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EMPIRICAL SCALING FORMULAS FOR CRITICAL CURRENT AND CRITICAL FIELD FOR COMMERCIAL NbTi*

M. S. Lubell
Fusion Energy Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

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Abstract

Short sample 4.2 K experimental facilities are plentiful, but equipment for measurements of current as functions of temperature and field is scarce. An analysis has been made of published data comprising at least six manufacturers and spanning a range of critical current density at 4.2 K, 8 T of 50 to 108 kA/cm^2, and linear equations have been found to fit the data over a wide range of field B and temperature T. For a constant temperature of 4.2 K, the following expression holds for B in the range of 3 to 10 T: $j_c(B, T = 4.2\ K) = j_o[1 - 0.096B]$, where $[B_{c2}(4.2\ K)]^{-1} = 0.096$ with a standard deviation of 3% for ten samples. The constant j_o can be determined for any sample from a *single point measurement* at a convenient field. For a constant field of 8 T, the following expression holds for T in the range of 2 to 5.5 K: $j_c(B = 8\ T, T) = j_o'[1 - 0.177T]$, where $[T_c(8\ T)]^{-1} = 0.177$ with a standard deviation of less than 1%. Linear equations have also been obtained for higher fields and lower temperatures. The critical field vs temperature is $B_{c2}(T) = B_{c2}(0)[1 - (T/T_c(0))^n]$, where $B_{c2}(0) = 14.5$ T, $T_c(0) = 9.2$ K, and $n = 1.7$ (not 2, which is used in theoretical derivations). For more accurate critical temperature calculations above 10 T, this equation can be used with the modification $B_{c2}(0) = 14.8$ T. No one simple power law for the upper critical field holds over the whole temperature range.

Introduction

In many superconducting magnet design projects, it is advantageous to perform a scoping study for the initial stage. To facilitiate this effort it is useful to have simple scaling rules or formulas to provide rapid results, which, although not exact, are accurate enough in their essential features to avoid misleading conclusions.

This paper presents the results of an analysis of both published and unpublished critical current data given as a function of both field and temperature. Simple formulas have been obtained for (1) the critical temperature as a function of field that is needed to obtain an estimate of the current sharing temperature and hence temperature margin, (2) the critical current density for constant temperature as a function of field, and (3) the critical current density for constant field as a function of temperature.

In this paper the following units are used: T (K), B (T), j (kA/cm^2), C (mJ/cm^3·K). All j_c equations are in 10^3 kA/cm^2.

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Experimental Source

Almost every superconducting magnet laboratory is equiped to perform short sample measurements (four-probe voltage vs current) at the helium boiling temperature (4.2 K) in an applied transverse magnetic field. Not many laboratories are able to handle high field measurements of very large conductors that require high currents. Only a very few laboratories have temperature controlled cryostats needed to perform short sample measurements over a wide range of field and temperature. Since the work of Hampshire, Sutton, and Taylor in 1969,[1] three other experimental groups have published data on commercial NbTi conductor over a wide range of field and temperature values.[2-4] Yet, surprisingly, no one has published data covering both high temperature (i.e., above 4.2 K) and low temperature (i.e., to superfluid helium, which also means high fields) on the same specimen.

It should be noted that the techniques for measuring critical current density are not standardized and the criteria on voltage sensitivity used by the various groups also are different.[5] In addition, the NbTi alloy compositions of the various vendors differ, with the nominal range of 44 to 50.5 wt % Ti being covered by the present data (the Fermilab composition is Nb-46.5 wt % Ti).

Nevertheless, the analysis presented here shows a remarkable consistency in the functional dependence of the NbTi data, which span a period of 13 years and include conductor from at least six manufacturers.

Perhaps, on reflection, the consistency should not be surprising. It is well known that the magnitude of the critical current density depends on the metallurgical properties (e.g., degree of cold working, amount of dislocations, etc.), whereas the values of the upper critical field and critical temperature are properties of the alloy composition and are independent of the metallurgical state. For NbTi alloys in the range of 44 to 50.5 wt % Ti, the B_{c2} and T_c values do not vary to any significant degree.[6-7] Therefore, the extrapolation procedure used to find the linear j_c equations merely reflects these facts, and one does not find much fluctuation in B_{c2} and T_c over time or from different manufacturers.

Critical Temperature and Upper Critical Field

Hawksworth and Larbalestier[8] have pointed out that the most accurate method for determining the bulk upper critical field is to plot the pinning force ($j \times B$) vs B at fixed temperature and to extrapolate the high field linear falloff with increasing field to zero pinning force. While we don't quarrel with this assessment, in the present work the linear portion of the critical current density is extrapolated to zero value for the upper critical field at fixed temperature. The slight curvature of j in j vs B graphs that occurs at the lowest values of critical current density is neglected as not being of technological importance. Likewise, the sharp increase in critical current

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density at the very low fields (<3 T) is also neglected, because functional dependences and scaling rules are rarely needed in this field range.

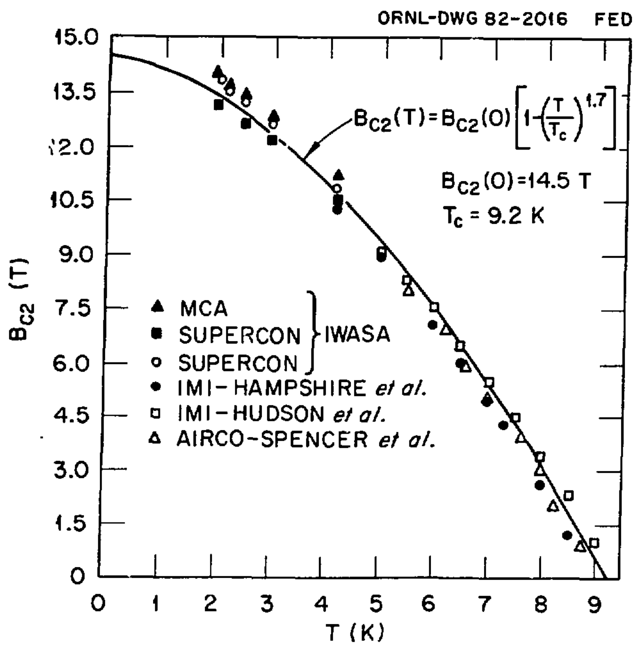

Fig. 1. Upper critical field vs temperature for NbTi commercial conductor of nominal composition 44 wt % Ti to 48 wt % Ti.

The upper critical field data are shown in Fig. 1. The best fit to the data up to B = 10 T is

$$B_{c2}(T) = B_{c2}(0)\left[1 - \left(\frac{T}{T_c(0)}\right)^n\right] \qquad (1)$$

where $B_{c2}(0) = 14.5$ T, $T_c(0) = 9.2$ K, and $n = 1.7$.

Note that in theoretical calculations one usually sees Eq. (1) used with n = 2. However, for commercial Nb-46.5 wt % Ti, the 1.7 power law fits the data better than a quadratic dependence on temperature. For more accurate critical temperature calculations above 10 T, a small adjustment to Eq. (1) is needed, namely, a slight increase in the upper critical field to $B_{c2}(0) = 14.8$ T. No one simple power law holds over the whole temperature range. The primary usefulness of such a figure is to find out what the critical temperature is for a known maximum field. Rearranging Eq. (1) to solve for T yields a useful formula for critical temperature as a function of field,

$$T_c(B) = 9.2[1 - (B/14.5)]^{0.59} \text{ for } B < 10 \text{ T}, \qquad (2a)$$

$$T_c(B) = 9.2[1 - (B/14.8)]^{0.59} \text{ for } B > 10 \text{ T}. \qquad (2b)$$

Current Sharing Tempera: re

The critical temperature for NbTi varies from 9.2 K in zero field to the value given by Eq. (2) in field B. The current sharing temperature varies from this value for zero current to the bath temperature for transport current $I_{op} = I_c$. If we make the plausible assumption that the current sharing temperature is a linear function of I_{op}/I_c, then the following expression can provide the current sharing temperature as a function of field with the reduced current I_{op}/I_c and the bath temperature T_b as parameters:

$$T_{cs} = T_b + [T_c(B) - T_b][1 - (I_{op}/I_c)]. \qquad (3)$$

Enthalpy Calculation

One useful application of Eqs. 2 and 3 is the calculation for the amount of energy suddenly deposited in a specimen that is needed to raise the temperature from the bath temperature to T_{cs}. For specific heat, we will combine the accepted value for copper with the recent field dependent measurements of Elrod et al.[9] Only small temperature excursions (i.e., up to 10 K) are considered. The density at absolute zero is used to obtain the heat capacity per unit volume.

$$C = \frac{10^{-3}}{f + 1}[(6.75f + 50.55)T^3 + (97.43f + 69.81B)T]$$

$$(\text{in mJ/cm}^3\cdot\text{K}), \qquad (4)$$

where f is the copper/superconducting ratio. Using Eqs. (2a), (3), and (4), a calculation was made to determine the enthalpy needed to raise a NbTi conductor from $T_b = 4.2$ K to T_{cs} for $I_{op}/I_c = 0.5$ and $I_{op}/I_c = 0.8$ as a function of copper/superconducting ratio. The shape of the curve in Fig. 2 and the magnitude are not surprising, but perhaps one forgets that it takes only 3 mJ/cm^3 or less of energy density to start producing Joule heating in a NbTi conductor in pool boiling helium. One interesting feature is that stability tests performed on a conductor operating at high reduced current in a 5-T field perhaps can be correlated with 8-T performance at more modest values of reduced operating current.

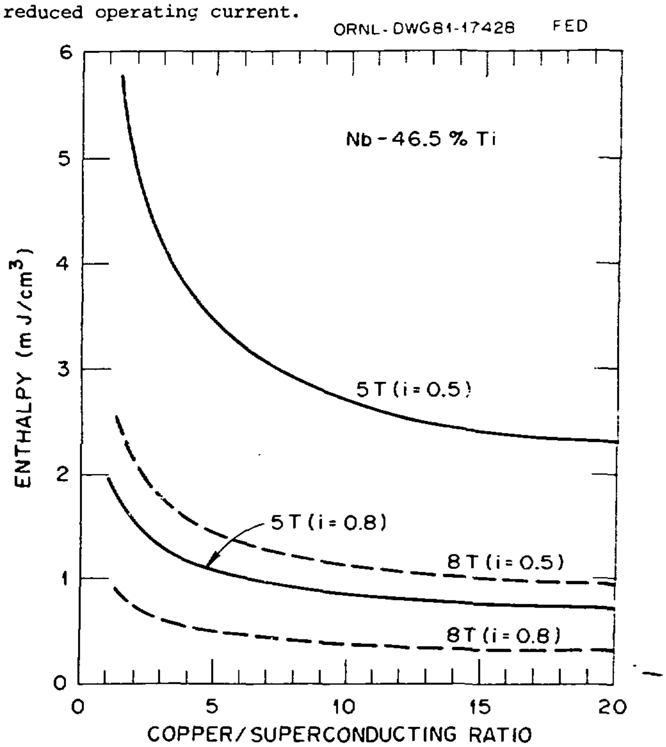

Fig. 2. Enthalpy of NbTi conductor vs copper/superconducting ratio for 5-T and 8-T fields and with operating currents of 0.5 and 0.8 of the critical current.

Critical Current Density

Variation With Field

Although there is no theoretical expression for the dependence of the critical current density on field at constant temperature for type II superconductors, a linear equation is an excellent approximation over the field range of most interest, $3\ T \leq B \leq 10\ T$. For each of the samples reported in the literature,[1-4,8,10] the appropriate linear equation has been determined. Examples for two of the investigations (Hudson et al.[3] and Spencer et al.[2]) are given in units of $10^3\ kA/cm^2$:

$$j_c = 550 - 50\ B \quad (5a)$$

$$j_c = 371 - 36.9\ B \quad (5b)$$

These and others not shown are not as distinct as might first appear. A general form for $j_c(B)$ at $T = 4.2$ K (a corresponding equation can be determined for other bath temperatures) is

$$j_c(B,\ T = 4.2\ K) = j_o(1 - 0.096\ B). \quad (6)$$

The constant j_o can be found for any sample from a *single measurement*. The coefficient of field $0.096 = [B_{c2}(T)]^{-1}$ represents an *effective upper critical field* for $T = 4.2$ K, in this case $B_{c2}(T = 4.2\ K) = 10.4$ T. This value is the mean of the ten measurements analyzed and has a standard deviation of 3%. Note that the samples measured span a wide spectrum of critical current density; $j_c(B = 8\ T,\ T = 4.2\ K)$ varies from 50 to 108 kA/cm^2.

Variation With Temperature

A linear variation with temperature for the critical current density at constant field was established a long time ago and is generally accepted as a reliable assumption. The appropriate linear equations for some of the samples studied have been determined for $B = 8$ T over the widest temperature range available (the case of superfluid helium is considered separately).

$$j_c(B = 8\ T,\ T) = j_o'(1 - 0.177\ T), \quad (7)$$

over the temperature range $2\ K < T < 5.5\ K$, where again the constant j_o' can be determined from a single measurement at 8 T (corresponding equations can be determined for other field values). The coefficient, 0.177, has a standard deviation of less than 1% over the data analyzed and represents the *effective critical temperature*, $0.177 = [T_c(B)]^{-1}$ or $T_c(B = 8\ T) = 5.65$ K.

The field value of interest for high-energy physics applications is 5 T. The temperature variation at this field value is

$$j(B = 5\ T,\ T) = j_o'(1 - 0.14\ T) \quad (8)$$

which holds over the range $2\ K < T < 7\ K$. The *effective critical temperature* is $T_c(B = 5\ T) = (0.14)^{-1} = 7.1$ K. The standard deviation is 2%.

Low Temperature, High Field Variation

There is much less information available in the range of superfluid helium ($T < 2.17$ K) and in fields above 10 T. As might be anticipated, the data have somewhat more scatter in this range as well. While a great deal of interest has focused on the alloys of NbTi (particularly NbTi with tantalum additions) for applications at 1.8 K, Hirabayashi et al.[11] have shown recently that the binary alloys are every bit as good as the ternaries at fields above 10 T at 1.8 K. In fact, the highest critical current density they report on at $B = 12$ T, $T = 1.8$ K is a binary NbTi with a value of 100 kA/cm^2. This is comparable with the best NbTi data measured at $B = 8$ T, $T = 4.2$ K.

The field variation at $T = 1.8$ K (another difficulty in low temperature data is that some samples are reported at 2 K while others are reported at 1.8 K) is

$$j_c(B,\ T = 1.8\ K) = j_o(1 - 0.0728\ B), \quad (9)$$

which is good over the range $5\ T < B < 13\ T$. The coefficient corresponds to an *effective upper critical field* of $B_{c2}(T = 1.8\ K) = (0.0728)^{-1} = 13.7$ T. The standard deviation for these data is 3%. The temperature variation at $B = 11$ T is

$$j_c(B = 11\ T,\ T) = j_o'(1 - 0.245\ T), \quad (10)$$

which holds over the temperature range $1.8\ K < T < 3.8$ K. The coefficient corresponds to an *effective critical temperature* of $T_c(11\ T) = (0.245)^{-1} = 4.1$ K. The standard deviation is 6%.

Conclusion

Except for the highest fields and lowest temperature or for some special purpose, there is sufficient good critical current density data on NbTi in the literature, in the author's opinion, to make further measurements unnecessary. A single short sample measurement at a convenient field and bath temperature is all that is needed to supply the magnitude of the critical current density and therefore the constant j_o or j_o' in the equations for the functional dependences given in the paper.

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