Variable-Temperature Critical-Current Measurements on a $\mathrm{Nb_3Sn}$ Wire

L. F. Goodrich and T. C. Stauffer

***Abstract*—We made variable-temperature critical-current (I_c) measurements on a commercial multifilamentary $\mathrm{Nb_3Sn}$ wire for temperatures (T) from 4 to 17 K and magnetic fields (H) from 0 to 12 T using transport current. The sample had a diameter of 0.811 mm and a Cu/non-Cu ratio of about 1.5. The measurements cover the range of critical currents from less than 0.01 A to over 700 A. To verify the measurements at variable temperature, we compared critical currents up to 400 A on a specimen that was immersed in liquid helium to those on the same specimen in flowing helium gas. This comparison indicated our ability to control and measure specimen temperature was within 40 mK. The critical-current data presented include electric field/current $(E - I)$ characteristics, and $E-T$ characteristics at constant I and H, $I_c(H)$ at constant T, and $I_c(T)$ at constant H. Such data may be used to determine the temperature margin of magnet applications.**

***Index Terms*—Critical-current measurement, niobium compound, superconducting wires, temperature control.**

I. INTRODUCTION

SUPERCONDUCTOR measurements at variable temperatures are needed to determine the temperature margin for magnet applications. The temperature margin is defined as the difference between the operating temperature and the temperature at which critical current (I_c) is equal to the operating current. The temperature margin is an important consideration in the design of superconducting magnets. When a magnet is operating, transient excursions in magnetic field (H) or current (I) are not expected; however, there are many events or effects that can cause transient excursions to higher temperatures (T), such as wire motion, ac losses, and radiation. The temperature margin of a wire is a key specification and would be more widely used if reliable variable-temperature I_c measurements were routinely available.

We made critical-current measurements on a $\mathrm{Nb_3Sn}$ wire for temperatures from 4.0 to 17 K and magnetic fields from 0 to 12 T using a transport current. The specimen was a commercial multifilamentary wire with a diameter of 0.811 mm and a Cu/non-Cu ratio of 1.5. It was a witness specimen that was reacted in June 2003 with cable-in-conduit conductor (CICC) test strand samples for a fusion energy project. The measurements cover the range of critical currents from less than 0.01 A to over 700 A using an electric field (E) criterion of 10 $\mu\mathrm{V/m}$ 0.1 $\mu\mathrm{V/cm}$). The data acquired include: electric field/current $(E-I)$ characteristics, electric field/temperature $(E-T)$ characteristics at constant I and H, $I_c(H)$ at constant T, and $I_c(T)$ at constant H. These data are needed to determine the temperature margin of magnets (especially applications that use CICC) and performance data for cryogen-free applications. The measured I_c at 10 $\mu\mathrm{V/m}$, 4.2 K, and 12 T was 152 A (n-value 33), which was close to or slightly higher than results from other laboratories on other specimens that were reacted at the same time.

II. PROCEDURE

A fairly detailed description of our variable-temperature apparatus has been published in [1]. One difference from that description is that the present measurements were made with a coil-specimen geometry [2] in a solenoidal magnet; however, the basic concept is the same. One further change since that publication is that we now control the temperature of each current contact with separate temperature controllers rather than controlling one contact and using a balance heater to keep the other at the same temperature. Magnetoresistance corrections were made to all thermometers (metal oxy-nitride resistors) [3], [4].

To verify the measurements at variable temperature, we compared critical currents up to 400 A on a specimen that was measured while immersed in liquid helium ("*liquid*") to those on the same specimen measured with helium gas flowing over the specimen ("*gas*"). For the rest of this paper, data from the first case will be referred to as *liquid* data and data from the second referred to as *gas* data. By comparing $E-I$ curves or I_c values we obtain the apparent difference in specimen temperature, which is a direct indication of our ability to control and measure specimen temperature in *gas*.

The specimen was reacted and measured on a thin-walled Ti-6Al-4V (percent by mass, Ti-6-4) tube. The Cr plating was removed from the specimen prior to the reaction heat treatment. The Ti-6-4 tube was the same as that used by the International Thermonuclear Experimental Reactor (ITER) project [5], except the ends had been machined so that there were only three turns between the current contacts (~30 cm active length) and the current contacts were longer. The voltage taps were separated by 10 cm. No Copper, solder (except for the voltage taps), or epoxy was applied to the specimen between the current contacts. The apparent I_c at 10 $\mu\mathrm{V/m}$, measured when the sample was normal, was less than about 0.01 A, indicating that the shunted current in the mandrel and specimen was very low.

The complete $E-I$ characteristics were measured at many temperatures, at certain currents, and in constant magnetic field in order to generate $E-T$ characteristics at constant current. Three or four determinations were made at most of the current

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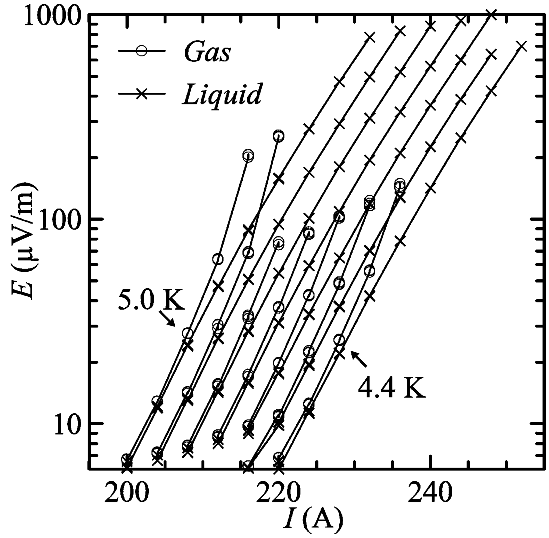

Fig. 1. Semilogarithmic plot of electric field versus current at 10 T and temperatures from 4.4 to 5.0 K in steps of 0.1 K, with data in *gas* and in *liquid* at each temperature.

set-points. The current set-points were approximately every 1, 1.5, 2, 3, or 4 A, depending on the level of current. Our supply could hit the set-points to within about 0.02 A.

A conservative estimate of the expanded uncertainty $(\mathrm{k} = 2)$ in these $\mathrm{Nb_3Sn}$ critical current measurements at 4.2 K due to systematic effects is 2.5%, and that due to random effects is 0.6%. The uncertainty at other temperatures is higher because of the increased sensitivity to temperature, magnetic field, and strain state.

III. *LIQUID/GAS* COMPARISON

Fig. 1 shows semilogarithmic $E - I$ characteristics at temperatures from 4.4 to 5 K in 0.1 K steps, at currents from 200 to 252 A in 4 A steps, and in a magnetic field of 10 T. These $E - I$ characteristics were measured with the specimen at various liquid-helium temperatures and with the specimen in flowing helium gas at those same temperature setpoints. A line connects the adjacent points of a given temperature to distinguish the curves. The multiple determinations of each point were combined and sorted by current. The same plotting technique was used in Figs. 1–4.

In general there was good agreement for voltages up to 20 $\mu\mathrm{V/m}$. The apparent temperature error between *liquid* and *gas* data was within 40 mK near 10 $\mu\mathrm{V/m}$. As expected, the curves diverged at higher voltages due to specimen heating. The points above 100 $\mu\mathrm{V/m}$ in *gas* were not as repeatable because the specimen was close to quenching (the point where the specimen reverts to the normal state). The multiple determinations of most of the *liquid* data cannot be distinguished except at the lowest and highest electric fields.

The electric field above which the specimen would quench was much lower in the *gas* measurements compared to those in *liquid*. The $E - I$ curves were acquired to the highest E possible below the quench, except for *liquid* data. Because the current set-points were quantized, to allow for $E - T$ curves at constant I, the highest E below quench also appears to be quantized. The highest E possible for the *liquid* case was above 1000 $\mu\mathrm{V/m}$ and is not shown on this plot.

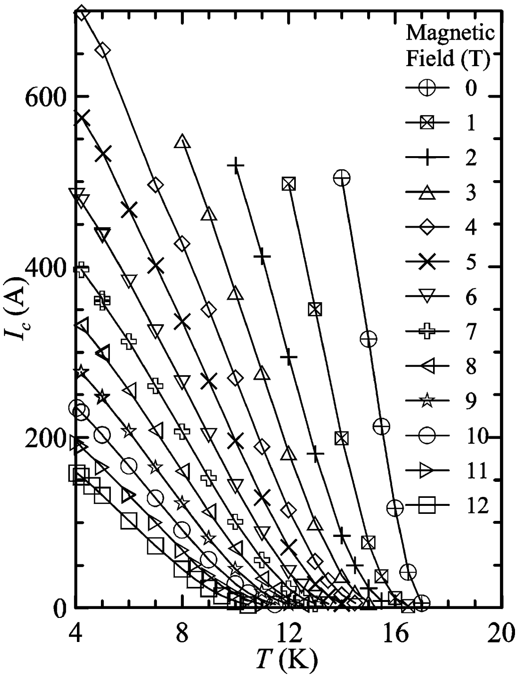

Fig. 2. Linear plot of critical current versus temperature at various magnetic fields.

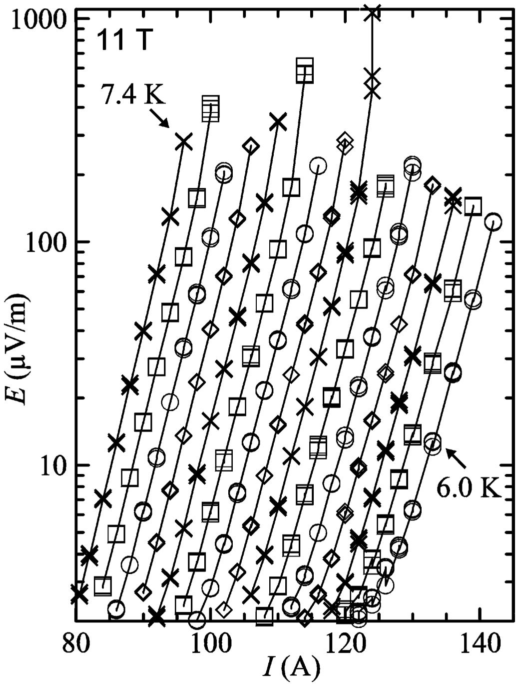

Fig. 3. Semilogarithmic plot of electric field versus current at 11 T and temperatures from 6.0 to 7.4 K in steps of 0.1 K.

The I_c versus T at magnetic fields from 0 to 12 T are shown in Fig. 2. These measurements cover the whole range of critical currents from less than 0.01 A to over 700 A using an electric-field criterion of 10 $\mu\mathrm{V/m}$; however, the points below 2 A were removed to reduce the overlap of curves. These data below 4.7 K are *liquid* data, and those above 5 K are *gas* data. At magnetic fields of 6 T and higher, these data at 5 K are from both *liquid*

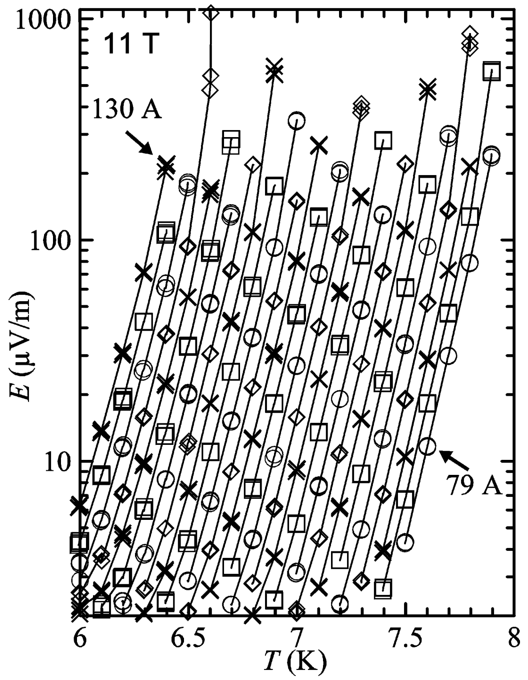

Fig. 4. Semilogarithmic plot of electric field versus temperature at 11 T and constant currents from 79 to 130 A. The current steps are every 1.5 A from 79 to 82 A and every 2 A from 82 to 130 A.

and *gas*. At the higher magnetic fields, the difference between the *liquid* and *gas* data cannot be distinguished. For the higher currents of the shown data, the I_c versus T curve is nearly linear. For this wire, it is expected that the I_c versus T curves will be nonlinear for currents above 600 A [3]. At lower magnetic fields, these *gas* data were limited to currents below 550 A. The curves below about 30 A exhibit a tail with higher temperatures.

IV. $E-I$ AND $E-T$ CURVES

Fig. 3 shows semilogarithmic $E-I$ characteristics at temperatures from 6.0 to 7.4 K in 0.1 K steps and in a magnetic field of 11 T. All of these data in Fig. 3 were *gas* data. The symbols are repeated in a regular pattern in order to use a limited number of symbols that are easily distinguished. Often $E-I$ characteristics are plotted on a full-logarithmic scale, and the slope of this plot gives the "n-value" of the characteristic [2], which is a figure of merit for the conductor [6]. We chose to plot on a semilogarithmic scale in order to place more meaningful tic marks along the x-axis. Also, over the very narrow range of the x-axis, there is not much visible difference between linear and logarithmic scales. The curves on the full-logarithmic plots are slightly straighter.

Fig. 4 shows semilogarithmic $E-T$ characteristics at currents from 79 to 130 A in a magnetic field of 11 T. The multiple determinations of each point were combined and sorted by temperature. The current steps were every 1.5 A for currents from 40 to 82 A, and every 2 A for currents from 82 to 130 A. These data on Fig. 4 are from the same set as those on Fig. 3. The $E-T$ curves at currents below 79 A and above 130 A were omitted for clarity and because they were shorter.

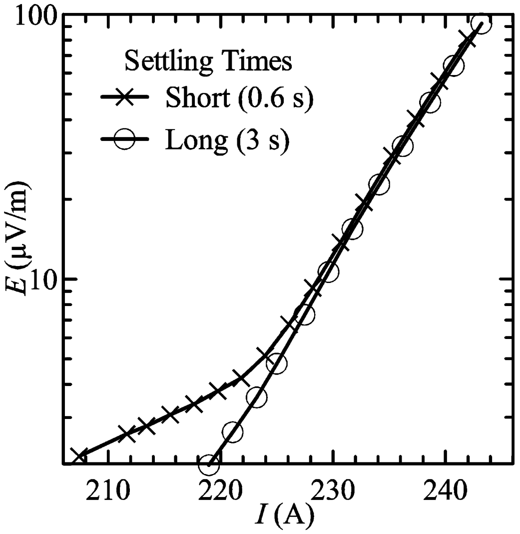

Fig. 5. Semilogarithmic plot of electric field versus current at 10 T and 4.2 K in liquid helium taken using short (0.6 s) and long (3 s) settling times.

The semilogarithmic curves of $E-T$ in Fig. 4 also show a shape similar to those of the $E-I$ curves that suggests that the $E-T$ curves could also be approximated by a constant slope on a full-logarithmic scale, which in the case of $E-T$ curves is defined as the m-value [7], [8]. For example, the n-value of the $E-I$ curve near 128 A and 6.1 K is about 30, and the m-value of the $E-T$ curve near that same point is about 45. To illustrate that there is no simple relationship between these two values, consider another example near 84 A and 7.4 K that has the n-value of about 24, compared to the m-value of about 69 near that same point.

Plots of $E-T$ characteristics at constant currents and fixed magnetic field directly indicate the temperature margin of a conductor. For this wire the margin when operated at 115 A, 4.5 K, and 11 T would be 2.0 K according to Fig. 4, where it can be seen that I_c at 10 $\mu\mathrm{V/m}$ is about 115 A at 6.5 K.

V. DISCUSSION

Measurements at electric fields below 10 $\mu\mathrm{V/m}$ indicated a problem with slowly decaying voltages [9]. For variable-temperature measurements at high current it is necessary to limit the settling times and the duty cycle of the current to reduce specimen heating. Thus, the slowly decaying voltages that occur after every change in transport current interfere with the low-E measurement. The lower E limit for the $E-I$ data of Fig. 1 was selected to reduce the distraction of the lower n-value at the lower E. Fig. 5 shows $E-I$ curves in liquid helium at 4.2 K and 10 T with short (0.6 s) and long (3 s) settling times after the current was ramped. This effect was noticeable below 5 $\mu\mathrm{V/m}$. This effect was not significant for the I_c measurements, but it did limit the useful range of the $E-I$ and $E-T$ curves.

Because the measurements shown on Fig. 5 were made with the specimen in liquid helium, we were able to study the effects of settling time, current duty cycle, and current history. The history of the sample current can affect the decay rate of the voltage that is induced with each current change [9]. The short settling time curve was taken with a low-duty-cycle current waveform that has the current returning to zero between each current set point (see Fig. 5 in [1]). The long settling time curve was taken with a high-duty cycle and the current stepping down through the set points before the current returns to zero. Different settling times, duty cycles, and current histories between these two limits were also studied, and the results were a logical progression from one curve to the other. These results are consistent with the long settling times observed in other $\mathrm{Nb_3Sn}$ and Nb-Ti wires [9].

VI. CONCLUSION

We made critical current measurements on a $\mathrm{Nb_3Sn}$ wire over as wide a range of current, temperature, and magnetic field as possible in our apparatus. The variable temperature measurements were verified by comparing measurements made with the specimen immersed in liquid helium to those made with the same specimen in flowing helium gas. The apparent temperature error between *liquid* and *gas* data was within 40 mK near 10 $\mu\mathrm{V/m}$. Above 20 $\mu\mathrm{V/m}$, the $E - I$ curves in *gas* showed signs of specimen heating, and the E where the specimen would quench in *liquid* was about 10 times that in *gas*. We focused the additional $E - I$ and $E - T$ data at magnetic fields of 10 and 11 T, which are close to the maximum design field for a fusion energy project. At 10 T, we acquired these data at 29 different temperatures from 7.4 to 10.2 K and at 9 temperatures from 4.4 to 5.2 K (for the *liquid/gas* comparison). At 11 T, we acquired these data at 38 temperatures from 6.0 to 9.7 K. These data will be useful in the design and evaluation of magnets for all applications, but especially when using cable-in-conduit conductors.

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