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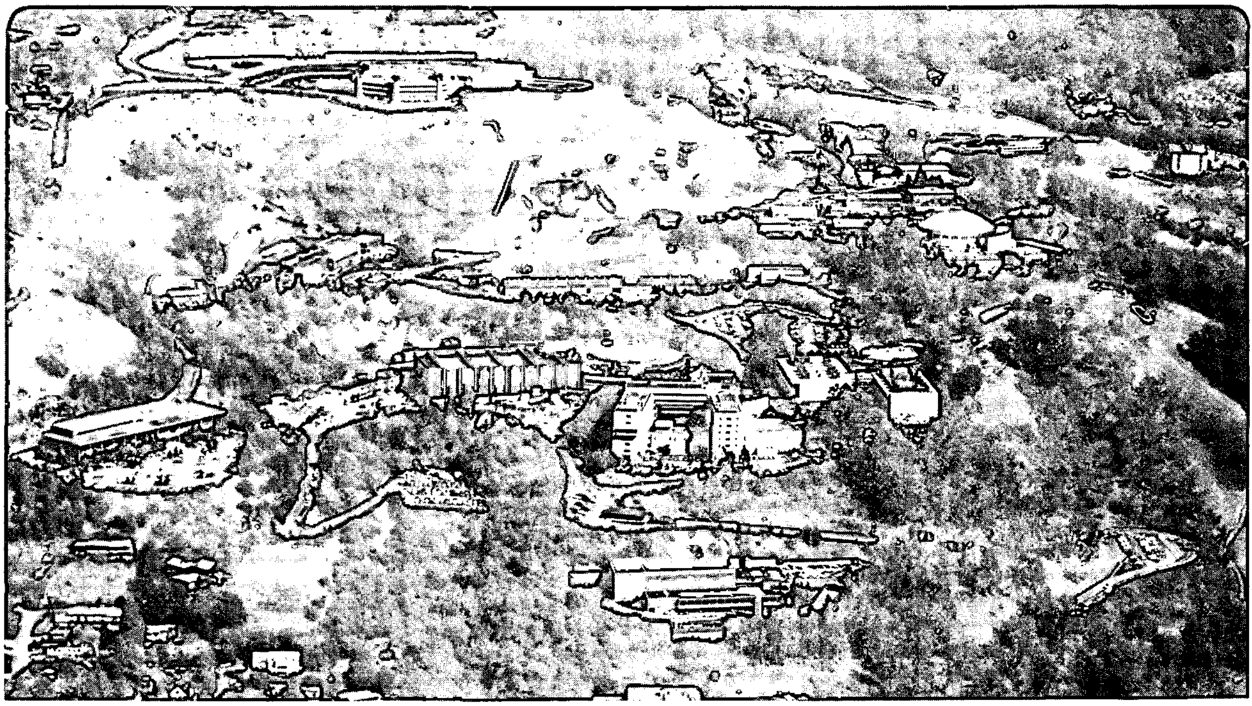

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CALCULATING THE J_c, B, T SURFACE FOR COMMERCIAL NIOBIUM TIN CONDUCTORS USING A REDUCED STATE MODEL

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ABSTRACT

This Report presents a method for calculating the Jc, B, T critical surface for commercial grade niobium tin given an effective T_c and B_{c2} and J_c over a range of magnetic inductions B. Given the effective T_c and B_{c2} and J_c, one can estimate the J_c over a range of magnetic inductions from 0.1 T to 0.8 times effective B_{c2} and a range of temperatures from 1.5 K to about 14 K. The effects of conductor strain can also be estimated using this method. A comparison between calculated values of J_c and measurements is illustrated for a number of cases. The method presented in this report can be used to estimate the performance of niobium tin in magnets at temperatures different from those where measured data is available. The method of calculating the J_c can also be used to estimate the effects of superconductor magnetization on the field quality at low fields.

THE REDUCED CRITICAL STATE METHOD

The reduced critical state method has been used to calculate the critical current density surface as a function of temperature and magnetic induction for niobium titanium[1], and other types of superconductors[2]. This reports shows how the reduced critical state method can be applied to commercial niobium tin superconductors. This method of modeling the critical current performance is different from the method used by L. T. Summers et al.[3].

The method used to calculate the critical surface for commercial niobium tin is based on the following assumptions: 1) There is a reversible critical temperature[4] T_c at zero field and there is a reversible critical induction[4] B_{c2} which are functions of the chemical composition of the superconductor. For the alloy superconductors such as Nb-Ti, T_c and B_{c2} are very close to the true critical temperature and upper critical field, but for niobium tin these functions are less than the true values of T_c and B_{C2}. For niobium tin, T_c and B_{c2} should be regarded as fitting parameters rather than true critical constants. (For the typical Niobium Tin conductors Tc = 16.6 to 17.2 K and B_{c2} =16 to 18 T.) 2) The critical current density J_c varies linearly with temperature. For most niobium tin conductors, this is true from about 1.8 K to very close to the local critical temperature T*. 3) In the absence of a complete J_c versus B curve (particularly at low fields), there is a ratio of $J_c(4.2K,B)/J_c(4.2K,5T)$ which applies to most materials. The above assumptions apply very well for the alloy conductors but the fit is not as good for niobium tin.

The reduced critical temperature T_{CR} and reduced critical induction B_{CR} are defined as follows:

$$T_{CR} = \frac{T_c(B)}{T_c(0)} \tag{1}$$

when $J_c = 0$ and

$$B_{CR} = \frac{B_{c2}(T)}{B_{c2}(0)} \tag{2}$$

when $J_c = 0$. B_{CR} can be stated in terms of T_{CR} using the following relationship:

$$B_{CR} = 1 - [T_{CR}]^N \tag{3}$$

For commercial niobium titanium and the alloy superconductors, $N = 1.7$. (See Ref. 1 and 2.) It turns out that $N = 1.7$ is also appropriate for niobium tin[3]. This value appears to be consistent with WHH theory as well[5]. Figure 1 shows the a plot of reduced magnetic field H_{CR} (Note: $B_{CR} = H_{CR}$.) versus reduced temperature T_{CR} for various samples of niobium titanium, niobium titanium tantalum, niobium zirconium and niobium tin.

The following expression can be used to calculate the critical current density of niobium tin:

$$J_c(T,B,e) = [J_c(T,B,0)]\,[F(e)] \tag{4}$$

where $J_c(T,B,e)$ is the critical current density of the conductor at a temperature T, an induction B and a strain of e; $J_c(T,B,0)$ is the critical current density at T and B with zero strain; F(e) is a strain degradation function[6,7].

The critical current density of the commercial niobium tin under a strain e_o (In most cases, e_o is the residual strain in the niobium tin due to processing.) can be calculated when the temperature is greater than T' using the following expression:

$$J_c(T,B,e_o) = J_c(T_o,B,e_o) + \frac{dJ_c(B)}{dT}(T - T_o) \tag{5}$$

where T_o is the operating temperature for which the critical current density has been measured, provided T_o is greater than T'.[2] (For niobium tin, $T' = 1.8$ K) For $T_o < T'$, a parabolic fit is required[1,2,3]. When $T_o > T'$, the value of dJ_c/dT is defined as follows:

$$\frac{dJ_c(B)}{dT} = \frac{J_c(T_o,B,e_o)}{T_o - T^*} \tag{6}$$

where from equation 3

$$T^* = [1 - B_{CR}]^{1/N}\, T_c(0) \tag{7}$$

Equation 5 is valid only over the range of magnetic induction B for which $J_c(T_o,B,e_o)$ is known. If the calculated value $J_c(T,B,e_o)$ is negative, then $J_c(T,B,e_o)$ is zero. The key elements for calculating an accurate value of $J_c(T,B,e_o)$ are the values of $T_c(0)$ and $B_{c2}(0)$ used for the material and the range of values of $J_c(T_o,B,e_o)$.

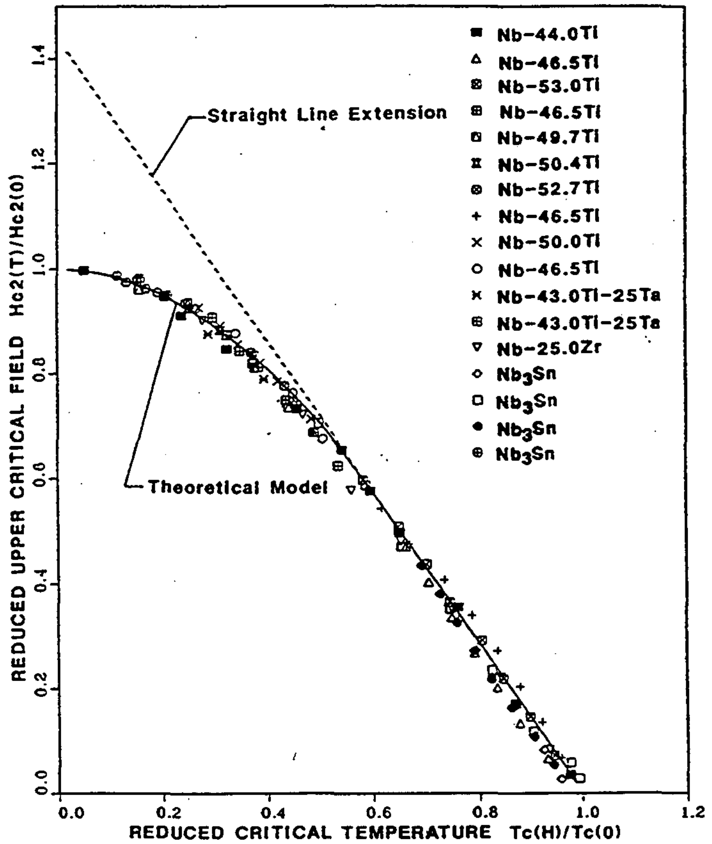

Fig. 1 Reduced Critical Field versus Reduced Critical Temperature for Various Commercial Superconductors

Strain Dependence of J_c

The longitudinal strain degradation function F(e) can be estimated for niobium tin using the following expression[6]:

$$F(e) = \left[\frac{B_{c2}(T_o,e) - B}{B_{c2}(T_o,0) - B}\right]^2 \tag{8}$$

where $B_{c2}(T_o,e)$ can be calculated in terms of e and $B_{c2}(T_o,0)$ using the following approximate expression:

$$\frac{B_{c2}(T_o,e)}{B_{c2}(T_o,0)} = 1 - 4000\, e^2 \tag{9}$$

which applies up to absolute values of strain e up to about 0.012. At this level of strain, the conductor will lose its current carrying capacity irreversibly. There are more general expressions for the effect of strain but given the level of the critical current density estimates given in this report, the expression given by equation 8 is adequate. Compressive strain on the conductor will also greatly reduce the critical current density of the niobium tin, but this form of critical current density degradation is more difficult to characterize, particularly when it is combined with longitudinal strain. Only the longitudinal strain term is included here.

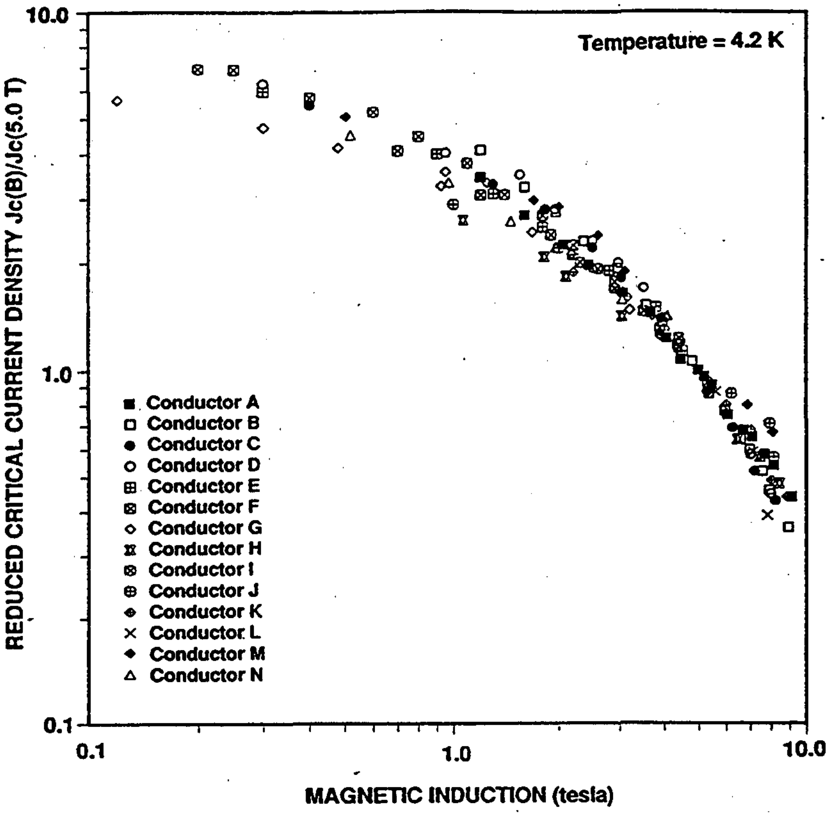

Fig. 2 The Ratio of the J_c at an Induction B to the J_c at 5 T for Niobium Tin Conductors as a Function of Magnetic Induction B

Low Field Dependence of J_c

There is very little low field measured J_c data for niobium tin. Most of the niobium tin measured J_c data is taken at inductions of 8 T or above using transport current. At inductions below 5 T, the J_c measured is influenced by the self field effect[8,9]. Calculations of J_c from magnetization measurements are the only reliable source of good low field J_c data. There are applications for niobium tin where low field J_c (true J_c) data is useful. An example of where one wants to know the J_c at low field is when one calculates the effects of superconductor magnetization on the quality of the field in a high field superconducting magnet while it is operating at low field (such as injection at low fields into a synchrotron or storage ring).

If one has measurements of the J_c in the 5 to 8 T range, one can estimate the low field J_c by using Figure 2. Figure 2 is a scatter plot which presents the ratio of $J_c(B,4.2K,e_o)$ at an induction B to the $J_c(5T,4.2K,e_o)$ at 5 tesla (Note: e_o has a range from 0.0015 to 0.005 for most multifilamentary niobium tin conductors.) for various samples of niobium tin[10-19]. The samples shown in Figure 2 include niobium tin ribbon made in 1967[8] as well as multifilamentary niobium tin samples made by various vendors over the last 25 years. Samples shown in Figure 2 include niobium tin made by the bronze process, the internal tin process and MJR material. Some of the samples have a small amount of titanium or tantalum in them. The scatter of the J_c ratio data in Figure 2 is larger than the scatter of similar low field ratio data plotted at low fields for niobium titanium[1,2]. The sample which has a small amount of titanium (about 1 percent) shows a low field critical current density ratio which is somewhat smaller than standard niobium tin.

COMPARISON OF CALCULATED J_c WITH MEASURED VALUES

The reduced critical state method was applied to a number of samples of niobium tin tape[10]., and multifilamentary niobium tin[11,20] for which there are measured values of J_c at a various magnetic inductions and temperatures. In all cases, the curves of predicted J_c versus B were fit to measured data at one temperature (generally 4.2 K) The calculated curves of J_c versus B fit the measured data precisely at the fitting temperature. At most temperature, the calculated values of J_c compare quite favorably with the measured points. Since there was measured J_c data at more than one temperature in all cases, the values of T_c and B_{c2} could be fit to the measured data. For the niobium tin samples, the reversible fit values of T_c were from 16.8 to 17.0 K instead of the text book value of the critical induction of 18.2 K. The reversible fit values of B_{c2} were from 16.5 to 16.8 T which is less than 70 percent of the text book value of the upper critical field for niobium tin. There are a couple of reasons for this. First, the theory is based upon the linearized reversible values of T_c and B_{c2}. Second, commercial niobium tin is anything but a pure sample of niobium tin. (The commercial materials often have impurities in it which enhance the J_c in the field range for which the conductor is designed. In processing, commercial materials often have mixed phases of niobium tin.)

Figure 3 compares calculated and measured values of J_c for a niobium tin tape produced in 1967. Figures 4 and 5 compare calculated values of J_c with measured values of J_c for two bronze process multifilamentary materials It should be noted that the J_c is defined in the same way as it was defined for the original measurements. The current density given in the niobium tin tape case shown in Figure 3 applies only to the two niobium tin layers which are are 2.48 mm wide by 0.0086 mm thick. The current density for the multifilamentary niobium tin in Figures 4 and 5 applies to the non copper area of the conductor.

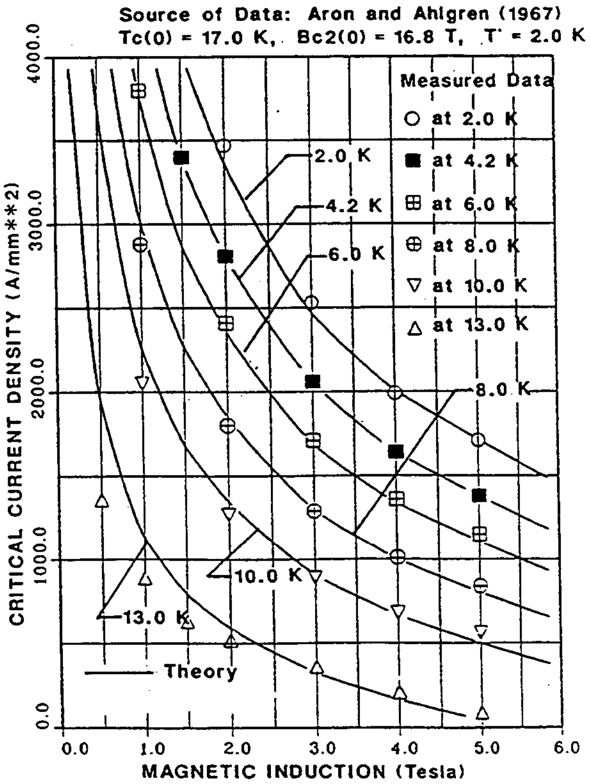

Fig. 3 Calculated and Measured Jc versus B and T for Niobium Tin Tape[10]

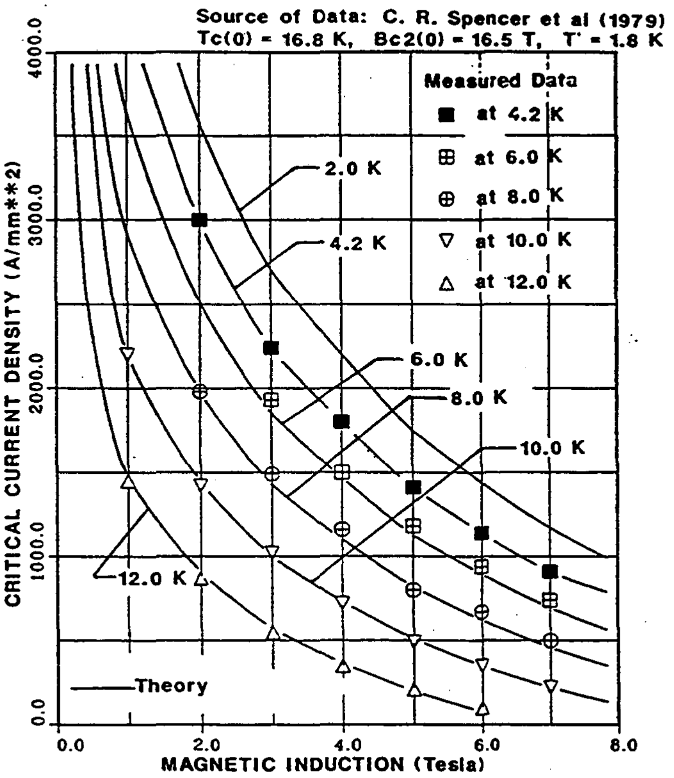

Fig. 4 Calculated and Measured Jc versus B and T for Multifilamentary Nb$_3$Sn[19]

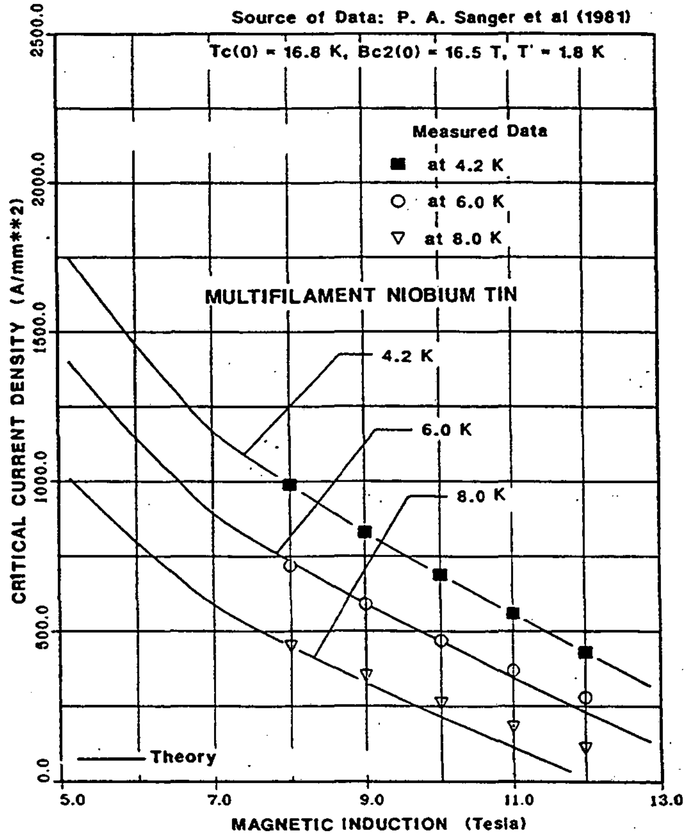

Fig. 5 Calculated and Measured Jc versus B and T for Multifilamentary Nb$_3$Sn[20]

CONCLUSIONS

The reduced state method of estimating J_c as a function of temperature, magnetic induction and strain is attractive because it can be applied over a wide range of temperatures (from 1.5 K to about 14 K) and magnetic inductions (from 0.1 T to about 0.8 B_{c2}). Unlike niobium titanium, where one can calculate $J_c(B,T)$ for the entire J_c, B T surface from measurements at one point, one must have some measured J_c data for the niobium tin over a range of magnetic inductions There is reasonably good agreement between the calculated values of J_c and the measurements over a range of magnetic inductions and temperatures.

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