Stability and Quench Protection of Coated YBCO "Composite" Tape

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***Abstract*—The paper presents results, experiment and simulation, of quench/recovery study of coated YBCO "composite" test samples, cooled by boiling liquid nitrogen and subjected to an over-current pulse. To operate stably and be protected from damage under adverse operating conditions of a real device, the YBCO tape must be a "composite," loaded with normal metal of a sufficient thickness that significantly increases the thickness of the original YBCO tape.**

***Index Terms*—YBCO-normal metal composite, stability and quench protection, liquid nitrogen cooling**

I. INTRODUCTION

BECAUSE HTS magnets, owing to their large energy margins, may be considered *almost* absolutely stable, it is generally agreed that every HTS magnet should be "adiabatic," i.e., no cryogen penetrating its winding for "local" cooling. For protection of an HTS magnet from damage upon an unlikely event of a quench, it is also agreed that its superconductor must be loaded with normal metal. A stability and protection study of LTS and HTS magnets, though focusing only on overheating and internal voltage issues and only during the period the magnet terminals are shunted, indicates that the normal metal be either highly-conductive if the magnet is to satisfy a cryostability or internal voltage protection criterion or low-conductive if it is to satisfy an overheating protection criterion [1].

As one of the steps towards achieving HTS "normal metal composites" optimal for HTS magnets or devices, HTS manufacturers have begun developing YBCO "composites" loaded with copper: in the form of either a copper strip soldered as by American Superconductor Corp. or a electroplated copper layer as by SuperPower Inc. (SPI).

Availability of YBCO composites, though limited in test sample length, has made it possible to study and perform experiments on stability and protection of YBCO samples, "bare" (original silver layer) and "composite" (to date, copper layer added) [2–9]. Although as stated above that every HTS magnet should be "adiabatic," our study on stability/protection of YBCO samples has focused on quench/recovery of test samples immersed in boiling liquid nitrogen [3,5,6]. This is because: 1) immersion of the test sample in liquid nitrogen ensures a uniform temperature at 77.3 K over the entire sample; 2) effects of heating at each electrode-sample connection may be easily minimized; and 3) perhaps most importantly the presence or absence of cooling is one of variables incorporated in developing simulation models for quench/recovery. We report here our latest results on quench/recovery of YBCO composites, prepared and supplied by SPI.

II. SIMULATION

A simulation model has the following major components: 1) electrical circuit for a YBCO composite test sample; 2) power balance over the test sample; and 3) convective heat transfer. Each is briefly described below.

A. Electrical Circuit Model for YBCO Composite

A YBCO composite test sample of length ℓ may be modeled by a 2-element parallel circuit model, one element being the normal metal ("matrix"), while the other YBCO. The voltage across the sample, $V_s(T)$, may be given by:

$$\begin{aligned} V_s(T) &= 0 && T_{op} \le T \le T_{cs}(I_{op}) && (1a) \\ &= R_m(T)[I_{op} - I_c(T)] && T_{cs}(I_{op}) \le T \le 93\,\mathrm{K} && (1b) \\ &= R_m(T) I_{op} && T \ge 93\,\mathrm{K} && (1c) \end{aligned}$$

In (1) $T_{cs}(I_{op})$ is the "current-sharing" temperature, i.e., $I_c(T_{cs}) = I_{op}$, where I_{op} is the transport current; $R_m(T)$ is the temperature-dependent matrix resistance. Note that although $V_s(T)$ in the current-sharing regime, as given by (1*b*), is determined by the product of $R_m(T)$ and the matrix current, $I_{op} - I_c(T)$, the same voltage along the superconductor, for $I_{op} \ge I_c(T_{op})$, may also be given by:

$$V_s(T) = V_c \left[\frac{I_{op} - I_c(T_{op})}{I_c(T_{op})} \right]^n \qquad (2)$$

where n is the superconductor's index.

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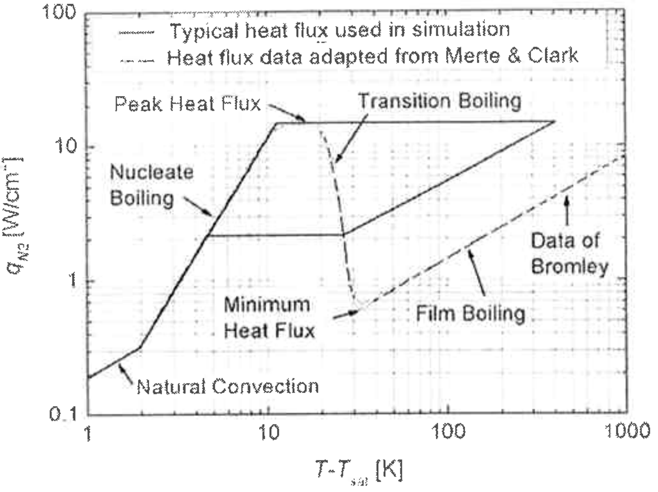


Fig. 1 $q_{N2}(T)$ vs. $T-T_{sat}$ plots for liquid nitrogen, adapted from the data of Merte and Clark [10]. T is the surface temperature; T_{sat} is the saturation temperature for nitrogen.

B. *Power Balance Equation & Convective Cooling*

Power Balance Equation For $T \geq T_{cs}$ (1), a power balance equation for a composite test sample of length ℓ, total cross sectional area A_{cd}, and total test sample area exposed directly to boiling liquid nitrogen A_q, may be given by:

$$A_{cd}\ell C_{cd}(T)\frac{dT}{dt} = G_j(T) - A_q q_{N2}(T) \qquad (3)$$

$C_{cd}(T)$ is the "effective" temperature-dependent heat capacity of the composite with T-dependent heat capacities of the composite's major constituents: 1) YBCO [11,12]; 2) nickel (for Hastaloy C) [13,14]; 3) silver; and 4) copper. $G_j(T)$ is given, depending on T, by either (1*b*) or (1*c*).

Convective Cooling Fig. 1 shows convective cooling data (circles) [10] and curves (solid lines) for $q_{N2}(T)$ in (3).

III. EXPERIMENT

A. *Test Sample*

Fig. 2 shows a schematic cross section drawing of the test samples, each 4 mm wide and with layer thicknesses of: 100 μm (substrate); 1 μm (buffer); 1.4 μm (YBCO); 3 μm (Ag); and 37 μm (each upper and lower Cu layers), applied in a single step to completely encases the coated conductor.

B. *Experimental Setup & Procedure*

Setup Each end of a test sample, 15-cm long, is soldered to a copper electrode with a 4.2-cm overlap. Two sets of voltage taps (5-cm and 10-cm) are soldered to the test sample about the axial midpoint ($z=0$). Three Au-chromel theromocuples (TC-1, TC-2, TC-3) are attached to the sample surface, with a 25-μm thick Kapton sheet as an electrical insulator and a Styrofoam pad at the top to insulate from liquid nitrogen. TC-2 is at $z = 0$, while TC-1 and TC-3 are, respectively, at $z = \pm 6.5$-cm. The test sample setup is placed in a bath of liquid nitrogen (77.3 K).

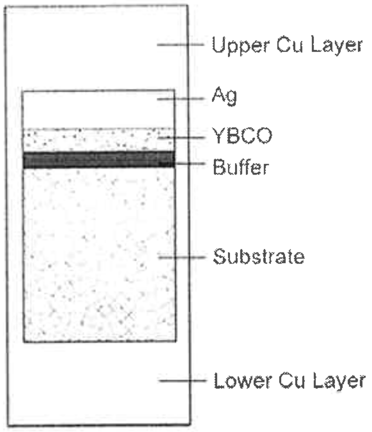


Fig. 2 Schematic drawing of the cross section of YBCO composite manufactured by SuperPower Inc. (SPC).

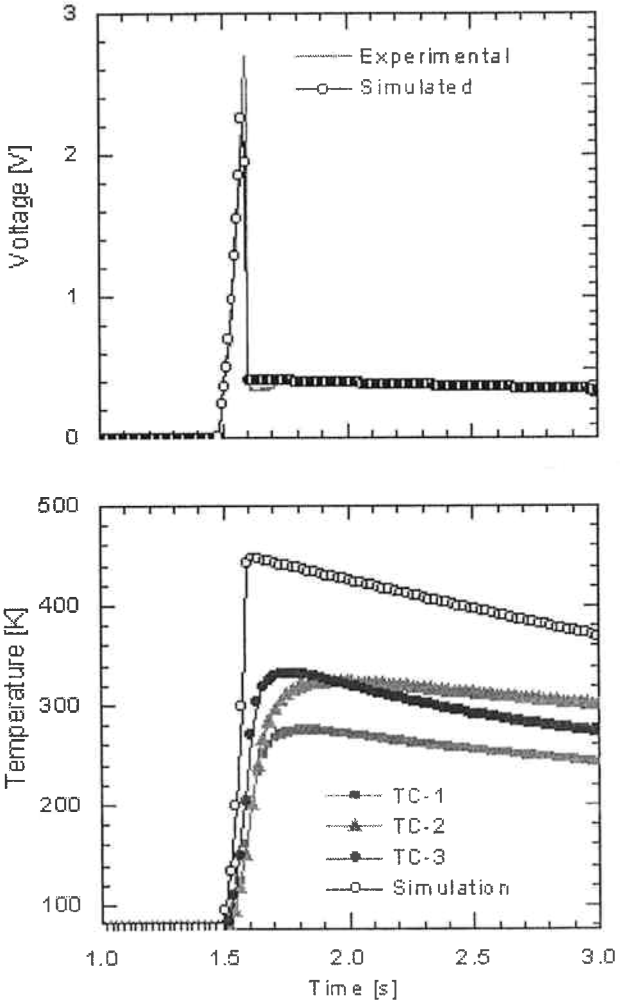


Fig. 3 Voltage (top; 5-cm taps) and temperature (bottom) vs. time traces, experiment and simulation (–o–o–), for Run 12 of Sample A ($I_c = 59$ A at 77.3 K), with $\tau_p = 100$ ms; $I_{op} = 51$ A ($=0.86 I_c$); $I_p = 355$ A ($=5.92 I_c$).

Procedure For each quench/recovery experimental run, test sample transport current undergoes the following sequence: a constant current, I_{op}; then an over-current pulse (duration τ_p) for *total* current of I_p; and back to I_{op}. When $R_m(T)I_{op}$ after pulsing is decreasing with time, I_{op} is kept on until the sample recovers; when $R_m(T)I_{op}$ is increasing, I_{op} is shut off when TC-2 inidicates a temperature of ~400 K. After each run I_c is measured to ensure that the sample remains undamaged.

IV. RESULTS & DISCUSSION

Experimental and simulation results for selected test samples are presented and discussed.

A. Sample A

Sample A had a measured I_c (with a 1-μV/cm criterion) of 59 A at 77.3 A, measured at the beginning. It was subjected to 13 pulsing runs. Fig. 3 shows voltage (top; 5-cm taps) and temperature (bottom) vs. time traces, experiment and simulation (-o-o-) for Run 12, with $\tau_p = 100$ ms; $I_{op} = 51$ A $(=0.86 I_c)$; $I_p = 355$ A $(=5.92 I_c)$.

Although a recovery was achieved after the pulse, the pulse's intense heating delayed it. With voltage traces, agreement between experiment and simulation is excellent; with temperature traces, simulation shows a peak of 450 K, while TC-3 ($z = +6.5$ cm) a peak of 330 K. The discrepancy in amplitude as well as a slight delay in response time observed in the measured signals, is due chiefly to the Kapton sheet that separated the sample surface and the thermocouples. Note that although simulation assumes a uniform heating along the z-axis, and thus a uniform axial temperature distribution, the measurement proved otherwise, indicating the presence of axial conduction, neglected in the simulation, towards each end of the sample where the temperature is anchored at 77.3 K by a thick copper electrode, axially 2.5 cm from each side thermocouple.

The follow-up I_c measurement after Run 12 confirmed that Sample A, despite heated to a temperature of 450 K (simulation), it remained undamaged. Clearly, the presence of copper layer is beneficial to the superconductor.

B. Sample B

Sample B had a measured I_c (with a 1-μV/cm criterion) of 40 A at 77.3 A at the beginning. It was subjected to 12 pulsing runs. Fig. 4 shows voltage (top; 5-cm taps) and temperature (bottom) vs. time traces, experiment and simulation (-o-o-) for Run 4, with $\tau_p = 300$ ms; $I_{op} = 36$ A $(=0.90 I_c)$; $I_p = 221$ A $(=6.13 I_c)$.

The measured voltage signal shows a "knee" at 0.112 V up to the ~halfway point of the pulse, when a thermal runaway occurs. At this point, the Joule dissipation per sample area exposed directly to liquid nitrogen is at a maximum of 12.4 W/cm^2, computed as $[(0.112\,\mathrm{V})\times(221\,\mathrm{A})]/[(5\,\mathrm{cm})\times(0.4\,\mathrm{cm})]$, which nearly matches a peak of 14.5 W/cm^2 in the nucleate boiling heat transfer flux data for liquid nitrogen shown in Fig. 1—note that these peak values can quite easily vary, mainly owing to variations on surface condition, ~±50% from data to data, demonstrating that the observed thermal runaway at the halfway point in Fig. 4 is indeed a clear evidence that cooling operating on the sample surface switched from nucleate boiling to film boiling that caused heating to exceed cooling.

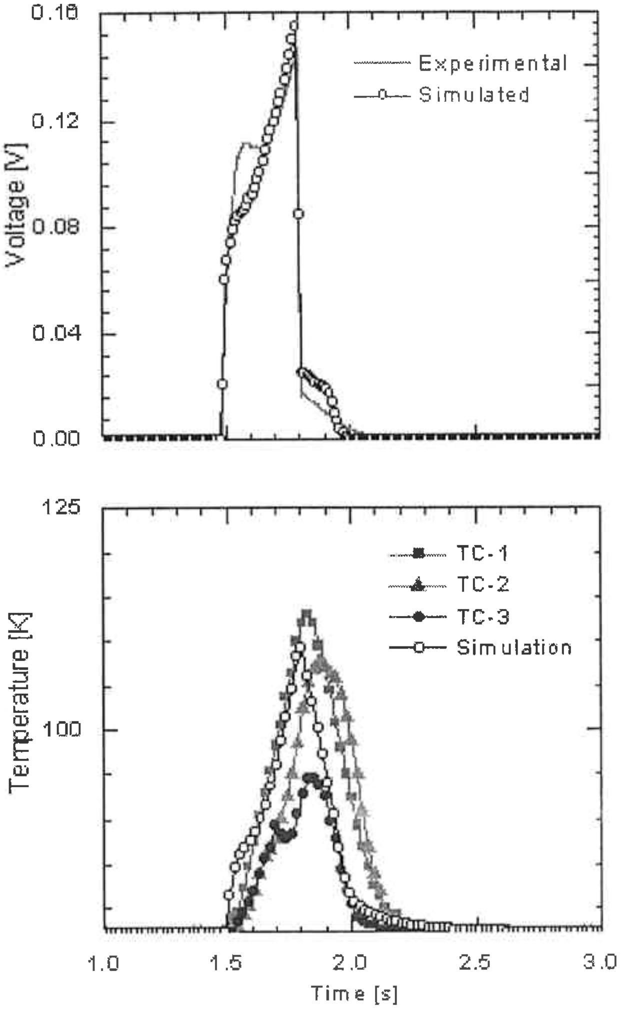


Fig. 4 Voltage (top; 5-cm taps) and temperature (bottom) vs. time traces, experiment and simulation (-o-o-), for Run 4 of Sample B ($I_c = 40$ A at 77.3 K), with $\tau_p = 100$ ms; $I_{op} = 36$ A $(= 0.90 I_c)$; $I_p = 221$ A $(=6.13 I_c)$.

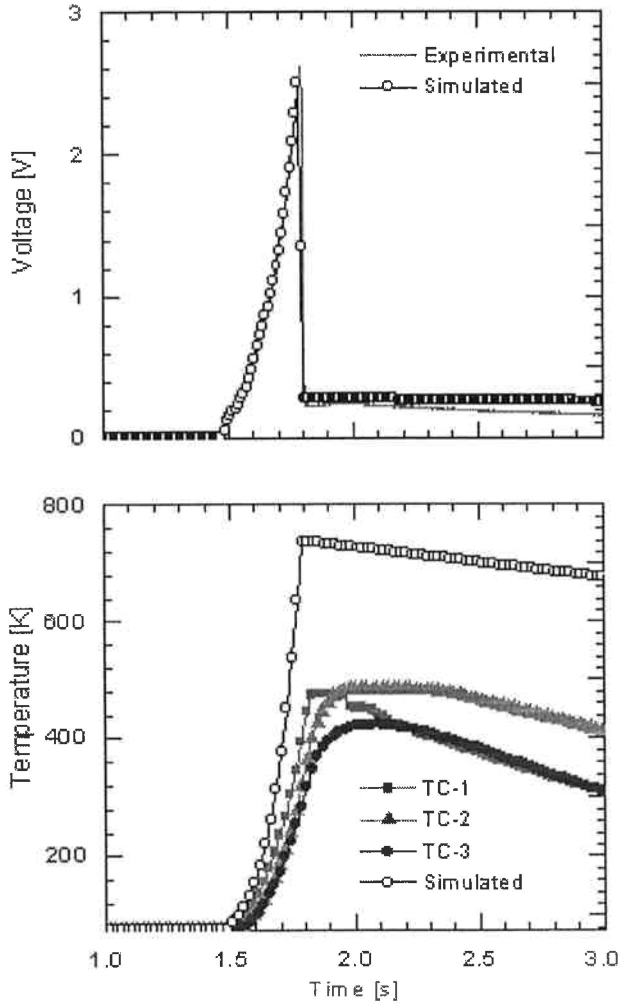
At the end of the pulse, the voltage drops from 145 mV to 16 mV or a Joule dissipation flux at the sample surface of 0.29 W/cm^2, well within the nucleate boiling range. However, recovery is not "instant," instead it takes ~0.3 s for recovery to be completed, apparently because heat transfer flux returns to the $T - T_{sat} \sim 1$ K point, tracing the film boiling line highlighted in Fig. 1.

As in Run 12 for Sample A (Fig. 3), thermocouple signals for Sample B (Fig. 4) also show a nonuniformity of the temperature distribution along the sample axis, once again showing that axial conduction towards each end of the sample is not completely negligible compared with convective cooling of liquid nitrogen.

Fig. 5 shows voltage and temperature vs. time traces similar to those of Fig. 4 for Run 11 of Sample B, with $\tau_p = 300\,\mathrm{ms}$; $I_{op} = 36\,\mathrm{A}$ $(= 0.90 I_c)$; $I_p = 355\,\mathrm{A}$ $(= 9.10 I_c)$.

The measured voltage signal unquestionably shows a thermal runway that begins the instant the pulse is applied. At the end of the pulse just before current is switched back to I_{op}, Joule dissipation flux on the test sample surface is $461.5\,\mathrm{W/cm^2}$, computed as $[(2.6\,\mathrm{V}) \times (355\,\mathrm{A})]/[(5\,\mathrm{cm}) \times (0.4\,\mathrm{cm})]$, which is more than ~ 30 times greater than a peak nucleate boiling flux of $\sim 15\,\mathrm{W/cm^2}$.

The temperature sensors, with delayed response times, indicated a peak sample temperature of 480 K, while simulation shows the test sample heated to 740 K. However, because the voltage was heading towards 0 after the pulse, the post-pulse current was kept at I_{op}. The I_c-measurement performed on Sample B after Run 11 once again demonstrated that Sample B remained intact despite it having heated to a temperature of at least $\sim 500\,\mathrm{K}$; we believe a computed peak temperature of 740 K is likely a suspect.



Voltage (top; 5-cm taps) and temperature (bottom) vs. time traces, experiment and simulation (—o—o—), for Run 11, Sample B ($I_c = 40\,\mathrm{A}$ at 77.3 K), with $\tau_p = 300\,\mathrm{ms}$; $I_{op} = 36\,\mathrm{A}$ $(= 0.90 I_c)$; $I_p = 355\,\mathrm{A}$ $(= 9.10 I_c)$.

V. CONCLUSIONS

A quench/recovery study, experimental and simulation, was performed on coated YBCO "composite" test samples. Each sample is copper-electroplated to completely encase the coated conductor. The latest results clearly have demonstrated that the presence of a copper layer of a significant thickness—at least one order of magnitude greater than that of the original silver layer—greatly "protects" the resultant "composite" against a large overcurrent pluse; in contrast "bare" (only thinly Ag-coated) samples could easily be damaged under similar conditions. Thus YBCO in these "composites" have been shown to remain intact even after repeatedly heated to a temperature close to 500 K. This "survival" temperature is likely to be the same even in bare samples too. However, a layer of conductive normal metal, though it obviously leads to a lower overall current density in the winding, should provide a crucial safety blanket that enables a composite to remain intact even under adverse operating conditions.

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