Title

A Method for Generating the Jc, B, T Surface for Niobium-Alloy Superconductors

Author

Green, M A

Publication Date

1989-03-01

LBL-27064

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

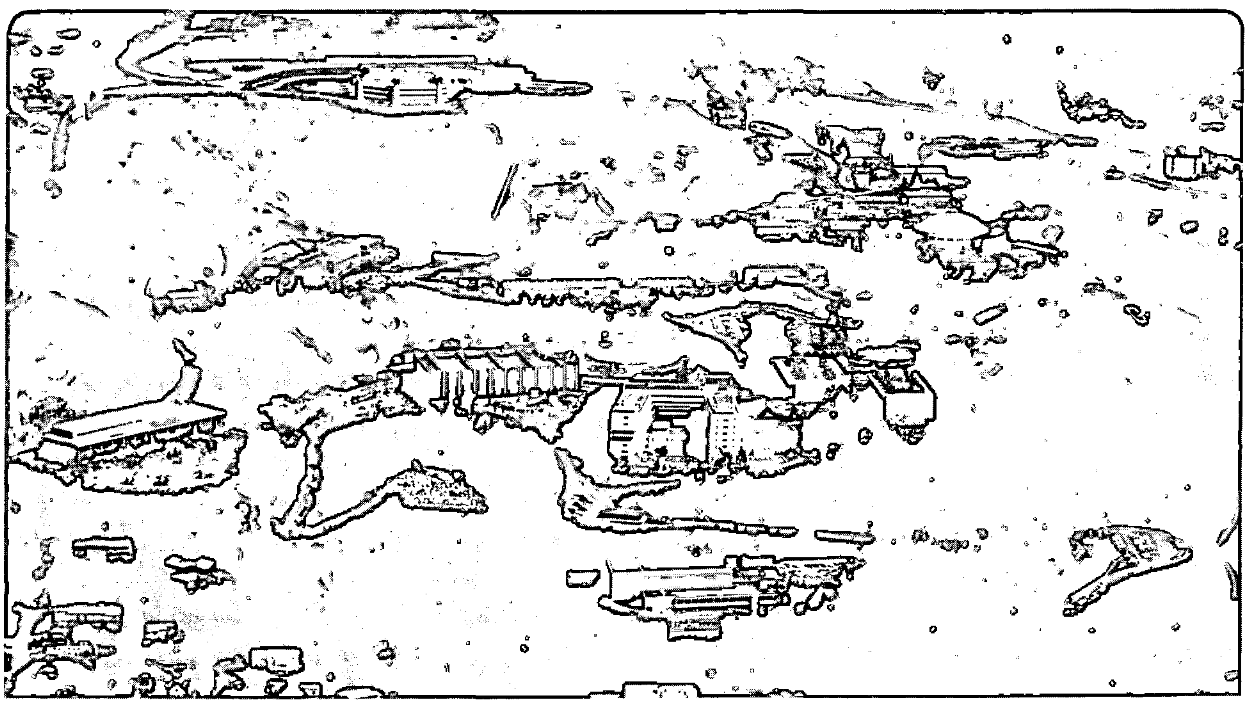
Engineering Division

Presented at the TMS Conference, Las Vegas, NV,
February 27–March 3, 1989, and to be published
in the Proceedings

A Method for Generating the J_c, B, T Surface for Niobium-Alloy Superconductors

M.A. Green

March 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

LBL-27064

A Method for Generating the J_c, B, T Surface for Niobium-Alloy Superconductors

Michael A. Green

Engineering Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

March 1989

A METHOD FOR GENERATING THE J_c, B, T SURFACE FOR NIOBIUM-ALLOY SUPERCONDUCTORS

Michael A. Green

Lawrence Berkeley Laboratory
Berkeley, CA 94720

ABSTRACT

This report shows how the J_c, B, T surface can be created for various niobium-alloy superconductors using a reduced critical state model. Using this method, one can calculate the J_c of the superconductor over a range of B and T given the J_c at 4.2 K over a limited range of B. The calculated value of J_c agrees favorably with measured values over a range of temperatures from 1.5 to 7.0 K and a range of inductions from 0.1 to B_{c2}. This method has been applied to various niobium-titanium-alloys, niobium-zirconium and niobium-tantalum-titanium. The paper compares calculated values of J_c with measured values of J_c for niobium-alloy superconductors manufactured since 1965. As an illustration, a computer generated J_c, B, T surface is presented for some of the superconductors.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

BACKGROUND

There is often the need to know the behavior of a niobium-alloy superconductor under conditions different from those measured by the manufacturer. For example, one often knows the superconductor critical current (critical current density, J_c) as a function of magnetic field (or magnetic induction, B) at the boiling point of helium (T = 4.22 K) over a limited range of magnetic inductions (e.g., 2 T to 8 T). Suppose, however, one wants to know the critical current density over a wide range of magnetic inductions (from 0 to B_{c2}) at a temperature of, e.g., 3.0 K. The measured data are often unavailable and costly to obtain. This report presents a method by which one can calculate the critical surface for a commercial superconductor given only the upper critical field, H_{c2}, the critical temperature, T_c, and some values of the critical current versus magnetic field at the boiling point of helium (or any other temperature).

The reduced critical state method is similar to the methods used to calculate the thermodynamic properties of a fluid. The J_c, B, T surface represents the phase change surface for a superconductor. The reduced critical state method presented here uses reduced critical temperature, reduced critical induction and reduced critical current density to calculate the entire J_c, T, B surface for superconductors such as niobium-titanium. The value of this method is demonstrated when one needs to calculate the effects of superconductor magnetization on the field in a dipole magnet (such as the SSC dipole) over various accelerator operating temperatures.

THE REDUCED CRITICAL STATE METHOD

The method used to calculate the critical surface for a commercial niobium-alloy superconductor is based on the following assumptions: 1) The critical temperature, T_c, at zero field and the upper critical induction ,B_{c2}, at zero temperature are functions only of the alloy composition of the superconductor. 2) The critical current density, J_c, is a function of the metallurgical treatment of the superconductor such as heat treatment and cold work, where as T_c and B_{c2} are independent of the treatment of the superconductor. 3) The critical current of the superconductor varies linearly with temperature above some temperature T^*. Below this temperature there is a parabolic temperature dependence. 4) J_c versus B is given at one temperature over a range of magnetic fields. In the absence of a complete J_c versus B curve (particularly at low fields), the ratio of $J_c(T,B)/J_c(T,5\ T)$ is identical for all materials of the same alloy. The assumptions given previously are reasonably valid for commercial niobium-titanium.[1-5]

If the above given assumptions are correct, one should be able to estimate J_c anywhere on the superconductor critical surface if one knows: (1) J_c versus magnetic induction, B, at a given temperature less than the T_c at zero field, and (2) T_c versus B at zero J_c. A reduced critical state model says that T_c as a function of magnetic field (or induction) at zero current can be determined provided one knows the zero-field value of critical temperature, $T_c(0)$, and the zero-temperature value of the upper critical induction $B_{c2}(0)$.

Reduced Critical Temperature Versus Reduced Critical Field

The reduced critical temperature, T_{cR}, and the reduced critical field, B_{cR}, are defined as follows:

$$T_{cR} = \frac{T_c(B)}{T_c(0)} \ , \qquad (1)$$

when J_c is zero, and

$$B_{cR} = \frac{B_{c2}(T)}{B_{c2}(0)} \quad , \qquad (2)$$

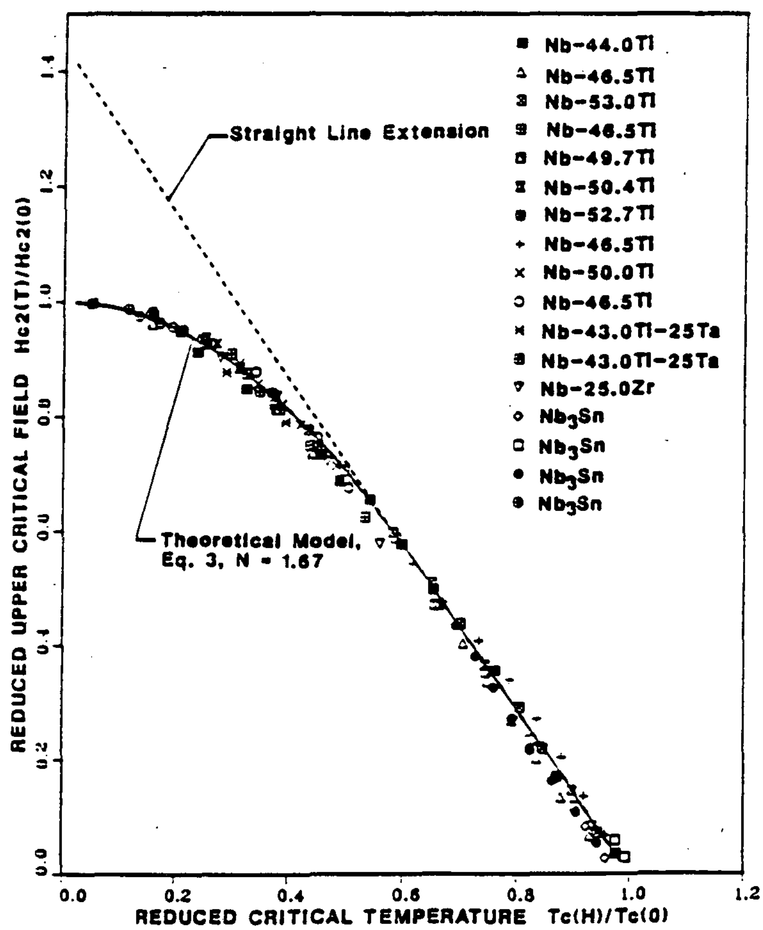
when J_c is zero. One can define upper critical induction (tesla) given upper critical field (A m^{-1}) using the following relationship:

$$B_{cR} = 1 - (T_{cR})^N \quad , \qquad (3)$$

where N is some number less than two. Lubell[6] states that N = 1.7 fits measured data for niobium-titanium. A look at niobium-titanium reduced-temperature data[1,5,6,7] suggests that N = 1.67 will give a somewhat better fit. A very good fit can also be achieved using a mixed quadratic and linear equation.[8]

Figure 1 shows that Eq. (3) fits to measured values of B_{cR} versus T_{cR} for niobium-titanium, niobium-titanium-tantalum, niobium-zirconium, niobium-tin ribbon, and multifilamentary niobium-tin in a bronze matrix.

Figure 1
REDUCED UPPER CRITICAL FIELD VERSUS REDUCED CRITICAL TEMPERATURE FOR VARIOUS COMMERCIAL SUPERCONDUCTORS



The J_C, B, T Surface

Once the B_{C2} versus T_C curve has been determined at zero critical current, a large part of the critical surface can be calculated, provided one knows the critical current versus magnetic induction at a temperature that is less than the critical temperature.

The current density in the superconductor, within the linear temperature dependence region above temperature T', at a given temperature T and a magnetic induction B can be calculated using the following equation:

$$J_C(T,B) = J_C(T_o,B) + \frac{dJ_C}{dT}(T - T_o) \quad , \tag{4}$$

where T_o is the temperature for which a known curve of J versus B is given and where

$$\frac{dJ_C(B)}{dT} = \frac{J_C(T_o,B)}{T_o - T^*} \quad . \tag{5}$$

When Eq. (3) is used to define B_{C2} at zero J versus T:

$$T^* = (1 - B_{CR})^{1/N}\ T_C(0) \quad . \tag{6}$$

Eq. (4) is valid only over the range of magnetic induction B for which $J(T_o,B)$ is given. If the value of J(T,B) calculated using Eq. (4) is negative, then J(T,B) is zero. Eq. (4) is not valid when T is less than T'.

The Paraboloid Temperature Fit at Temperatures Below T'

Morgan of Brookhaven National Laboratory[9] and others have observed that J_C in niobium-titanium below about 3.5 to 4.0 K no longer has a linear temperature dependence. A parabolic temperature dependence can be used to determine the J_C versus T dependence below a parabolic breakpoint temperature T'. The parabola should have the property that $dJ_C/dT = 0$ at $T = 0$ and dJ/dT = the linear dJ_C/dT at $T = T'$. J_C versus T should be a continuous function from $T = 0$ to $T = T^*$. (See Figure 2.)

Let us look at the case where T_o is greater than T', and T is less than T'. The following set of equations now applies (at least for niobium-titanium):

$$J_C(T,B) = AA - CCT^2 \quad , \tag{7}$$

where

$$AA = \frac{dJ_C}{dT}\,\frac{T'}{2} - T^* \quad , \tag{8a}$$

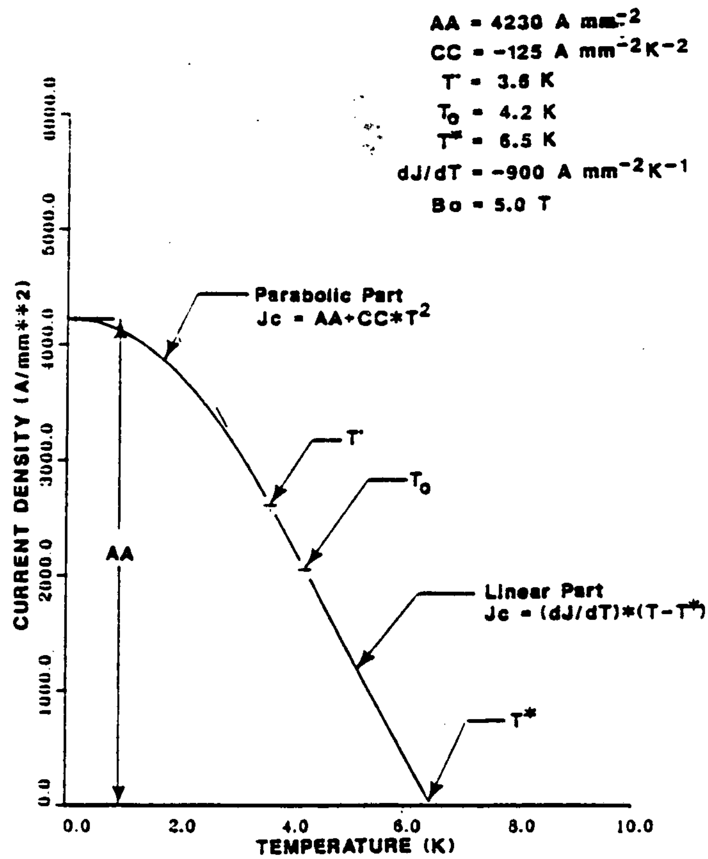
and

$$CC = -\frac{1}{2T'}\,\frac{dJ_C}{dT} \quad , \tag{8b}$$

where T^* is determined by Eq. (6), and dJ_C/dT is determined by Eq. (5), because T_o is above T'. When T is greater than T', and T_o is greater than T', Eq. (4) is used as before.

Figure 2

LINEAR PLUS PARABOLIC TEMPERATURE DEPENDENCE OF CRITICAL CURRENT DENSITY IN NIOBIUM TITANIUM



Let us look at the cases where T_o is less than T'. One can modify Eq. (7) to obtain with an estimate of the linear temperature dependence dJ_c/dT. This equation will take the following form:

$$\frac{dJ_c}{dT} = \frac{J_c(T_o,B)}{\frac{T'}{2} + \frac{T_o^2}{2T'} - T^*} , \qquad (9)$$

when $T_o < T'$. Use Eq. (5) when $T_o > T'$. For the case where T is also less than T', one uses Eq. (7) with the value of dJ_c/dT calculated from Eq. (9).

When $T_o < T'$ and $T > T'$, Eq. (9) is used to calculate the linear dJ_c/dT, and the following equation is used to estimate J(T,B):

$$J_c(T,B) = \frac{dJ_c}{dT}(T - T^*) , \qquad (10)$$

where dJ_c/dT is defined by Eq. (9), and T^* is defined by Eq. (6).

Selection of $T_c(0)$ and $B_{c2}(0)$

Superconducting alloys such as Nb-Ti, Nb-Ti-Ta, and Nb-Zr generally have set values of $T_c(0)$. The upper critical induction $B_{c2}(0)$ quoted in the literature, often the value of surface-current critical induction $B_{c3}(0)$, is generally a little high. The value of B_{c2} where the bulk current density goes to zero can be from 0.5 to 1.2 T lower than the highest value of B_{c3}.[10,11] $B_{c2}(0)$ can be fitted to the measured data of J_c versus B. If one does this, the fit will be improved in one region at the expense of another region. The critical temperature $T_c(0)$ is often a set value when the filament diameter is above 1 μm. With niobium-titanium, the value of $T_c(0)$ and $B_{c2}(0)$ are depressed as the filament diameter drops below 0.2 μm.[12]

The value of T' is a function of both the alloy and the processing of the alloy. T' is best determined using measured data. In the absence of measured data, use the following values for T': for Nb-Ti use T' ~ 0.4 $T_c(0)$, for Nb-Ta-Ti use T' ~ 0.5 $T_c(0)$, and for Nb-Zr use T' ~ 0.3 $T_c(0)$.

CRITICAL CURRENT DENSITY AS A FUNCTION OF TEMPERATURE AND MAGNETIC INDUCTION FOR NIOBIUM-TITANIUM AND OTHER NIOBIUM-ALLOY CONDUCTORS

The calculation of the critical current density $J_c(T,B)$ at induction B and temperature T requires that one knows the $J_c(T_o,B)$, where T_o is the temperature at which critical current density is known. The value of J_c is often known at the boiling point of helium, 4.22 K. At a magnetic induction of about 1.0 T and above, the value of J_c is often known. Below 1.0 T, there are almost no valid measured data of critical current density except those taken using magnetization measurements.

The J_c Versus B at 4.2 K

Most critical current density measurements are made using short sample measurements. This technique has two serious flaws: 1) There is a conductor size effect which comes into play. Conductors generate a self field when they carry transport current. 2) Short sample measurements do not reflect the true J_c of the conductor. Sausaging will reduce the critical current of the conductor without reducing J_c. The use of magnetization techniques will permit one to measure the true superconductor J_c even at low fields.

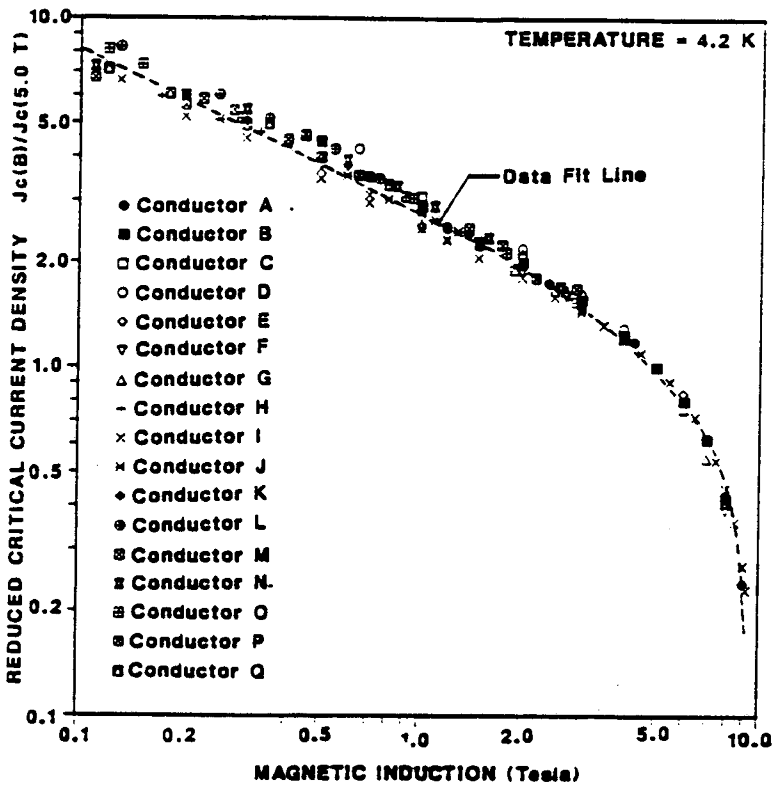
It has been observed in niobium-titanium that the J_c at 0.3 T and 4.2 K is roughly 5 to 6 times the J_c at 5.0 T and 4.2 K. This has been observed in samples of niobium-titanium made during the last 25 years. Figure 3 shows the ratio of J_c at an induction B to J_c at 5 T for a variety of niobium-titanium superconductors at 4.2 K. Figure 3 shows that niobium-titanium has the same J_c ratio (to ± 15 percent) regardless of when the superconductor was made. The data used to generate Figure 3 can be found in References 8 and 13. Nb-Ta-Ti and Nb-Zr follow the same general sort of low field behavior as the Nb-Ti superconductor shown in Figure 3.

A Comparison of Measured J_c with Calculated J_c

This paper presents a comparison of measured and calculated J_c for six different materials. They are: 1) Nb-44 w% Ti (1972)[1,2], 2) Nb-46.5 w% Ti (1987)[11], 3) Nb-52.7 w% Ti (1979)[3], 4) Nb-43 w% Ti - 25 w% Ta (1979)[10], 5) Nb-44 w% Ti - 15 w% Ta (1988)[14], and 6) Nb-25 w% Zr (1967)[15]. The niobium-titanium includes old low J_c conductor through modern conductor with a range of titanium contents. The

Figure 3

REDUCED CRITICAL CURRENT DENSITY
VERSUS MAGNETIC INDUCTION
FOR VARIOUS SAMPLES OF NIOBIUM TITANIUM



niobium-titanium-tantalum includes two batches with different properties. The niobium-zirconium is an early commercial superconductor which was probably made in 1963.

The comparison with measured J_c and calculated J_c for the three niobium-titanium samples is shown in Figures 4, 5 and 6. In all three cases, the data was fit at 4.22 K (the darkened squares or circles). Figure 7 shows the J_c, T, B surface for a modern (J_c(4.2 K, 5.0 T) = 3000 A mm^{-2}) niobium-titanium superconductor which would be suitable for the SSC.

The niobium-titanium-tantalum cases are shown in Figures 8 and 9. The measured J_c in these cases comes very close to the calculated J_c for these cases, just as it does for the three niobium-titanium cases. The niobium-zirconium measured J_c data (see Figure 10) does not agree with the calculated values (based on a fit at 3.0 K) very well.

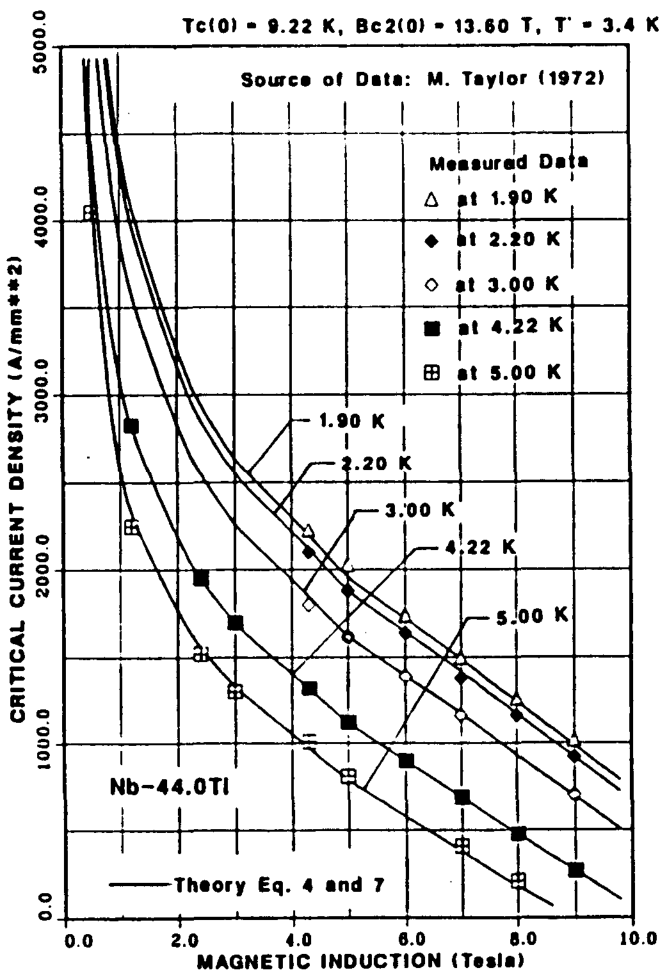


Figure 4 A Comparison of Measured and Calculated Critical Current Density as a Function of Magnetic Induction and Temperature for Nb-44.0w%Ti Jc(5.0T,4.2K) = 1150 A per square mm

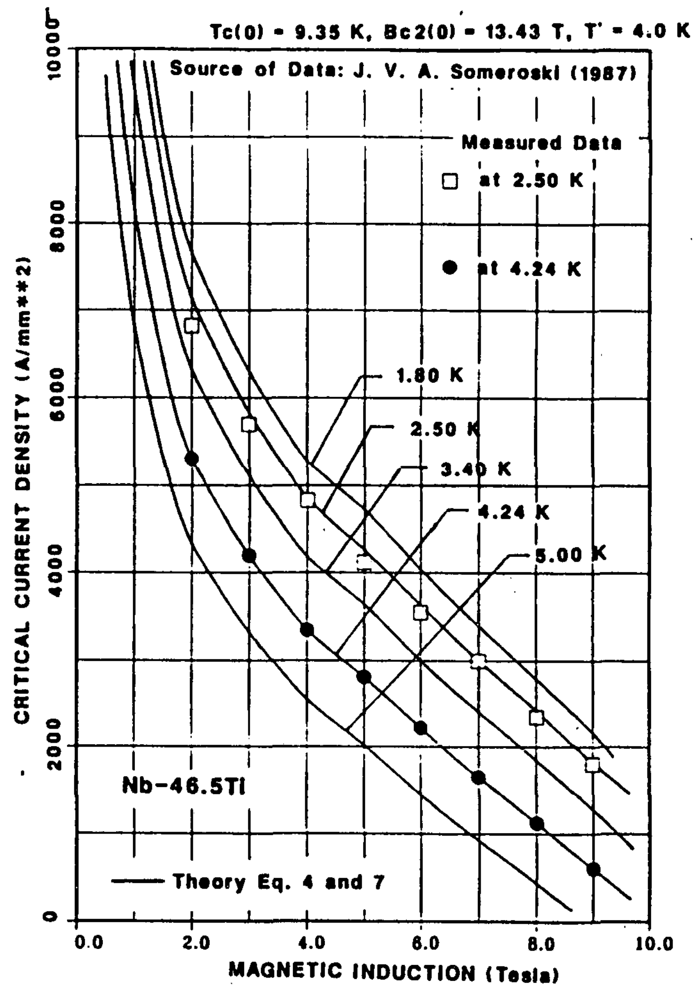


Figure 5 A Comparison of Measured and Calculated Critical Current Density as a Function of Magnetic Induction and Temperature for Nb-46.5w%Ti Jc(5.0T,4.2K) = 2850 A per square mm

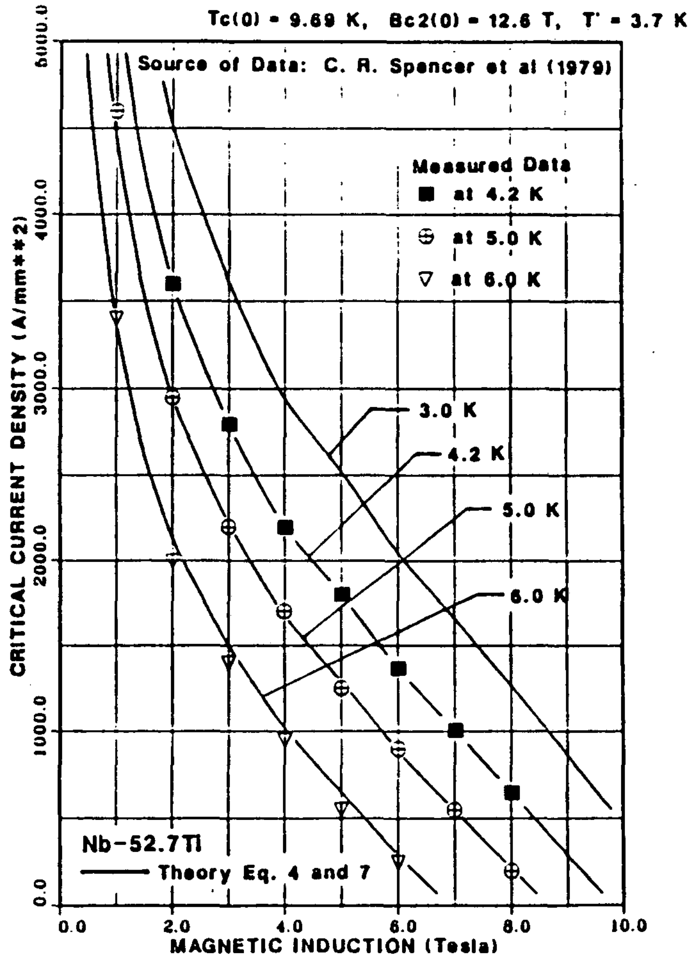
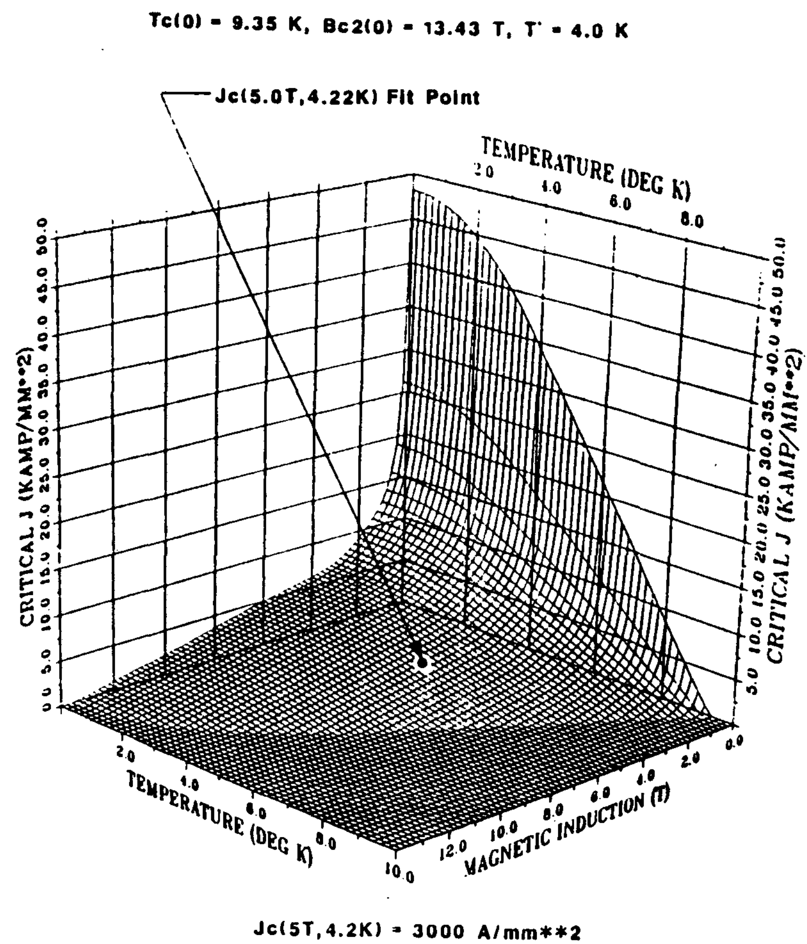


Figure 6 A Comparison of Measured and Calculated Critical Current Density as a Function of Magnetic Induction and Temperature for Nb-52.7w%Ti
Jc(5.0T,4.2K) = 1850 A per square mm

Figure 7 A Three Dimensional Plot of the Jc, B, T Surface for Nb-46.5w%Ti which was made from a Single Point at 4.2 K and 5.0 T (See Fig. 3.)
Jc(5.0T,4.2K) = 3000 A per square mm



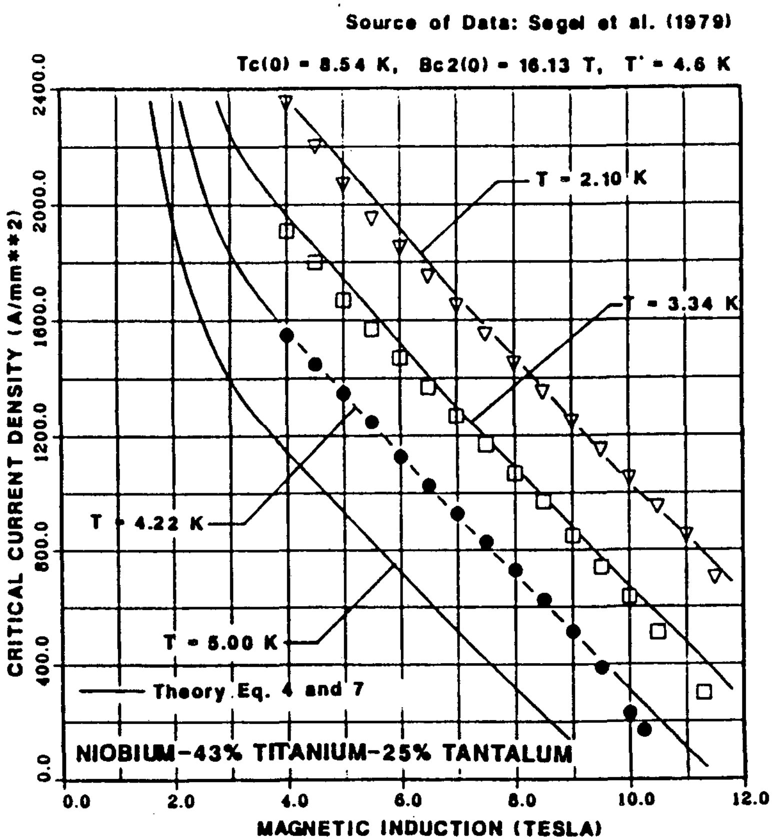


Figure 8 A Comparison of Measured and Calculated Critical Current Density as a Function of Magnetic Induction and Temperature for Nb-43%Ti-25%Ta by Weight, Jc(5.0T,4.2K) = 1430 A per square mm

Figure 9 A Comparison of Measured and Calculated Critical Current Density as a Function of Magnetic Induction and Temperature for Nb-44%Ti-15%Ta by weight, Jc(5.0T,4.2K) = 3200 A per square mm

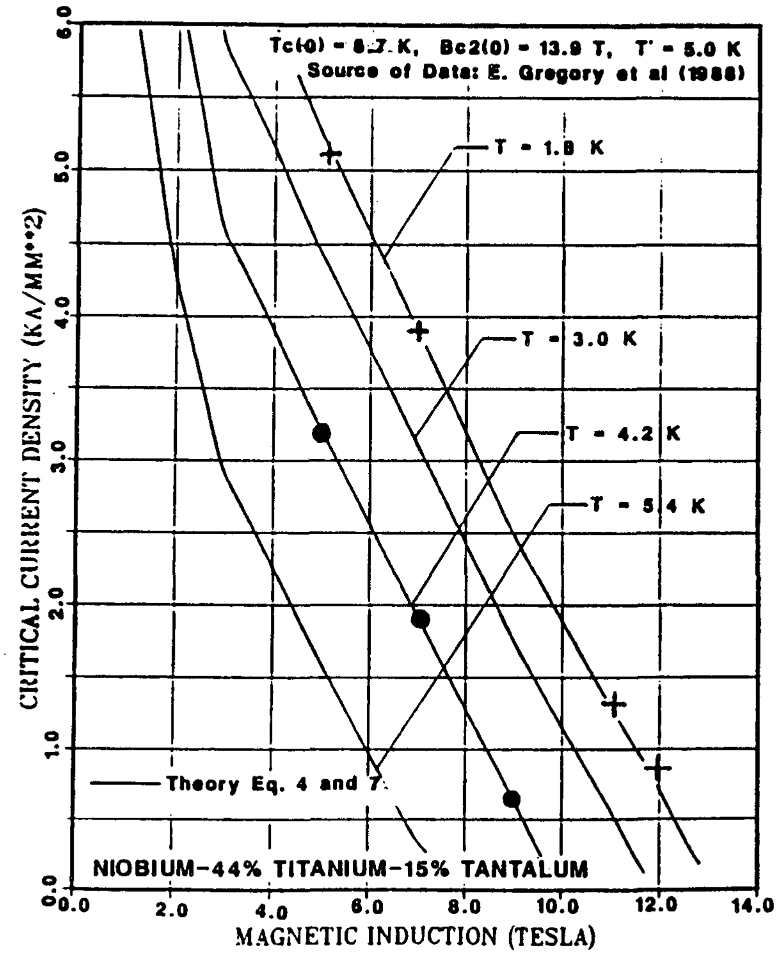
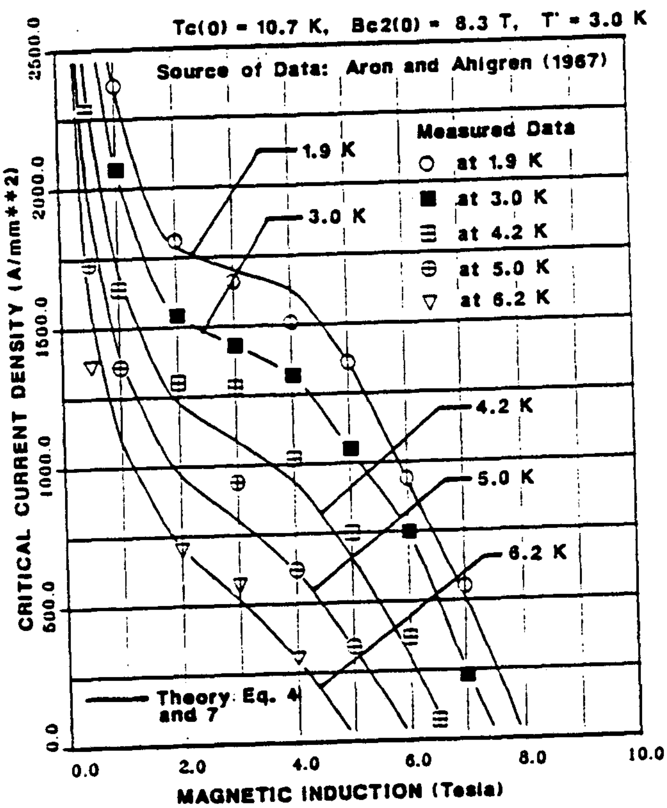


Figure 10
CRITICAL CURRENT DENSITY VERSUS TEMPERATURE AND MAGNETIC INDUCTION
LINEAR PLUS PARABOLIC TEMPERATURE FIT
Nb-25.0Zr



CONCLUDING COMMENTS

Many superconducting materials are well behaved in terms of the prediction of their J_c as a function of T and B given $T_c(0)$, $B_{c2}(0)$, and some measured data points at some temperature T_o (e.g., 4.2 K). A relatively simple linear theory can be used to predict J_c for temperatures above T' for both niobium-titanium and niobium-titanium-tantalum given J_c versus B data at 4.2 K, T', $T_c(0)$, and $B_{c2}(0)$. Below some temperature T', which is about 3.7 K for niobium-titanium and 4.6 to 5.0 K for niobium-titanium-tantalum, the fitting theory is a little more complicated in that a parabolic temperature fit is required below T'.

The observation that the critical current density of niobium-titanium at some induction B and at 4.2 K divided by the critical current density at 5.0 T and at 4.2 K as a function B lies on a line is an important one. The scatter about this line is about 15 percent. This kind of relationship appears to hold up for niobium-titanium-tantalum and to a lesser degree niobium-zirconium.

This observation suggested by Figure 3 shows that the entire J_c, B, T surface can be roughly defined by as little as four parameters: $T_c(0)$, $B_{c2}(0)$, T' and J_c(4.2 K, 5 T). The calculation method given in this report permits one to fit the J_c, B, T surface to measured data. This fit is improved if one has measured values of J_c at more than one temperature over a range of magnetic inductions.

ACKNOWLEDGMENTS

The author acknowledges with thanks his many conversations with A. K. Ghosh of Brookhaven National Laboratory. Much of his collected data was used to create Figure 2. The author acknowledges discussions he has had with R. Scanlan and C. Taylor of the Lawrence Berkeley Laboratory concerning superconductors. The author thanks D. C. Larbalestier of the University of Wisconsin for information gained from him during conversations at the University of Wisconsin.

REFERENCES

1. R. Hampshire et al., "Effect of Temperature on the Critical Current Density of Nb-44 w% Ti Alloy," Low Temperature and Electric Power, London: International Institute of Refrigeration Commission I, Annexe M69-I, pp. 251-257, 1969.

2. R. G. Hampshire and M. T. Taylor, J Phys, F, 2, p. 89, 1972.

3. C. R. Spencer et al., IEEE Transactions on Magnetics MAG-15, No. 1, p. 76, 1979.

4. K. F. Hwang and D. C. Larbalestier, IEEE Transactions on Magnetics MAG-15, No. 1, p. 400, 1979.

5. P. A. Hudson et al., IEEE Transactions on Magnetics MAG-17, No. 5, p. 1649, 1981.

6. M. S. Lubell, IEEE Transactions on Magnetics MAG-19, No. 3, p. 754, 1983.

7. N. R. Werthamer, E. Helfand and P. C. Hohenberg, "Temperature and Purity Dependence of Superconducting Critical Field H_{c2}," Phys Rev, 147, p. 295, 1966.

8. M. A. Green, "Generation of the J_c, H_c, T_c Surface for Commercial Superconductor Using Reduced State Parameters," Lawrence Berkeley Laboratory Report LBL-24875, April 1988.

9. G. Morgan, "Analytic Forms of Critical Current Data," Brookhaven National Laboratory Report SSC-MD-84, December 1984.

10. D. C. Larbalestier, IEEE Transactions on Magnetics MAG-17, No. 5, p. 1668, 1981.

11. J. V. A. Someroski et al., IEEE Transactions on Magnetics MAG-23, No. 2, p. 1629, 1987.

12. K. Yasohama et al., IEEE Transactions on Magnetics MAG-23, No. 2, p. 1728, 1987.

13. M. A. Green, IEEE Transactions on Magnetics MAG-25, No. 2, p. 2119, 1989.

14. E. Gregory et al., Proceedings of the Twelfth International Cryogenic Engineering Conference, Southampton UK, July 12-15, 1988, Butterworth and Co., Guildford UK, p. 874, 1988.

15. P. R. Aron and G. W. Ahlgren, Advances in Cryogenic Engineering 13, p. 21, Plenum Press, New York, 1967.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720