperature of interest) to zero. The intercept is defined as T_c^*. At high fields the value of T_c^* can be quite low. Data on multifilamentary wires of NbTi give T_c^* = 5.4 K at 8 T[13] and 8.4 K for multifilamentary Nb_3Sn at 12 T.[14] Especially at high fields, the variation in bath temperature from day to day can be a significant fraction of the quantity $T_c^* - T$ and thus have a large effect on the I_c measurement.

Another temperature-related consideration is the minimization of thermoelectric voltages that occur because of the large temperature gradients encountered by the voltage leads in a typical experiment. These voltages can be greatly reduced by proper thermal anchoring of the leads in the region of the sample[15] and by the use of continuous copper wires from the sample to the voltmeter input. This involves making feedthroughs for the top plate of the cryostat. Using this technique the thermoelectric voltages can be reduced to the order of several tens of nanovolts and, more importantly, they tend to remain constant over the time required to make a measurement.

Current Transfer

This topic has been mentioned several times already. It can be a problem in even the best designed experiment in that it introduces current-dependent voltages of significant size. Frequently one has no choice but to try to remove these extraneous signals during the data analysis. The voltages arise because current flows through the normal metal stabilizer of the superconductor in the process of attaining an equilibrium distribution. The situations that lead to this current flow may result from a number of causes. Current entering the sample from the bus bar is a major source of transfer voltage (such as that encountered in the short geometry) as illustrated for the low current parts of the V-I curves in Fig. 8. In addition, transit through a region of field gradient (such as that encountered in the long geometry) or, similarly, a change in the direction of the current path with respect to the field (such as that encountered in the hairpin geometry) will cause current redistribution regardless of the length of the sample in the low or parallel field region. The situation is further complicated by the twist of the superconducting filaments that may result in negative current transfer voltages, i.e., the transferring current is apparently flowing against the voltage gradient. While all this has been explained in the references previously listed, it is another matter to properly handle data that contain these voltages.

Simply put, the data analysis problem is to subtract off the current transfer voltage so that the chosen electric field criterion can be applied to the intrinsic V-I curve. When the current transfer voltage is a small fraction of the total signal at I_c, there is clearly no problem. Also, for relatively insensitive measurements, such as are often encountered in routine testing, the current transfer voltage can usually be approximated by a straight line at low current and thus easily extrapolated out to the I_c region. In other cases where the voltage is not linear with current and is of significant size, a reasonable approach is to plot log V versus log I similar to Fig. 8 which should result in a break in slope between the current-transfer region and the intrinsic flux-flow region. The lower current transfer portion can then be approximated by a straight line (power law) and subtracted from the data. This was done for the data presented here and the slope of log V versus log I in the current transfer region was as high as 2 to 3. If a large number of samples are involved, this technique may not be feasible and a change in experimental design is suggested. In any case, however, when the current transfer voltage is large compared to the criterion, it is easy to over or underestimate the current transfer contribution and get erroneous results. This is illustrated by the variation in I_c shown in Table 3 for the different sample holders (see Fig. 8 also). If very precise data are required it is best to go to a coil sample.

VI. SUMMARY

The data and discussion presented in the previous sections should allow one to construct an apparatus and carry out a successful critical current measurement. Clearly, several levels of sophistication can be achieved and the choice is really one of money, time, and needs. Table 5 provides a summary of the suggested accuracies for the various parameters and their effect on the final measurement. In some cases (e.g., uniformity and angle of H) these figures assume that the conditions are not at the extreme limit for the total length of the sample between the voltage taps. The resulting error from all sources listed is <5%.

Table 5. Tolerance for Critical Current Variables

Variable	Suggested Uncertainty, %	Resultant ΔI_c, %
I	1	1
I, ripple	5	1
E_c	12 (10% ℓ, 6% V)	1
H	1	2.5
H, ripple	1	0.5
H, uniformity	2	1.5
H, angle	7°	1
T	0.5	1
ε, bending	0.1 Nb_3Sn 2 NbTi	2
ε, tensile	0.05 Nb_3Sn 0.5 NbTi	2

We should reemphasize that the work presented here is for relatively small conductors with I_c < 600 A. The very large conductors now available present a few additional problems that have not been addressed such as complicated strain configurations, internal motion, large self fields, and probably complex voltage patterns in the flux flow region. In any event, the average laboratory is not equipped to handle conductors of this size and those few that are, should be well aware of the problems.

There are two further developments that we feel would contribute greatly to the critical current measurement. A more thorough understanding of stability in practical composites and the availability of a "standard" multifilamentary superconductor for evaluating new apparatus and maintaining the accuracy of frequently used systems. Both of these topics are now being investigated at NBS.

VII. ACKNOWLEDGMENTS

The help and support of the remainder of the Group at NBS, especially A. F. Clark and J. W. Ekin are gratefully acknowledged. The ASTM committee B01.08 on Superconductors has provided guidance and served as a sounding board for many of the ideas presented here. The support and interest of D. Sutter and D. Beard of DoE and P. Marston of MIT made this work possible. Ms. V. Grove once again made production of the finished manuscript a painless operation.

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Table 3a. Comparison of Critical Current Data for Various Sample Geometries as a Function of Magnetic Field and Criterion for a NbTi conductor. (Entries give percent difference with respect to the coil I_c.)

	Field, T	2	3	4	5	6	7	8	9
E_c = 1 μV/cm	Coil, I_c	455.2	350.7	284.6	234.3	190.4	150.4	111.3	72.3
	Long	---	-1.3	-1.1	-0.8	-0.6	-0.3	---	---
	Hairpin	0.6	0.5	0.6	0.6	1.0	1.0	1.4	---
	Short	0.3	0.6	0.7	0.8	1.4	1.5	2.1	2.3
E_c = 0.1 μV/cm	Coil, I_c	431.5	332.0	269.2	221.4	179.8	141.8	104.6	67.0
	Long	---	-1.4	-1.3	-1.0	-0.6	-0.4	---	---
	Hairpin	1.3	1.2	1.4	1.4	1.8	1.7	1.9	---
	Short	0.3	0.8	0.9	1.1	1.5	1.5	2.1	2.5
E_c = 0.01 μV/cm	Coil, I_c	411.1	315.7	255.4	210.5	170.6	134.0	98.2	62.2
	Long	---	-2.6	-2.7	-1.9	-0.6	-0.3	---	---
	Hairpin	0.2	2.0	3.0	0.7	1.4	2.2	-0.2	---
	Short	-2.2	0.6	1.3	0.8	2.1	2.9	2.7	4.4

Table 3b. Comparison of Critical Current Data for Various Sample Geometries as a Function of Magnetic Field and Criterion for a Nb_3Sn Conductor. (Entries give percent difference with respect to the coil I_c.)

Criterion	Field, T	2	3	4	5	6	7	8
E_c = 10 μV/cm	Coil, I_c	539.1	397.4	307.9	247.3	202.9	167.4	139.4
	Long	-0.4	-1.4	-1.4	-1.6	-1.6	-1.3	---
	Hairpin	-2.2	-2.9	-2.7	-2.9	-3.3	-3.5	-3.7
	Short	-2.5	-2.4	-2.3	-2.3	-2.4	-2.3	-2.2
E_c = 1 μV/cm	Coil, I_c	480.4	354.8	275.5	221.4	181.4	149.7	124.6
	Long	2.2	0.7	0.3	0.0	-0.2	0.1	---
	Hairpin	-2.8	-2.3	-1.9	-2.4	-2.6	-2.9	-3.2
	Short	-10.7	-8.4	-6.2	-4.4	-4.7	-2.7	-1.3
E_c = 0.1 μV/cm	Coil, I_c	416.8	308.8	239.3	191.8	156.8	129.5	107.6
	Long	5.2	5.6	4.4	4.8	4.2	4.5	---
	Hairpin	-13.5	-12.3	-11.1	-12.5	-9.3	-10.0	-8.1
	Short	-18.9	-17.5	-15.8	-15.3	-17.7	-14.0	-11.5

Table 4. Values for n of the Test Sample.

Range of E, μV/cm / Field T	NbTi rectangular sample #1			NbTi round sample #2		Nb_3Sn MF sample #3			Nb_3Sn tape sample #4		
	1.0/0.1	0.1/0.01	0.01/.001	1.0/0.1	0.1/.01	10/1.0	1.0/0.1	0.1/0.01	10/1.0	1.0/0.1	0.1/.01
2	43.0	47.7	43.5	55.4	84.2	20.0	16.2	17.4	73.1	150	279
3	42.1	45.3	31.8	57.2	80.2	20.3	16.6	16.4	71.4	173	261
4	41.3	45.2	34.2	56.7	75.0	20.7	16.4	16.5	72.4	162	208
5	40.6	46.8	41.6	53.7	68.7	20.8	16.0	15.6	70.0	151	191
6	40.4	45.9	39.1	50.7	61.8	20.6	15.8	15.4	65.4	143	184
7	39.1	43.2	36.3	45.5	53.5	20.6	15.9	14.4	59.4	126	166
8	36.9	37.5	31.2	36.8	43.3	20.5	15.6	13.4	52.4	109	150
9	30.0	30.9	27.0	27.1	31.4	20.4	15.3	12.4	45.1	89	107
9.5	25.0	24.2	24.5	--	--	20.2	15.0	12.0	41.0	82	96
10	19.1	18.5	19.4	--	--	20.0	15.0	11.4	--	--	--

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APPENDIX A

ASTM
Subcommittee B01.08 on Superconductors

Monday, August 10, 1981, 3-6 pm

Council Room, Town & Country Hotel, San Diego, CA

AGENDA

1.	Description of ASTM Standards process	A. F. Clark
2.	Status of draft standards, vote results a) definitions of terms b) measurement of critical current	A. F. Clark
3.	Research report	F. R. Fickett and L. F. Goodrich
4.	Task committee discussion of negative ballots a) definitions b) critical current	 S. J. St. Lorant R. E. Schwall
5.	Discussion of new tasks a) large conductor critical current b) ac losses c) critical field d) stability e) monitoring adopted standards	A. F. Clark

Minutes - ASTM B01.08
Subcommittee on Superconductors
August 10, 1981 3:00 pm
Council Room, Town and Country Hotel, San Diego, CA

The meeting was called to order at 3:00 pm by the Chairman, A. F. Clark. After introductions, he outlined the approval process for any draft standard through the subcommittee ballot, main committee ballot, and finally the full ASTM society ballot and the requirements at each level and methods for resolving negative votes. The responses on subcommittee balloting on the two draft standards on definitions and critical current were as follows:

a) Definitions of terms for Superconductors

65% return 93% Affirmative

1 negative ballot, some comments and also suggestions from the ASTM Committee on Terminology

b) Critical current measurement for conductors for less than 600 amps

70% return 75% Affirmative

4 negative ballots (one late) and several comments

A summary of the objections from the negative ballots was prepared by the NBS staff along with recommended actions to be considered by the subcommittee (copy attached).

Fred Fickett (NBS) then outlined briefly all of the back-up research performed by the wire manufacturers, DoE, and NBS as resource information available for the subcommittee deliberations.

The task group chairman for the definitions, Steve St. Lorant (Stanford Linear Accelerator), led discussion of the criticism and corrections to the draft standard for definitions. The one negative ballot was easily resolved by changing H_c to H_{c2} and several other suggested changes were considered as improvements. The changes were adopted unanimously by the subcommittee.

The task group chairman for critical current, Bob Schwall (Intermagnetics General Corp.), then led the discussion on the negative ballots and other suggested changes to the critical current draft standard. These were done point by point through the standard and changes were either adopted or denied. Major changes included adding a bandwidth specification for periodic and random deviations, improving the criteria accuracy, relaxing the field homogeneity requirement, clarifying the role of a sample protection shunt during the measurement, and deleting the recheck requirement. Several non-negative ballot comments were also considered resulting in some minor additions for clarification. The changes were then reviewed and adopted unanimously by the subcommittee.

Steve St. Lorant and Bob Schwall were then urged to provide focal points for feedback on any problems or additions to the definitions and critical current standards, respectively. The NBS staff will incorporate the changes and send the revised standards to ASTM for the main committee ballots.

New tasks were discussed and it was decided that large conductor critical current, ac losses, and stability should take priority. The next step in critical current was decided to cover up to about 5000 amps and Bruce Strauss (Magnetic Corporation of America) agreed to provide a review of the state-of-the-art to this level. Loss measurement research is being initiated at NBS under the partial sponsorship of DoE and this work and stability will be discussed at the next meeting. Because of travel restrictions it was decided to continue to hold meetings in conjunction with superconductivity-related conferences whenever possible.

List of Attendees
ASTM B01.08 Subcommittee on Superconductors

Name	Address
Don Beard	DoE, Germantown, MD
Karl-Juergen Best	Vacuumschmelze GmbH, Hanau, FRG
Al Clark	NBS, Boulder, CO 80303
Fred Fickett	NBS, Boulder, CO 80303
Loren F. Goodrich	NBS, Boulder, CO 80303
Moyses Kuchnir	Fermilab, Batavia, IL 60510
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APPENDIX B
DRAFT STANDARD FOR TERMINOLOGY

ASTM Designation B XXX-82

Standard Definitions of Terms Relating to SUPERCONDUCTORS

This standard is issued under the fixed designation B XXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval.

aspect ratio - ratio of the longer to the shorter transverse dimensions of a rectangular composite superconductor. NEW

barrier - any material limiting passage through itself of solids, liquids, semisolids, gases, or forms of energy such as ultraviolet light. F 17, F-2*

braid, n - a narrow tubular or flat fabric produced by intertwining strands of materials according to a definite pattern. D 123, D-13

cable (concentric lay conductor) - conductor constructed with a central core surrounded by one or more layers of helically laid wires. Several types are as follows:

compact round conductor - a conductor constructed with a central core surrounded by one or more layers of helically laid wires and formed into final shape by rolling, drawing, or other means.

conventional concentric conductor - conductor constructed with a round central core surrounded by one or more layers of helically laid round wires. The direction of lay is reversed in successive layers, and generally with an increase in length of lay for successive layers.

equilay conductor - conductor constructed with a central core surrounded by more than one layer of helically laid wires, all layers having a common length of lay, direction of lay being reversed in successive layers.

parallel core conductor - conductor constructed with a central core of parallel-laid wires surrounded by one layer of helically laid wires.

rope-lay conductor - conductor constructed of a bunch-stranded or a concentric-stranded member or members, as a central core, around which are laid one or more helical layers of such members.

unidirectional conductor - conductor constructed with a central core surrounded by more than one layer of helically laid wires, all layers having a common direction of lay, with increase in length of lay for each successive layer.

unilay conductor - conductor constructed with a central core surrounded by more than one layer of helically laid wires, all layers having a common length and direction of lay. B 354, B-1

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*The numbers indicate that the definition is taken directly from the Compilation of ASTM Standard Definitions, 4th edition, 1979 and cite the standard in which it is used (e.g. D 2864) and the subcommittee with jurisdiction (e.g. D-27). If new for this standard it is designated NEW.

component - an individual piece or a complete assembly of individual pieces. F 303, F-7

composite conductor - a conductor consisting of two or more types of material, each type of material being plain, clad, or coated; assembled together to operate mechanically and electrically as a single conductor. NEW

composite superconductor - a conductor incorporating superconductive material. Some types are as follows:

composite conductor - see composite conductor.

coreless conductor - a conductor constructed of one or more layers of helically laid wires and formed into final shape by rolling, drawing, or other means.

tape - a conductor constructed in the form of a flat ribbon or strip.

tubular conductor - a conductor constructed in the form of a tube.

hollow conductor (also tubular conductor) - a conductor in which the individual elements are disposed about one or more hollow passages, the direction of which is along the axial length of the conductor. NEW

composition - the quantity of each of the components of a mixture; usually expressed in terms of the weight percentage, or the atomic percentage of each of the components in the mixture. E 7, E-4

conductivity, electrical - the ratio of the current density carried through a specimen to the potential gradient paralleling the current. This is numerically equal to the conductance between opposite faces of a unit cube of material. It is the reciprocal of resistivity. D 2864, D-27

conductor - a wire or combination of wires not insulated from one another, suitable for carrying an electric current. B 354, B-1

critical current, I_c - the maximum electrical current below which a superconductor exhibits superconductivity at some given temperature and magnetic field. NEW

critical current density, J_c - the critical current divided by the total cross-sectional area of the conductor. NEW

critical magnetic field strength, H_{c2} - the maximum magnetic field below which a superconductor exhibits superconductivity at zero current and temperature. NEW

critical temperature, T_c - the maximum temperature below which a superconductor exhibits superconductivity at zero magnetic field and current. NEW

critical transition temperature - see transition temperature.

current, constant, I_{dc} - the steady current which is located in a winding and which produces a magnetostatic condition. A 340, A-6

current density (cd) - current per unit area. B 374, B-8 diamagnetic material - a material whose relative permeability is less than unity.

Note - The intrinsic induction, B_i, is oppositely directed to the applied magnetizing force H. A 340, A-6

filamentary (multifilamentary) superconductor - a composite superconductor consisting of at least one superconductive wire embedded in a matrix. NEW

flux density - see magnetic induction.

fully transposed conductor - a conductor in which every strand occupies every relative position in the conductor at regularly specified intervals along its length. NEW

magnetic field strength - the measured intensity of a magnetic field at a point, usually expressed in. E 269, E-7

magnetic flux, ϕ - the product of the magnetic induction, B, and the area of a surface (or cross section), A, when the magnetic induction B is uniformly distributed and normal to the plane of the surface.

$$\phi = BA$$

where:
ϕ = magnetic flux,
B = magnetic induction, and
A = area of the surface.

Note 1 - If the magnetic induction is not uniformly distributed over the surface, the flux, ϕ, is the surface integral of the normal component of B over the area.

$$\phi = \iint_s B \cdot dA$$

Note 2 - Magnetic flux is a scalar and has no direction. A 340, A-6

magnetic flux jump - the collective, discontinuous motion of magnetic flux lines in a superconductor, produced by mechanical, thermal, magnetic, or electrical disturbances. NEW

magnetic flux pinning - the trapping of magnetic flux lines at defects in the superconducting material. NEW

magnetic induction (also flux density), B - that magnetic vector quantity which at any point in a magnetic field is measured either by the mechanical force experienced by an element of electric current at the point, or by the electromotive force induced in an elementary loop during any change in flux linkages with the loop at the point.

Note 1 - If the magnetic induction, B, is uniformly distributed and normal to a surface or cross section, then the magnetic induction is:

$$B = \frac{\phi}{A}$$

where:
B = magnetic induction,
ϕ = total flux, and
A = area.

Note 2 - B_{in} is the instantaneous value of the magnetic induction and B_m is the maximum value of the magnetic induction. A 340, A-6

matrix of composite superconductor - the continuous longitudinal phase of a pure metal, a polyphase alloy or mechanical mixture that is not in the superconducting state at the normal operating conditions of the embedded superconductor. NEW

mixed matrix of composite superconductor - matrix composed of more than one component. NEW

normal state - the thermodynamic state in which a superconductive material no longer exhibits any of the characteristics of the superconducting state. NEW

quench - the abrupt and uncontrolled loss of superconductivity produced by a disturbance. NEW

stabilizer - a metal, but not necessarily the matrix, in electrical contact with a superconductor, to act as an electrical shunt in the event that the superconductor reverts to the normal state. NEW

strand, n - one of the wires of any stranded conductor. B 354, B-1

stranded conductor - a conductor composed of a group of wires, usually twisted, or of any combination of such groups of wires. B 354, B-1

superconducting - adjective describing a material exhibiting superconductivity NEW

superconducting state - the thermodynamic state in which the material exhibits superconductivity. NEW

superconducting transition - that combination of temperature, T, electric current density, J, and magnetic field, H, values at which a transition from the superconducting to the normal state takes place.

Note - A representation of this relationship is shown in the Figure 1. NEW

superconductive - adjective describing a material exhibiting the characteristics of normal conductivity, but which shows superconductivity under appropriate conditions. NEW

superconductivity - a property of many metals, alloys and chemical compounds by virtue of which their electrical resistivity vanishes and they become strongly diamagnetic under appropriate conditions. NEW

superconductor - a material that exhibits superconductivity under appropriate conditions. NEW tape - a composite superconductor in the form of a flat ribbon or strip. NEW

temperature - the thermal state of matter as measured on a definite scale. E 41, G 3

temperature, absolute - (a) temperature measured on the thermodynamic scale, designated as kelvins (K).
(b) Temperature measured from absolute zero (-273.15°C or -459.67°F). The numerical values are the same for both the Kelvin scale and the ideal gas scale. D 1356, D-22

transition temperature (also critical transition temperature) - the maximum temperature below which a superconductor exhibits superconductivity at a given magnetic field and current. NEW

transposed conductor - a composite conductor in which filaments or strands occupy different relative positions about the conductor axis in a regular manner. NEW

transposition length - the length in which a filament or strand returns to its original relative position in a transposed conductor. NEW

trapped magnetic flux - the magnetic flux retained in a superconductor when the applied magnetic field is reduced or reversed in direction. NEW

twist, n - the number of turns per unit length made by a filament or strand about a conductor axis. NEW

twist pitch (also twisted length) - the length in which a filament or strand returns to its original relative position in a twisted conductor. NEW

twisted length - same as twist pitch.

twisted conductor - a composite conductor in which the filaments or strands are displaced about the conductor axis. NEW

volume percent superconductor - that percentage by volume of a composite superconductor which is superconducting under normal operating conditions. NEW

wire - a rod or filament of drawn or rolled metal whose length is great in comparison with the major axis of its cross section. B 354, B-1

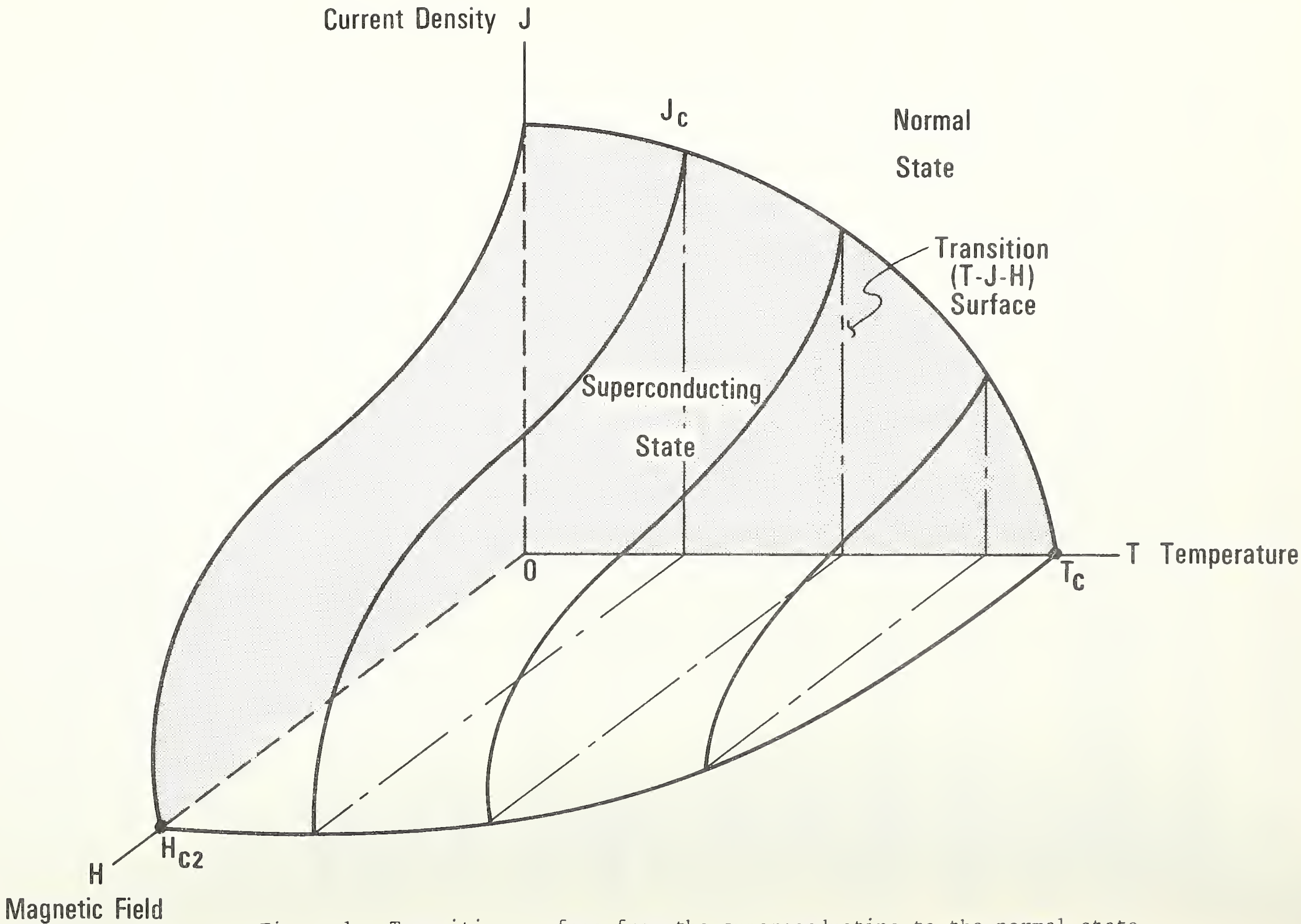

Figure 1. Transition surface from the superconducting to the normal state.

APPENDIX C
DRAFT STANDARD FOR CRITICAL CURRENT

ASTM Designation B XXY-82

Standard Test Method for DC CRITICAL CURRENT OF COMPOSITE SUPERCONDUCTORS

This standard is issued under the fixed designation B XXY; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval.

1. Scope

1.1 This method covers the procedure for the determination of the dc critical current of composite superconductors.

1.2 This method is intended for use with superconductors having a critical current of less than 600 amperes under test conditions and at magnetic fields of less than 0.8 of the upper critical magnetic field.

2. Applicable Documents

2.1 ASTM Standards
B XXX Definitions of Terms for Superconductors.
ASTM Standards on Metallic Electrical Conductors - Volume 23 (1982).

3. Summary of Method

3.1 A direct current is applied to the superconductor specimen and the voltage generated along a section of the specimen is measured. The current is increased from zero and the voltage-current characteristic is generated. The critical current is defined as the current at which a specified electric field is exceeded in the specimen.

4. Significance and Use

4.1 The critical currents of composite superconductors are used to establish design limits for applications of superconducting wires. The operating conditions of superconductors in these applications determine much of their behavior and tests made with this method may be used to provide part of the information needed to determine the suitability of a specific superconductor.

4.2 Results obtained from this method can also be used for detecting changes in the superconducting properties of a composite superconductor due to processing variables, handling, aging, or other application or environmental conditions. This method is useful for quality control, acceptance, or research testing if the precautions below are observed.

4.3 The critical current of composite superconductors depends on many variables. These variables need to be considered in both the testing and the application of these materials. (Ref. 1)

4.3.1 Test conditions such as magnetic field, temperature and relative orientation of specimen, current and magnetic field are determined by the particular application.

4.3.2 The test configuration may be determined by the particular conductor through the tolerances required by sections 8.1 and 8.4.

4.3.3 The specific critical current criterion may be determined by the particular application.

4.3.4 It may be appropriate to measure a number of test specimens if there are irregularities in testing.

4.4 A precaution is needed in the interpretation of results when the reference line of the V-I curve (8.5, 8.5.1) has a finite slope. The current transfer correction is to be used to correct for a true current transfer. Voltages may occur from other sources.

4.4.1 A current transfer voltage will result from having a voltage tap near (near is determined by resistivity of the matrix and electrical field criterion) to a current contact, or having a gradient in the magnetic field near the region between voltage taps or having a field-sample orientation change near the region between voltage taps. (Refs. 1, 2, and 3)

5. Terminology

5.1 Refer to B XXX Definitions of Terms for Superconductors for general terminology for the field of superconductivity.

6. Safety Precautions

6.1 Very large direct currents with very low voltages do not necessarily provide a direct personal hazard, but accidental shorting of the leads with another conductor, such as tools or transfer lines, can release significant amounts of energy and cause arcs or burns. Care must be taken to isolate and protect current leads from shorting. Also the stored energy in superconducting magnets commonly used for the background magnetic field can cause similar large current pulses or deposite large amounts of thermal energy in the cryogenic systems causing rapid boil off or even explosive conditions.

6.2 The use of cryogenic liquids is essential to cool the superconductors to allow transition into the superconducting state. Direct contact with cold liquid transfer lines, storage dewars, or apparatus components can cause immediate freezing, as can direct contact with a spilled cryogen. Normal safety precautions for the handling of cryogenic liquids must be observed.

7. Test Specimen

7.1 The test procedure is intended for specimens with a critical current of less than 600 amperes under test conditions.

7.2 There shall be no joints or splices in the test specimen unless otherwise specified.

7.3 The test specimen should, wherever possible, have the same residual strain state as the final product.

8. Procedure

8.1 The (maximum) bending strain, induced during mounting of the specimen, shall not exceed 0.1% for Nb_3Sn (and other brittle materials) or 2% for Nb-Ti (and other ductile materials). The tensile strain, induced by the differential thermal contraction of the specimen and holder, shall not exceed 0.05% for Nb_3Sn (and other brittle material) and 0.5% for Nb-Ti (and other ductile material). (Ref. 4)

8.1.1 Pre-reaction forming of brittle conductors to the test configuration may be required.

8.1.2 Matching the thermal contraction of the specimen and specimen holder may be required (Ref. 5). Suitable materials for construction of the specimen holder are NEMA G-10 and G-11 with the specimen in the plane of the fabric (Ref. 6).

8.2 Solder voltage taps to the specimen in accordance with the limits in 8.1, 8.3, and 10.7.2.

8.3 Measure the distance along the specimen between the voltage taps, L, to an accuracy of 10% or 50 mm, whichever is smaller.

8.4 The critical current, I_c, shall be determined by using an electric field criterion, E_c, of 100 μV/m unless otherwise specified.

8.4.1 There are other criteria that could be used (resistivity, power), but E_c is considered to be an expedient criterion (Ref. 7).

8.4.2 The specified E_c may be calculated on the basis of any other criteria if so desired.

8.5 Record the V-I characteristic of the test specimen under test conditions.

8.5.1 A valid V-I characteristic shall give I_c to a precision of 2% for both increasing and decreasing current. If a number of I_c measurements are to be made on a specimen at the same temperature, this current reversal test has to be performed for only the lowest magnetic field to be reported.

8.6 Draw a straight line through the lower current (less than 0.8 of the resulting I_c) portion of the V-I curve to serve as a reference line (see Fig. 1). Determine I_c by finding the point on the V-I curve where the voltage, measured relative to the reference line, is LE_c.

8.6.1 A finite slope of the reference line may be due to current transfer (Refs. 1, 2, and 3) and in that case the line serves as an approximate correction to this effect. A valid determination of I_c requires that the voltage of the reference line at I_c must be less than LE_c.

9. Report

9.1 Identification of test specimen should be made by the manufacturer's lot number. This number should insure unique identification. Subsequent processing not identified by the lot number should be reported.

9.2 The following test conditions shall be reported:

9.2.1 Test magnetic field,

9.2.2 Test temperature,

9.2.3 Length between voltage taps and total specimen length,

9.2.4 Test configuration (geometry, angle between the specimen axis and the magnetic field, orientation of specimen with respect to magnetic field if the specimen is rectangular).

9.3 Modified tolerances (per 10.2) shall be reported.

9.4 The value of I_c and E_c shall be reported.

9.5 For routine tests, report only such of the items above as apply.

10. Precision and Accuracy

10.1 The suggested tolerances listed below of the many variables affecting the critical current should provide an accuracy of 5% on test specimens having a critical current of less than 600 amperes under test conditions and at magnetic fields of less than 0.8 of the upper critical magnetic field. The individual test should have a precision of 2%.

10.2 Because of the large number of variables that affect the critical current (Ref. 1), the range of composite superconductors and the testing techniques, all of the tolerances listed below may not be considered appropriate or reasonable to obtain in all cases. In these cases, the appropriate sections may be modified. Any such modification shall be made part of the report.

10.3 The critical current shall be determined from a voltage-current characteristic measured with a four-terminal technique.

10.3.1 The current source shall provide a current having a maximum periodic and random deviation of less than ± 5% at I_c within the bandwidth 10 Hz to 10 MHz.

10.3.2 A four-terminal standard resistor, with an accuracy of at least 1%, shall be used to determine the sample current.

10.3.3 A recorder and necessary pre-amplifiers, filters and/or voltmeters shall be used to record the V-I characteristic. The resulting record should allow determination of E_c to an accuracy of 12% and the corresponding current to an accuracy of 1%, with a precision of 0.5%.

10.4 A quench protect circuit may be necessary to allow the positive completion of step 8.5.1 (Ref. 1).

10.5 A dewar will provide the necessary environment for measuring I_c. Unless otherwise specified, the specimen shall be measured immersed in liquid helium. The liquid temperature shall be reported to an accuracy of ± 0.5%.

10.6 A magnet system shall provide the magnetic field to an accuracy of 1% and a precision of 0.5%.

10.6.1 The magnetic field shall have a uniformity of ± 2% over the length of the specimen between the voltage contacts.

10.6.2 The maximum periodic and random deviation of the magnetic field shall be less than ± 1%.

10.7 The test fixture shall provide adequate support for the specimen and orientation of the specimen with respect to the magnetic field.

10.7.1 The specimen support is adequate if it allows for the positive completion of step 8.5.1.

10.7.2 The angle between the specimen axis and the magnetic field shall be determined to an accuracy of 7° for the length of the specimen between the voltage taps. Unless otherwise specified, the angle shall be 90 ± 7°.

10.7.3 In the case of a rectangular specimen, the magnetic field shall be parallel to the wide face of the specimen unless otherwise specified. The angle between the magnetic field and the wide face shall be reported to an accuracy of 7° for the length of the specimen between the voltage taps.

10.7.4 The test configuration of the specimen (straight, hairpin, bifilar coil, pancake coil, or solenoidal coil) will be chosen by the tester unless otherwise specified.

10.8 A shunt may be used to protect the specimen when the specimen is in the normal state as long as less than 1% of the current will flow in the shunt at I_c. The shunt will not be in immediate contact with the specimen unless otherwise specified.

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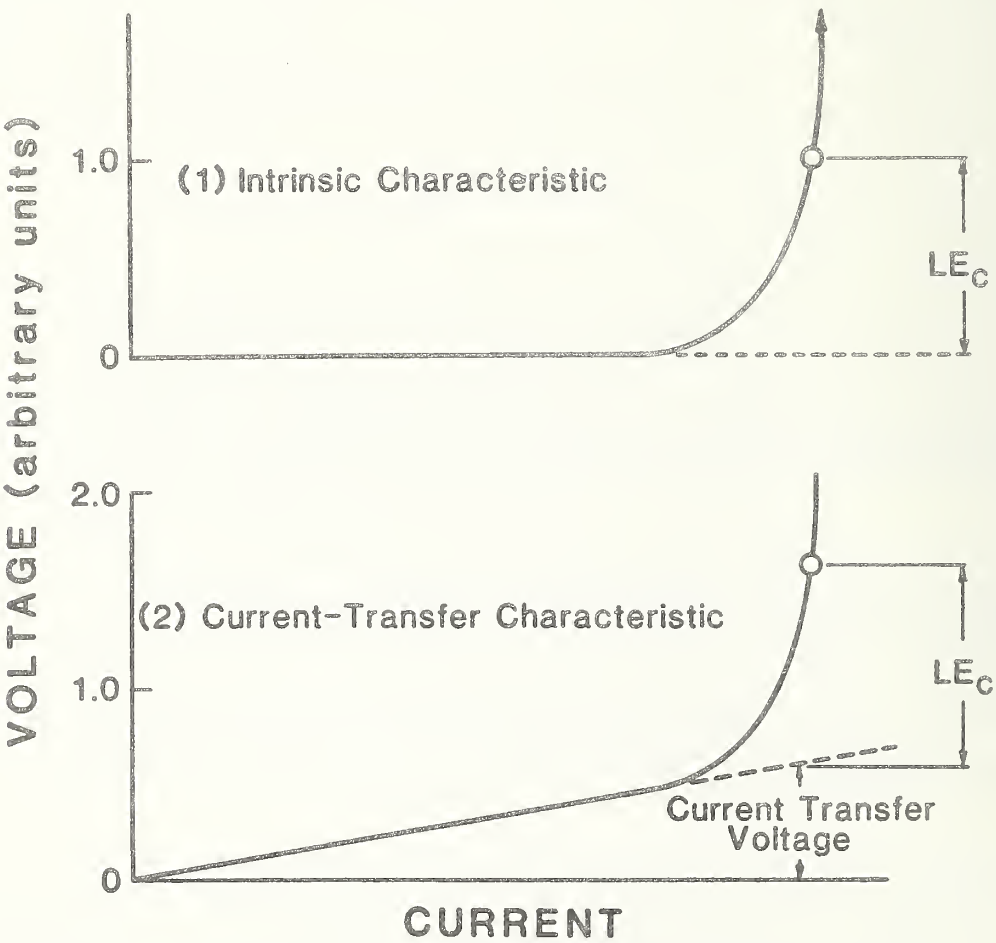

Fig. 1. Schematic representation of the composite superconductor's V-I characteristic in two regions: 1) Intrinsic characteristic showing the usual resistive transition as I approaches I_c and 2) current-transfer characteristic exhibiting a linear region at low current. The reference line described in section 8.6 is shown as the dashed line.

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10. SUPPLEMENTARY NOTES

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

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

A cooperative program with the Department of Energy, the National Bureau of Standards, and private industry is in progress to develop standard measurement practices for use in large scale applications of superconductivity. The goal is the adoption of voluntary standards for the critical parameters and other characterizations of practical superconductors. Progress for the period October 1980 through January 1982 is reported. The major effort was the development of a standard test method for critical current, the necessary back-up research, and the coordination of the adoption of the test method and a standard terminology through the subcommittee level in ASTM.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

critical current; critical parameters; losses; measurement methods; standards; superconductor.

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