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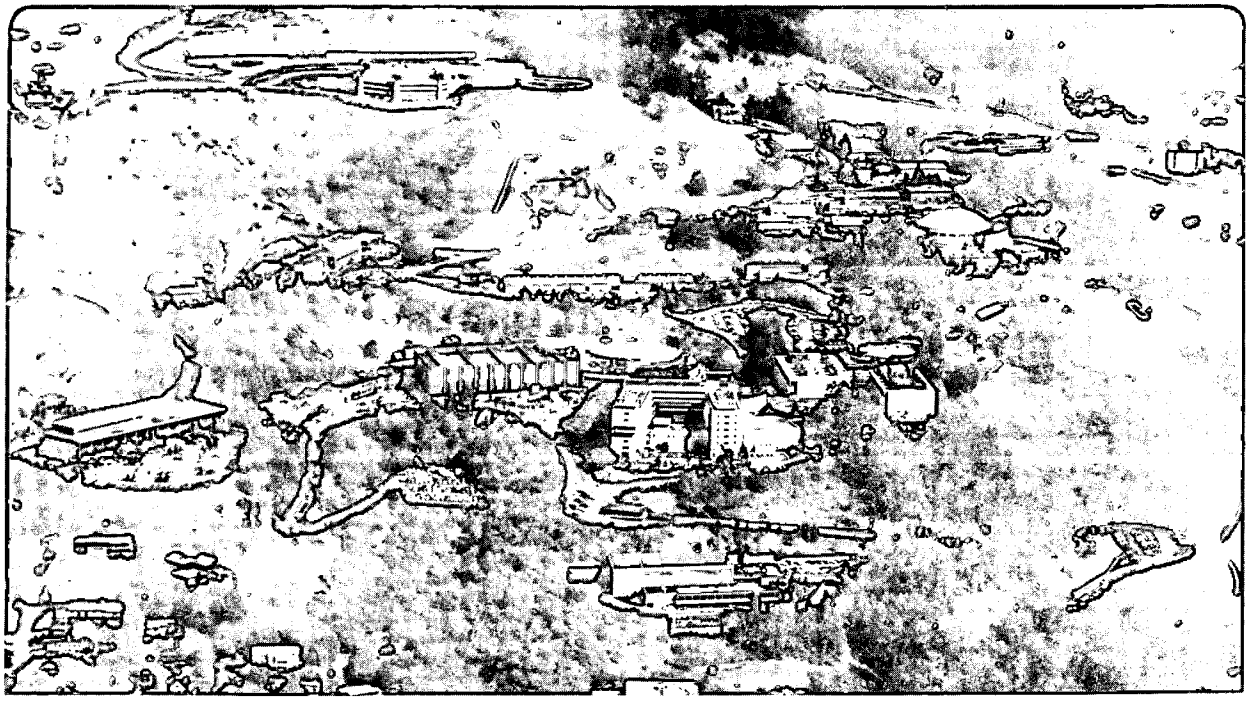

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ABSTRACT

Superconducting magnets with well coupled low resistance secondary circuits have been observed to become fully normal faster than quench propagation in the coil would permit. This process is referred to as "quench back." Quench back observed at the Lawrence Berkeley Laboratory (LBL) was caused by heating the secondary circuit from the current induced from the primary circuit as normal region in the superconducting coil propagated. This paper develops the theory for thermal quench back in thin solenoid magnets and compares this theory with measurements made in two one-meter diameter superconducting solenoid magnets.

1. Introduction

The Lawrence Berkeley Laboratory (LBL) has built and tested superconducting solenoid magnets with closely coupled shorted secondary circuits which are an integral part of the magnet quench protection system.[1,2,3] The role of these shorted secondary circuits as part of the quench protection system is as follows:

1) Current is shifted from the superconducting circuit to the secondary circuit inductively which reduces the hot spot temperature in the superconductor.[4]
2) The secondary circuit can absorb a substantial amount of the magnet stored energy during a quench. This reduces the hot spot temperature in the superconductor further.
3) Since the rate of flux decay is slower than the rate of superconducting coil current decay, the voltages in the magnet system during the quench are reduced over the same superconducting coil without a secondary circuit.
4) The shorted secondary circuit permits some unusual types of external active quench protection to be used (i.e., the varistor resistor or the center tap discharge systems[5]).
5) The shorted secondary circuit causes the whole superconducting coil to become normal in a time which is smaller than would occur by ordinary normal region propagation within the coil.[1,6] This phenomena is referred to as "quench back."

Before continuing our discussion of the shorted secondary circuit concept, it is useful to point out this concept was discussed in the

literature before the LBL experiments. Maddock and James[7] discussed the concept of a coupled secondary circuit and its usefulness in protecting cryostable magnets. The paper concluded that the shorted secondary circuit material would be better used if it were combined with the primary circuit. This conclusion is correct in cryostable magnets which are protected by an ordinary resistor, but it is believed that this conclusion does not hold in high current density magnets where quench back occurs. Maddock and James did not look at the varistor resistor quench protection system. The shorted secondary circuit improves the performance of the varistor resistor quench protection system whether or not quench back is present.[3,8] (All that is required is good coupling between the primary and secondary circuits.)

When LBL built its first thin superconducting test solenoid, the aluminum winding form was the shorted secondary circuit. The use of the aluminum bore tube as a secondary resulted in a lighter magnet. The winding form was to cause the current in this superconducting coil to decrease more quickly during a quench and the winding form was to absorb a substantial portion of the magnet stored energy.[9] Quench back was not discovered until the testing of these magnets. The result of quench back was even lower hot spot temperatures.

Quench back in superconducting magnets has two causes:[2,10] 1) normal regions are induced by heat transfer from other parts; we call this form of quench back "thermal quench back." 2) Normal regions can also be induced by A.C. losses in the superconductor due to changing magnetic fields; we call this form of quench back "magnetic

quench back". Thermal quench back has been the dominant form of quench back observed in the various LBL magnet tests. Magnetic quench back will not be discussed further; the theory for thermal quench back is developed here.

2. A Theory for Thermal Quench Back in Thin Superconducting Solenoids

The theory for thermal quench back given here is restricted to relatively thin solenoids which were tested by LBL. As a result, quench propagation through the thickness of the coil can be ignored. Thermal quench back has two important time periods associated with it. The first time period is the time in which the secondary circuit heats up to a temperature of around 10K. The first time period is defined as t_Q. The second time period is the time for heat to flow from the secondary circuit to the superconductor. This time period is defined as t_H.

At low currents in a superconducting coil, the first time period t_Q (the time needed to transfer enough current to heat the secondary circuit) is the dominant one in the overall quench back time t_{QB}. As the current density in the superconductor gets higher, the second time period t_H becomes more important. In order to simplify the calculation of the quench back time t_{QB} one can assume that;

$$t_{QB} = t_Q + t_H \tag{1}$$

The first time period t_Q is a function the rate of growth of the normal region in the coil before quench back, and the shift of the

current from the primary to the secondary circuit before quench back. The second time period t_H is a function of the thickness of the insulation between the secondary circuit and the superconducting coil and the thickness of the superconducting layer immediately adjacent to the secondary circuit.

a) The growth of the normal region in the coil before quench back.

Normal region growth starts out three dimensional. In thin superconducting solenoids the normal region growth quickly becomes two dimensional. The time for this transition is short so it is assumed that this time is zero. The two dimensional growth of the normal region in the superconducting coil continues until it becomes one dimensional or quench back occurs.

When quench propagation is two dimensional in a thin solenoid, the growth of the magnet resistance R(t) is;

$$R(t) = R_{o2}\alpha V_L{}^2 t^2 \tag{2}$$

when time $t \leq t^*$ where t^* is the shorter of two times t1 or t2 which are defined as follows

$$t1 = \frac{\pi a_1}{V_L} \tag{2a}$$

and

$$t2 = \frac{\ell_1}{\alpha V_L} \tag{2b}$$

where a_1 is the radius of the solenoid; ℓ_1 is the length of the solenoid coil (Note: that ℓ_1 is defined as the maximum length which when applied yields the most conservative solution.); V_L is the normal region propagation velocity along the wire; and α is the ratio of turn to turn normal region propagation to normal region propagation velocity along the wire. The value of R_{o2} given in Eq. 2 is defined as follows;

$$R_{o2} = \frac{N_1 \rho_1}{\ell_1 A_{c1}} \left(\frac{r + 1}{r} \right) \tag{2c}$$

where N_1 is the number of turns in the coil; ρ_1 is the resistivity of the matrix material of the super-conductor at a temperature just above critical temperature; r is the normal metal to superconductor ratios in the superconducting wire; ℓ_1 is the coil width; and A_{c1} is the cross sectional area of the superconductor (matrix material plus superconductor).

The quench propagation becomes one dimensional at $t = t^*$. If $t^* = t1$ the growth of the magnet resistance takes the following form

$$R(t) = R(t1) + R_{o1} \alpha V_L (t - t1) \tag{3}$$

If $t^* = t2$ the growth of the magnet resistance takes the following form:

$$R(t) = R(t2) + R_{o1} V_L (t - t2) \tag{4}$$

Note Eq. (3) applies when a quench propagate along a magnet turn faster than it does across the coil width. (The thin solenoids described in this report are examples of this type of magnet.) Equation (4) applies when the propagation across the width of the coil is faster than along a turn. (A large diameter small cross-section coil might be an example of this type of magnet.) It should be noted that there is one special case of a magnet which has one dimensional propagation which does not fit either Eqs. (3) or (4). This is the ultra pure aluminum stabilized thin solenoid.[11] The turn to turn propagation velocity can be so slow that all propagation is along the wire going around and around the coil. This special case is not discussed here.

The value of R_{o1} depends on which equation describes the one dimensional quench propagation. If Eq. (3) describes the resistance growth t* = t1 then;

$$R_{o1} = \frac{2\pi a_1}{\ell_1} \frac{N_1 \rho_1}{A_{c1}} \left(\frac{r + 1}{r} \right) \tag{3a}$$

where a_1, ℓ_1, ρ_1, and A_{c1} are previously defined. If Eq. (9) describes the resistance growth, t* = t2 then;

$$R_{o1} = \frac{2N_1 \rho_1}{A_{c1}} \left(\frac{r + 1}{r} \right) \tag{4a}$$

again N_1, ρ_1, r, and A_{c1} are previously defined.

Before leaving this study of normal region growth, it is useful to point out that Eqs. (2), (3), and (4) assume that once the coil has gone normal its resistance doesn't change. Early in the quench, before a significant portion of the magnet energy is dumped into the coils or the magnet secondary circuits this is close to being true.

The quench velocity along the wire V_L is complicated to calculate. A theory for this calculation is given in Ref. (12). Otherwise one should measure the velocity V_L. The functional form for the quench velocity along a niobium titanium in copper wire at low fields is shown in Fig. 1. To first order, there is little dependence of V_L upon r or ρ_1. Increased temperature speeds up V_L as does increased magnetic field.[13]

The ratio of turn to turn to longitudinal quench velocity α in a coil with rectangular conductors can be expressed approximately using the following expression, which is derived from equations given in Ref. (14);

$$\alpha = \left[\frac{\rho_1 k_i}{L\ T_c} \ \frac{a}{S} \ \frac{b'}{b} \ \frac{r+1}{r} \right]^{1/2} \tag{5a}$$

when b'/b is greater than 0.5 and

$$\alpha \simeq 0.7 \left[\frac{\rho_1 k_i}{L\ T_c} \ \frac{a}{S} \ \frac{r+1}{r} \right]^{1/2} \tag{5b}$$

when b'/b is less than 0.5. k_i is the thermal conductivity of the insulation between the turns; ρ_1 is the resistivity of the matrix material in the superconductor; r is the normal metal (matrix) to superconductor ratio; L is the Lorentz number ($L = 2.45 \times 10^{-8} \Omega WK^{-2}$); and T_c is the critical temperature of the superconductor (use $T_C = 7K$). The values of a, b, b' and s are given as follows: a is the width of the conductor in the turn to turn propagation direction; b is the thickness of the conductor; b' is the width of the flat face at the edge of the conductor (Note: b' = b when there are no rounded corners on the rectangular conductor); and s is the thickness of the insulation between turns.

For thin superconducting coils with round conductors, the ratio of turn to turn to longitudinal normal region propagation velocity α takes the same form as Eq. (5b) except a is defined as the diameter of the round superconductor.

b) The shift of the current from the superconducting coil to the secondary circuit.

The superconducting coil closely coupled with a single secondary circuit is represented schematically in Fig. 2. The electrical behavior of the coupled circuit can be represented by a pair of coupled differential equations

$$L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} + i_1 R_1 = 0$$
$$L_2 \frac{di_2}{dt} + M \frac{di_1}{dt} + i_2 R_2 = 0 \qquad (6)$$

with $i_1 = i_0$ and $i_2 = 0$ at $t = 0$.

When the coupling between the two circuits is good the solution to the coupled equations takes the following form

$$i_1 = \frac{i_o}{(\tau_L - \tau_s)} \left[(\tau_1 - \tau_s) e^{-t/\tau_L} + (\tau_L - \tau_1) e^{-t/\tau_s} \right] ,$$

$$i_2 = \frac{M_{12}\, i_o}{L_2(\tau_L - \tau_s)} \left[(\tau_2 + \tau_s) e^{-t/\tau_L} - (\tau_2 + \tau_s) e^{-t/\tau_s} \right] , \tag{7}$$

where τ_1, τ_2, τ_L, τ_s, are defined as follows

$$\tau_1 = \frac{L_1}{R_1} , \tag{7a}$$

$$\tau_2 = \frac{L_2}{R_2} \tag{7b}$$

$$\tau_L = \tau_1 + \tau_2 \tag{7c}$$

$$\tau_s = \frac{\varepsilon\, \tau_1 \tau_2}{\tau_1 + \tau_2} , \tag{7d}$$

$$\varepsilon = 1 - \frac{M_{12}^2}{L_1 L_2} , \tag{7c}$$

where L_1 is the inductance of the primary circuit (the superconducting coil); L_2 is the inductance of the secondary circuit; R_1 is the resistance of the primary circuit given in Eqs. (2), (3), and (4); R_2 is the resistance of the secondary circuit; and M_{12} is the mutual inductance between the two circuits. This theory assumes that L_1, L_2, M_{12}, and R_2 are constant before quench back occurs.

i_1 and i_2 can be calculated directly from Eq. (7), or when τ_s is small and when it is early in the quench before much energy has been absorbed by the coil or the secondaries a simplified form can be used;

$$i_1 = \frac{\tau_1}{\tau_1+\tau_2} i_o \quad ,$$

$$i_2 = \frac{\tau_2}{\tau_1+\tau_2} \frac{N_1}{N_2} i_o \quad . \tag{8}$$

where i_o is the starting current; N_1 is the number of turns in the superconducting coil; N_2 is the number of turn in the secondary circuit; and τ_1 and τ_2 are defined by (7a) and (7b).

c) The time required for the secondary circuit to reach quench back temperature.

Using an adiabatic theory[15] which assumes no heat transfer out of the secondary circuit one can define a function F_2^* which is a function of the integral of current density in the secondary circuit squared with time

$$F_2^* = F_2(T_Q) - F_2(T_o) = \int_0^{t_Q} J_2(t)^2 dt \tag{9}$$

where

$$F_2(T_Q) \simeq \int_0^{T_Q} \frac{C_2(T)}{\rho_2(T)}\, dT = \frac{H_2(T_Q)}{\rho_2} \tag{9a}$$

$$F_2(T_o) = \int_0^{T_o} \frac{C_2(T)}{\rho_2(T)} dT = \frac{H_2(T_o)}{\rho_2} \tag{9b}$$

$$J_2(t) = \frac{i_2(t)}{A_{c2}} \tag{9c}$$

where i_2 is defined by Eq. 7; A_{c2} is the cross-sectional area of the secondary circuit; H_2 is the enthalpy per unit volume of the material in the secondary circuit at temperature T_Q and T_o (Note $H_2 = 0$ at 0K) ρ_2 is the electrical resistivity of the secondary circuit material; (Note ρ_2 has a constant value from 0 to 15 K); T_o is the starting temperature (say 4.5 K); T_Q is the temperature of the secondary circuit needed to induce quench back (about 10 K for niobium-titanium magnets) and t_Q is the time needed to heat the secondary circuit from T_o to T_Q. Using Eqs. (8) and (9) (close coupling is assumed and not much energy is lost by resistive heating) one gets the following form for the heating of the secondary circuit to the quench back temperature T_Q

$$F_2^* = \frac{\Delta H_2}{\rho} = \int_0^{t_Q} \left[\frac{\tau_2}{\tau_1+\tau_2} \frac{N_1}{N_2} \frac{i_o}{A_{c2}} \right]^2 dt \tag{10}$$

where τ_1, τ_2, N_1, N_2, and i_o have been previously defined from Eq. (8) and A_{c2} is defined by Eq. (9c).

The value of τ_1 in Eq. (10) can be found using the following relationships:

$$\tau_1 \simeq \frac{L_1}{R_{o2}\ \alpha\ V_L{}^2 t^2} \tag{11a}$$

when $o \leq t \leq t^*$ and R_{o2} is defined by Eq. (2c).

$$\tau_1 \simeq \frac{L_1}{R(t1) + R_{o1}\alpha V_L(t - t1)} \tag{11b}$$

when $t^* \leq t \leq t^{**}$, $t^* = t1$ and R_{o1} is defined by Eq. (3a).

$$\tau_1 \simeq \frac{L_1}{R(t2) + R_{o1}V_L(t - t2)} \tag{11c}$$

when $t^* \leq t \leq t^{**}$, $t^* = t2$ and R_{o1} is defined by Eq. (4a). Note t^{**} is defined as the longer of the two times t_1 and t_2. (The coil is completely normal when $t > t^{**}$; quench back can't occur.)

Table 1 shows the enthalpy as a function of temperature from 4.5 to 15 K. This table can be used to calculate the value of ΔH_2 given in Eq. (10). The resistivity of the superconductor matrix material ρ_1 and the secondary circuit material ρ_2 is a function of the material, its purity, and the magnetic field it is in. Table 2 shows the 15 K resistivity of various coppers and aluminum at 0.0 T and 1.0 T.

Table 1. Enthalpy of various materials as a function of temperature from 4.5 to 15 K.

	Enthalpy ($J\ m^{-3}$)			
Temperature	Aluminum*	Copper*	Nb-Ti+	Epoxy**
4.5	1620	1600	8800	9000
5.0	2110	2230	11300	13000
6.0	3270	3830	17200	24000
7.0	4860	6330	24900	40000
8.0	7020	9790	34700	62000
10.0	13200	21400	--	120000
12.0	22400	40100	--	200000
15.0	48600	95200	--	360000

*See Reference 16 for tables and charts of specific heat.

+See Reference 17 for method of enthalpy calculation.

**Estimate--good data is hard to find.

Table 2. The resistivity of coppers and aluminums at 15K as a function of residual resistivity and magnetic field[16]

Material	RRR*	Resistivity (ohm m) B=0.0 T	Resistivity (ohm m) B=1.0 T
Copper	10	1.55×10^{-9}	1.6×10^{-9}
	30	5.17×10^{-10}	5.8×10^{-10}
	100	1.55×10^{-10}	2.0×10^{-10}
	300	5.17×10^{-11}	1.0×10^{-10}
Aluminum	14	1.8×10^{-9}	1.8×10^{-9}
	25	1.0×10^{-9}	1.1×10^{-9}
	100	2.45×10^{-10}	3.5×10^{-10}
	300	8.12×10^{-11}	1.3×10^{-10}
	1000	2.45×10^{-11}	5.0×10^{-11}

* RRR $= \frac{\rho(273K)}{\rho(4.2K)}$ = residual resistivity ratio

Solving Eq. (10) for t_Q directly does not lead to a closed form solution. One can make a first order estimate of t_Q if several assumptions are made. They are:

1) The current in the primary circuit drops only a little before quench back occurs. This assumption is even valid when $i_1 > 0.7\ i_o$.
2) The velocity of quench propagation along the wire does not change with time. Quench velocity is determined by J_o.
3) The energy dissipated in the coil and its secondaries is small compared to the total magnetic energy stored in the coil before quench back.
4) The coupling is good so that t_{QB} is large compared to τ_s.
5) $\tau_2 << \tau_1$ during most of the time before quench back occurs.

When one tries to calculate the quench back time t_{QB}, one doesn't always know whether the quench propagation is two dimensional or one dimensional. In general, thin solenoids with a diameter greater than 0.8 meters will have dominantly one dimensional normal region propagation. As a result, the LBL one meter diameter solenoids have one dimensional normal region propagation.

If the normal region propagation within the coil is two dimensional, an approximate solution of Eq. (10) for t_Q is;

$$t_Q \simeq \left[5F_2{}^* \left(\frac{L_1 R_2 N_2 A_{c2}}{L_2 R_{o2} N_1 \alpha V_L{}^2 i_o} \right)^2 \right]^{1/5} \tag{12}$$

where F_2^* is determined by Eq. (9) and Table 1. L_1, L_2, N_1, N_2, R_2, i_o and A_{c2} are previously defined. V_L can be determined by measurement or by the use of the method given in Ref. 12. α is calculated using Eqs. (5a) or (5b), and R_{o2} is calculated using Eq. (2c).

If the normal region propagation within the coil is one dimensional, the approximate solutions of Eq. (10) for t_Q are;

$$t_Q \simeq \frac{t1}{2} + \left[3F_2^* \left(\frac{L_1 R_2 N_2 A_{c2}}{L_2 R_{o1} N_1 \alpha V_L i_o} \right)^2 \right]^{1/3} \tag{13}$$

when t* = t1 (one dimensional propagation is from turn to turn) and

$$t_Q \simeq \frac{t2}{2} + \left[3F_2^* \left(\frac{L_1 R_2 N_2 A_{c2}}{L_2 R_{o1} N_1 V_L i_o} \right)^2 \right]^{1/3} \tag{14}$$

when t* = t2 (one dimensional propagation around the coil along the wire), where F_2^*, L_1, L_2, N_1, R_2, V_L, i_o, A_{c2} and α are defined as before. In Eq. (13) R_{o1} is defined by Eq. (3a); in Eq. (14) R_{o1} is defined by Eq. (4a).

Equations (12), (13) and (14) apply to most thin solenoid superconducting magnets. Other cases are discussed in some detail in Ref. 18.

d) The time required to transfer heat from the secondary circuit to the superconductor.

The second term in Eq. (1) is the time period associated with the transfer of heat from the secondary circuit to the superconductor to

drive it normal. The time period for heat transfer t_H can be represented by the sum of two terms. The first is the time required for heat to pass through the electrical insulation between the secondary circuit and the superconductor. The second term is the time required for heating the superconductor up to its critical temperature. An approximate expression for t_H;

$$t_H \approx \frac{bw\ \Delta H_{sc}}{k_{in}\ \Delta T} + \frac{w^2\ \Delta H_i}{k_{in}\ \Delta T} \tag{15}$$

where b is the superconductor thickness (Note: for round wire coils $b \approx \pi a/4$); w is the thickness of the insulation between the superconductor and the secondary circuit; k_{in} is the insulation thermal conductivity; and ΔT is defined as the difference between T_2 and T_o. ΔH_{sc} is the enthalpy change needed to drive the superconductor normal and ΔH_i is the average enthalpy change in the insulation layer.

ΔH_i is relatively easy to calculate but ΔH_{sc} is not. ΔH_{sc} includes a sensible specific heat term and a term due to the magnetization of the superconductor.[12,17,18] Tables 3 and 4 give values of ΔH_i, k_{in}, and ΔH_{sc} which can be applied in Eq. (15) to calculate the heat transfer time t_H. Both tables assume $T_o = 4.5$.

Table 3. Enthalpy change H_i and average thermal conductivity k_i as a function of the temperature difference ΔT of the heated shorted secondary and the initial temperature $\Delta T = T_Q - T_O$ and the thickness of the insulation.

Thickness*	ΔT(K)	k_i ($Wm^{-1}K^{-1}$)	ΔH_i (Jm^{-3})
0.2 mm	2	0.045	16000
	5	0.051	60000
	10	0.063	200000
0.5 mm	2	0.119	15000
	5	0.127	55000
	10	0.136	180000
1.0 mm**	2	0.130	14000
	5	0.139	50000
	10	0.148	160000

*The insulation is 0.1 mm Formvar, and the rest is epoxy glass.
**For insulation thicker than 1.0 mm, use the same values as for 1.0 mm.

Table 4. Enthalpy change ΔH_{SC} as a function of magnetic induction in the material and the copper-to-superconductor ratio r.
(Note: T_0 = 4.5 K)

Induction	ΔH_{SC} (J m^{-3})**		
	r = 1.0	r = 1.8	r = 2.5
0.5	24500	19300	16800
1.0	12100	9300	7900
1.5	8200	6300	5300
2.0	5000	3500	3000

*The material is copper based Nb-Ti multifilamentary superconductor
**These values apply for a magnet similar to the thin solenoid magnets described here.

3. Measurement of Quench Back in the A and B Thin Superconducting Solenoid Magnets and a Comparison with Theory

Thermal quench back was first observed and identified by LBL during induced quenches in the A and B one-meter diameter solenoids.[1] The magnets, which were approximately half a meter long, were built with two layers of 1.0 mm diameter superconductor wound on an 1100-0 aluminum bobbin which forms the shorted secondary circuit. Figure 3 shows one of the one meter diameter test solenoids. Figure 4 shows a cross-section of the thin solenoid coil. Table 5 shows the physical parameters of the A and B solenoid magnets.

The bobbin thickness was 6.35 mm and the thickness of the insulation between the superconducting coil and the bobbin was about 0.35 mm. The 1100-0 aluminum bobbin, which has a 4.5 K resistivity of 1.8×10^{-9} ohm m, was closely coupled inductively (about 99 percent) to the superconducting coil. The coils and their secondary circuits were cooled indirectly by forced two phase helium in tubes outside of the coil (see Fig. 4).

The A and B thin solenoid magnets were instrumented with small coils, about 1 centimeter in diameter, for inducing quenches. The coils used to induce the quenches were at the end of the bobbins. As a result, the rate of normal region growth was restricted. A normal region about 1 centimeter in diameter was induced in the superconducting coil through superconductor a.c. loss by discharging a 1000 μF capacitor into the small coil.

Quench back was observed by a sharp drop in the coil current and by a sharp increase in the $d\phi/dt$ voltage measured by a coil wound around the outside of the magnets. Since the time when the quench was induced is known, the quench back time was easily measured. Figure 5 shows the magnetic flux generated by currents in the coil and the bobbin. Quench back occurs when the magnetic flux generated by the coil current ϕ_c takes a sudden drop. The magnetic flux generated by current in the bobbin ϕ_{AL} rises as ϕ_c drops. The method of calculation used to generate Fig. 5 is described in Ref. 2.

Figure 6 shows a plot of i_1/i_o versus time after the quench was induced for quenches induced at various starting currents i_o in the B thin solenoid. The start and finish of quench back are indicated by a circle and an inverted triangle respectively. Quench back is clearly evident in all the quenches above 100 A. The 100 A quench could barely be established, and quench back appears to be absent in this case. Figure 7 shows the measured quench back time versus starting current in the A and B magnet. From Fig. 7, it is clear that quench back in the B magnet occurs more quickly than in the A magnet. In all cases in Figures 6 and 7, the quench was induced at the end of the superconducting coil. Quench back was observed to occur in a shorter time when the quench was induced at the center of the coil or at more than one place in the coil.[2,20] This observation can be predicted by the theory.

A comparison of theory with experimental measurements was made using Eq. (13) to calculate t_Q and Eq. (15) to calculate t_H. Since the LBL one meter diameter solenoids were wound with Nb-Ti

Table 5. Parameters and constants for the A and B magnets.

	A Magnet	B Magnet
Magnet Parameters		
Coil diameter $2a_1$ (m)	1.021	1.021
Coil length ℓ_1 (m)	0.461	0.464
Number turns N_1	835	832
Coil inductance L_1 (H)	0.789	0.782
Bore tube inductance L_2 (H)	1.04×10^{-6}	1.04×10^{-6}
Bore tube cross-section A_{c2} (m^2)	3.18×10^{-3}	3.18×10^{-3}
Bore tube resistance at 10 K R_2 (ohm)	1.77×10^{-6}	1.77×10^{-6}
Superconductor Parameters		
Number of filaments	2300	2700
Conductor diameter D_w (mm)	0.99	1.00
Copper to superconductor ratio r	1.8	1.0
Twist pitch (mm)	10	10
Matrix copper resistivity at 10°K and B=0 ρ_1 (ohm m)	2.39×10^{-10}	2.83×10^{-10}
Conductor cross-section area A_{c1} (m^2)	7.85×10^{-7}	7.85×10^{-7}

superconductor, the quench back temperature of the bobbin T_Q was assumed to be 10K. The initial starting temperature T_o is assumed to be 4.5K. ΔH_2 can be found for the 1100-0 aluminum using Table 1. Since the 1100-0 aluminum in the bobbin has a measured resistivity ρ_2 of 1.8×10^{-9} ohm m, the value of F_2^* used in Eq. (13) is 6.44×10^{12} $A^2m^{-4}s$. (Note: $F_2^* = \Delta H_2/\rho_2$ from Eq. (10).)

Table 6 shows the value of J_o (the starting current density in the superconductor; $J_o = i_o/A_{c1}$.), ρ_i, V_L, α, R_{o1}, t_i and ΔH_{sc} as a function of the starting current in the superconducting coil i_o. In order to calculate the various values given in Tables 6 and 7 the following constants are given (see Table 5): $a_1 = 0.51$ m, $\ell_1 = 0.46$ m, $a = 10^{-3}$ m, $S = 1.25\times10^{-4}$ m, $k_i = 0.036$ $Wm^{-1}K^{-1}$, $N_2 = 1$, $L = 2.45\times10^{-8}$ ohm WK^{-2}, and $T_c = 7K$. The values of r, N_1, A_{c1}, A_{c2}, L_1, L_2 and R_2 can be found in Table 5.

The values of V_L used in Table 6 and in Eq. (13) can come from Fig. 1 or from the measured values given in Fig. 8. Figure 8 presents measured quench velocities along the wire as a function of superconductor overall current density (excluding insulation). These measurements include the C magnet measurements given in Fig. 1. The LBL along the wire quench velocity measurements are compared with a fit of the measured quench velocity data taken by Scherer and Turowski.[13,14] The quench velocity data given in Fig. 8 shows agreement with the theoretical curve given in Fig. 1.[12]

Table 7 compares the calculated quench back time t_{QB} using Eq. (13) and Eq. (15) with measured quench back time in the A and B thin

Table 6. The values of various current dependent parameters needed to calculate quench back time in the LBL A and B thin solenoid coils.

i_o (A)	J_o (Am^{-2})	ρ_1* (ohm m)	V_L (ms^{-1})	α*	R_{o1}* (ohm m^{-1})	tl (s)	ΔH_{SC} (Jm^{-3})
A Magnet							
200	2.55×10^8	2.32×10^{-10}	3.5	0.0189	2.75	0.458	20000
300	3.82×10^8	2.44×10^{-10}	6.0	0.0191	2.81	0.267	16000
400	5.10×10^8	2.50×10^{-10}	8.0	0.0193	2.83	0.200	12000
500	6.37×10^8	2.55×10^{-10}	12.0	0.0195	2.94	0.146	9500
700	8.92×10^8	2.60×10^{-10}	26.0	0.0198	3.00	0.062	7500
B Magnet							
195	2.48×10^8	2.83×10^{-10}	3.5	0.0230	4.02	0.458	25000
390	4.96×10^8	2.87×10^{-10}	7.6	0.0233	4.16	0.211	15000
585	7.45×10^8	2.95×10^{-10}	16.0	0.0236	4.26	0.100	11000
780	9.92×10^8	3.04×10^{-10}	29.0	0.0239	4.33	0.055	8500
920	11.72×10^8	3.10×10^{-10}	35.0	0.0241	4.40	0.046	8000

*Includes estimated effects of magneto-resistance.

Table 7. Calculated values of t_Q, t_H, and t_{QB} compared with measured quench back times in the A and B magnets.

i_o (A)	J_o (Am^{-2})	t_Q (s)	t_H (s)	t_{QB} (s)	t_{QB} measured (s)
A Magnet					
200	2.55×10^8	0.930	0.029	0.959	0.74–0.90
300	3.82×10^8	0.517	0.027	0.544	0.43–0.50
400	5.10×10^8	0.364	0.025	0.389	0.26–0.31
500	6.37×10^8	0.237	0.023	0.260	0.16–0.24
700	8.92×10^8	0.108	0.022	0.130	0.10–0.12
B Magnet					
195	2.48×10^8	0.703	0.032	0.735	0.56–0.68
390	4.96×10^8	0.288	0.026	0.314	0.20–0.28
585	7.45×10^8	0.133	0.023	0.156	0.13–0.17
780	9.92×10^8	0.073	0.022	0.095	0.09–0.10
920	11.72×10^8	0.058	0.021	0.079	0.07–0.08

solenoid magnets as a function of starting current i_o. The theory agrees reasonably well with experiment. Figure 9 compares the theoretical calculations of quench back with the B magnet measured data. (Note: in all cases in Fig. 9 and Table 7, the quenches were induced at the end of the coil. This assumption also applies for the theoretical value of R_{o1} given in Table 6.)

From Table 7 and Fig. 7, it is clear that for a given starting current density J_o, the quench back time is longer for the A magnet than for the B magnet. Both R_{o1} and α are greater for the B magnet. The increased value of R_{o1} reflects the lower copper to super conductor ratio r and a larger superconductor matrix resistivity ρ_1. The larger value of α is due to the increased value of ρ_1 alone.

Both the A and B thin solenoids were quenched without external quench protection even though the current density in the overall superconductor cross-section was as high as 1.17×10^9 Am^{-2}. Quench back from the secondary circuit (the bobbin) contributed to the successful testing of these solenoids. There are theoretical arguments that suggest the quench back process can be controlled so that large high current density coils can be quenched safely without external quench protection. This will be discussed in a future paper.

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FIGURE CAPTIONS

Fig. 1. The quench velocity along the wire as function of current density in the overall superconductor cross-section. The measured quench velocities are for a 2200 filament conductor 1.5 mmø, r = 1.8, wound in a coil.

Fig. 2. The electrical circuit diagram of a quenching superconducting magnet with a closely coupled conductive bobbin.

Fig. 3. The B one meter diameter test coil.

Fig. 4. A cross-section of the one-meter diameter test solenoid magnet.

Fig. 5. Measured magnetic flux during a 700 A quench of the a magnet. ϕ_C is flux generated by current in the superconductor; ϕ_{AL} is flux generated by current in the bore tube and $\phi = \phi_C + \phi_{AL}$.

Fig. 6. The ratio of coil current to starting coil current versus time from the start of quench in B magnet.

Fig. 7. Measured quench back time versus current in the A and B magnets.

Fig. 8. Measured quench velocities V_L as a function of superconductor overall current density J_o.

Fig. 9. Calculated and measured quench back time versus starting current in the B thin solenoid magnet.

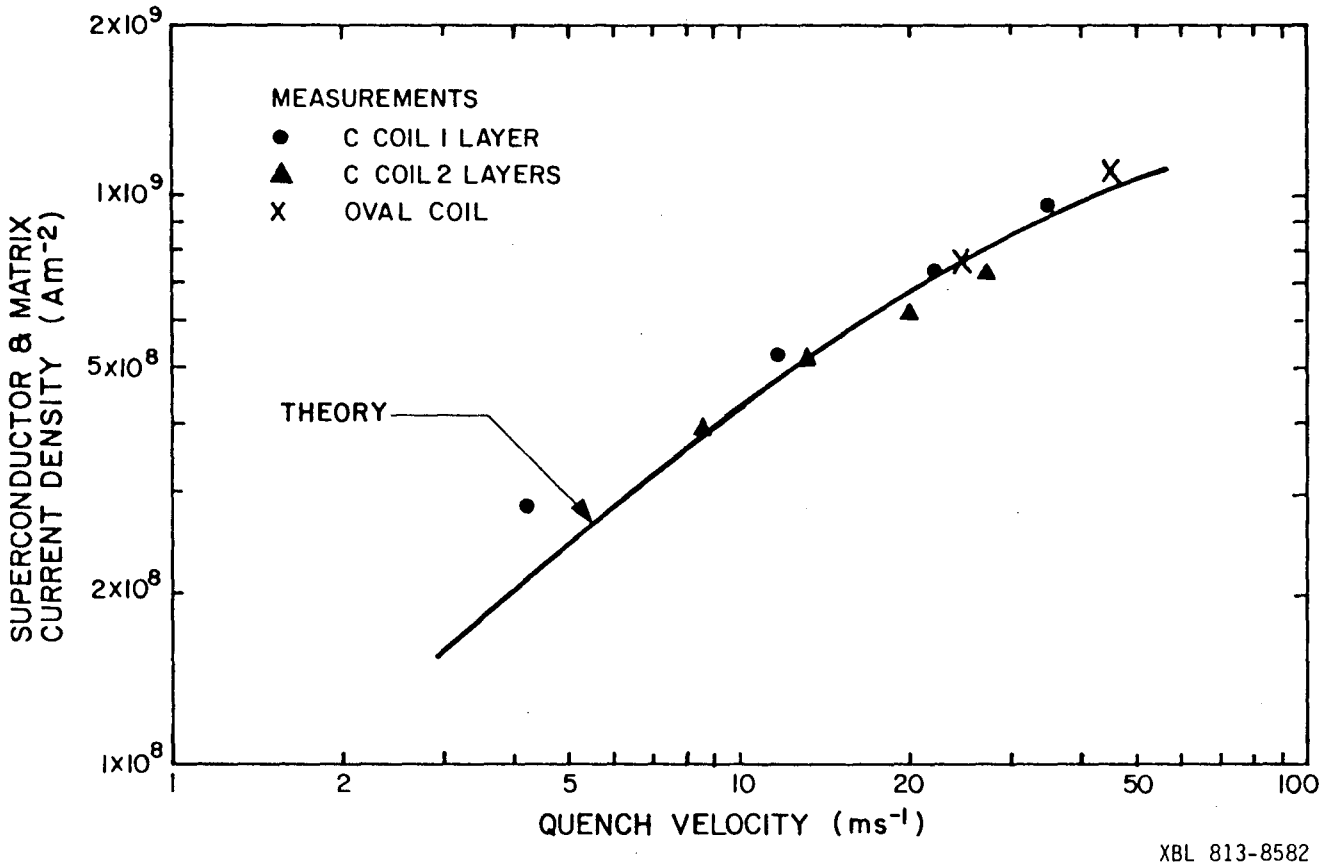
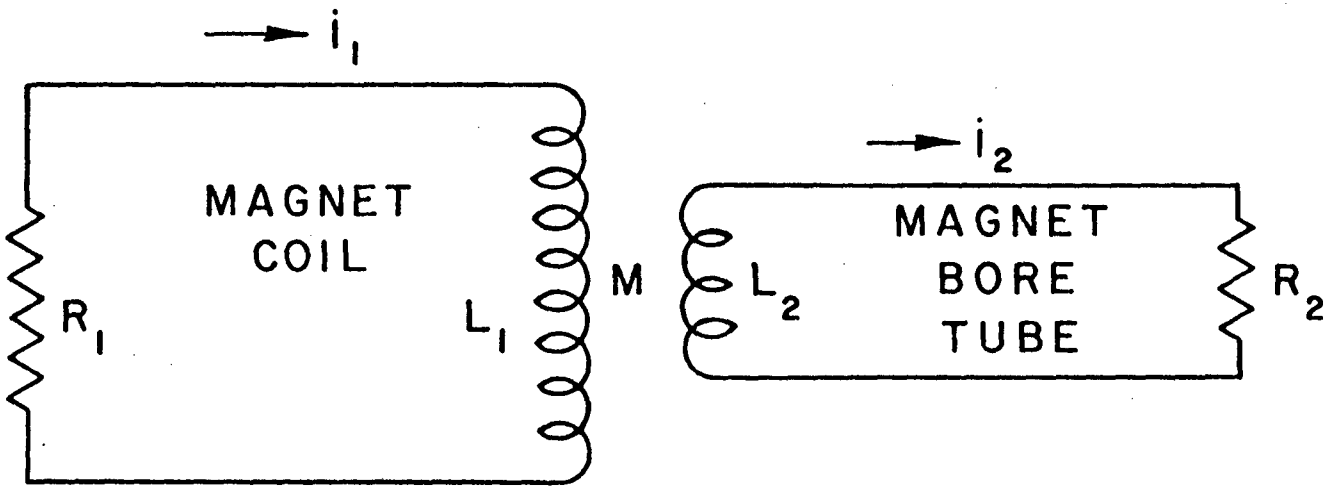
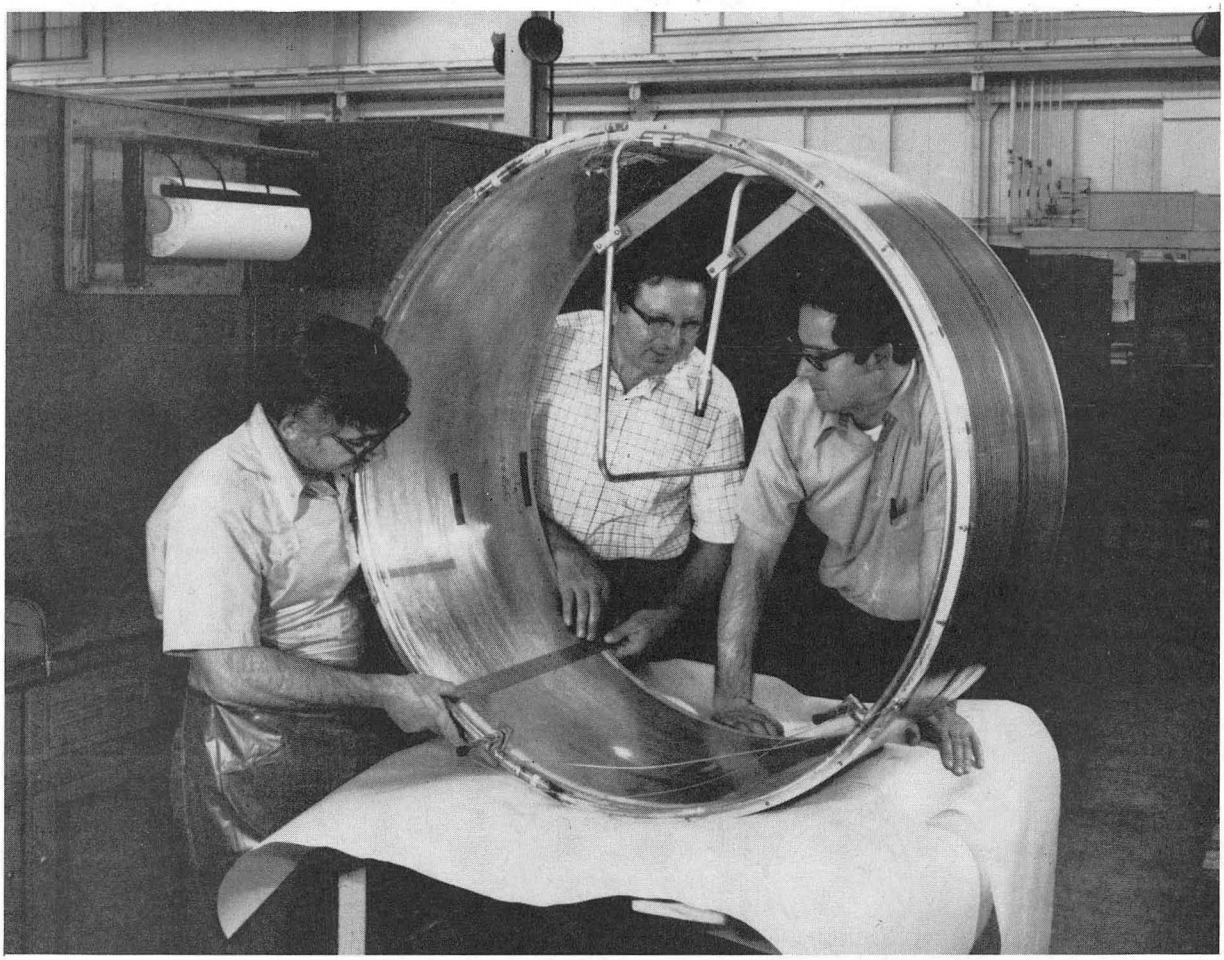

MEASUREMENTS
C COIL 1 LAYER
C COIL 2 LAYERS
X OVAL COIL
THEORY
SUPERCONDUCTOR & MATRIX CURRENT DENSITY (Am^{-2})
2x10^9
1x10^9
5x10^8
2x10^8
1x10^8
1
2
5
10
20
50
100
QUENCH VELOCITY (ms^{-1})
XBL 813-8582

Figure 1



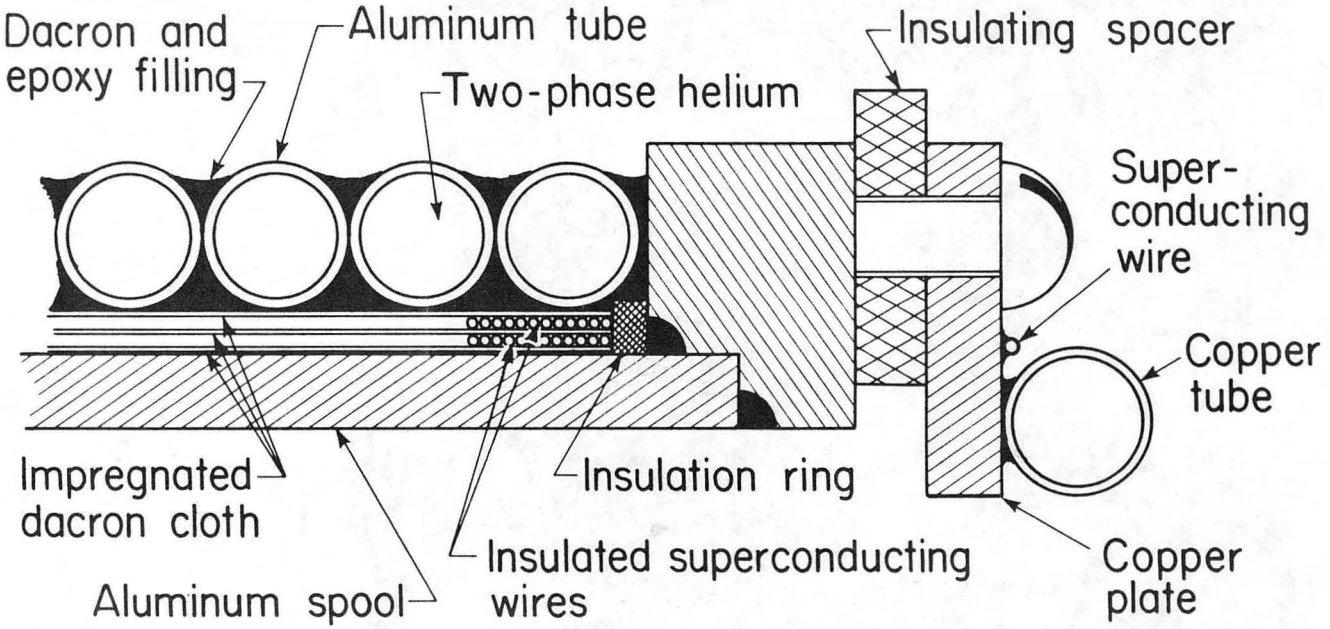
XBL 773-7855A

Figure 2



CBB 762-2054

Figure 3



XBL 757-3453

Figure 4

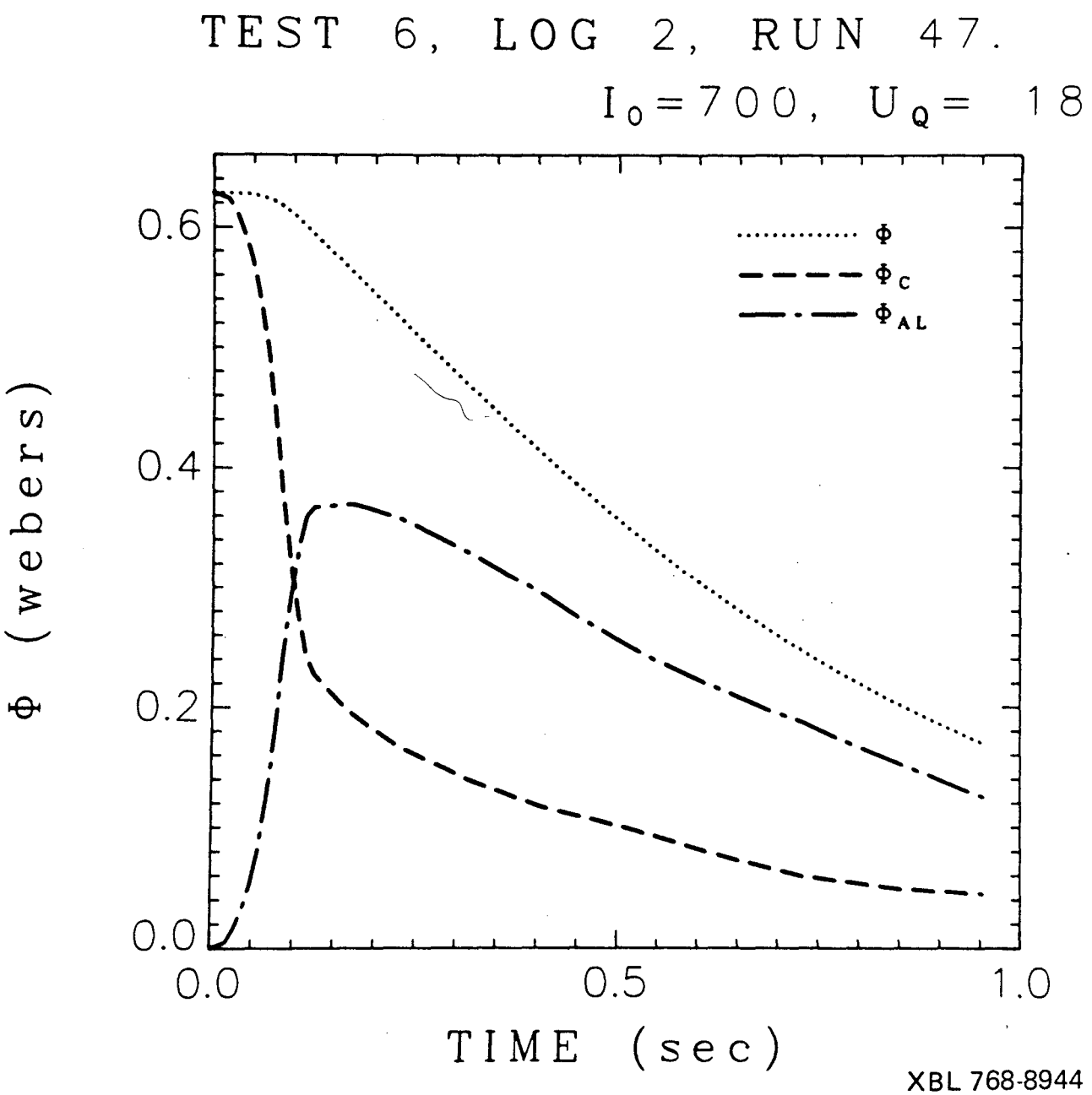

TEST 6, LOG 2, RUN 47.
$I_0 = 700$, $U_Q = 18$
0.6
0.4
0.2
0.0
Φ (webers)
Φ
Φ_C
Φ_{AL}
0.0
0.5
1.0
TIME (sec)
XBL 768-8944

Figure 5

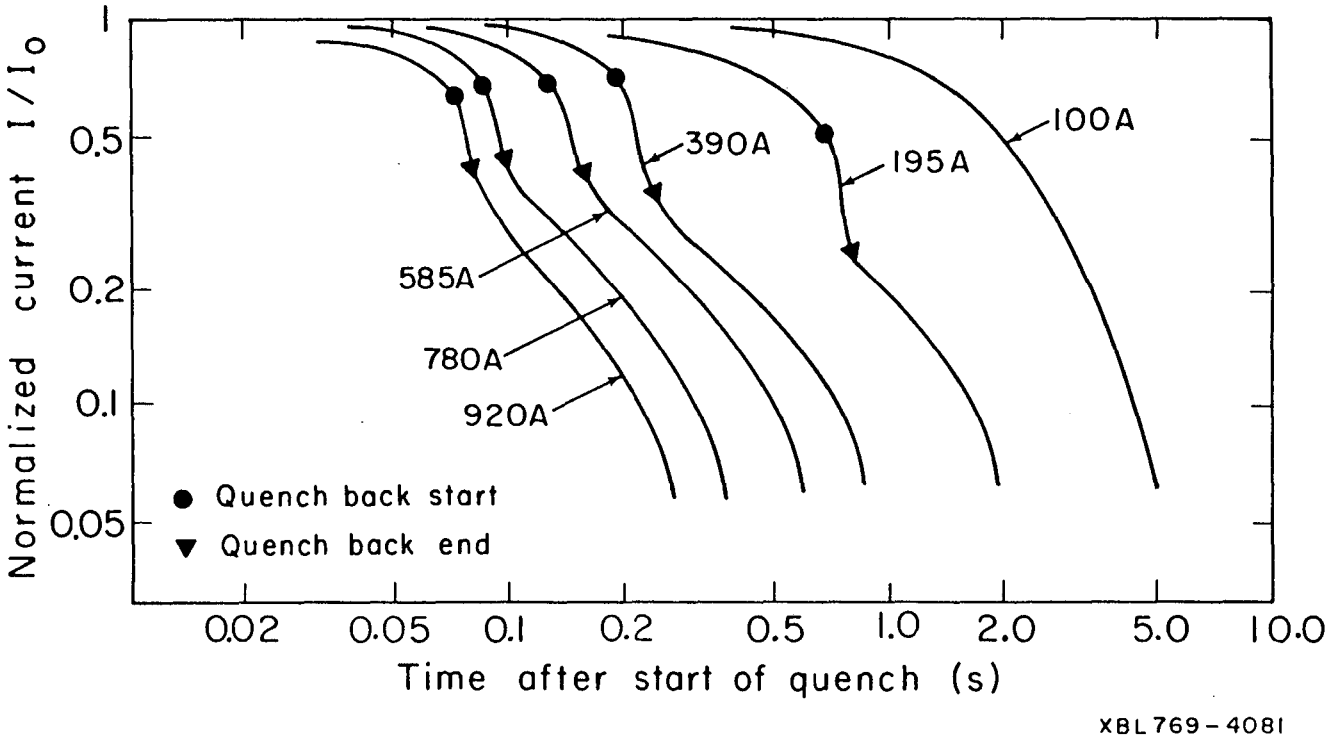
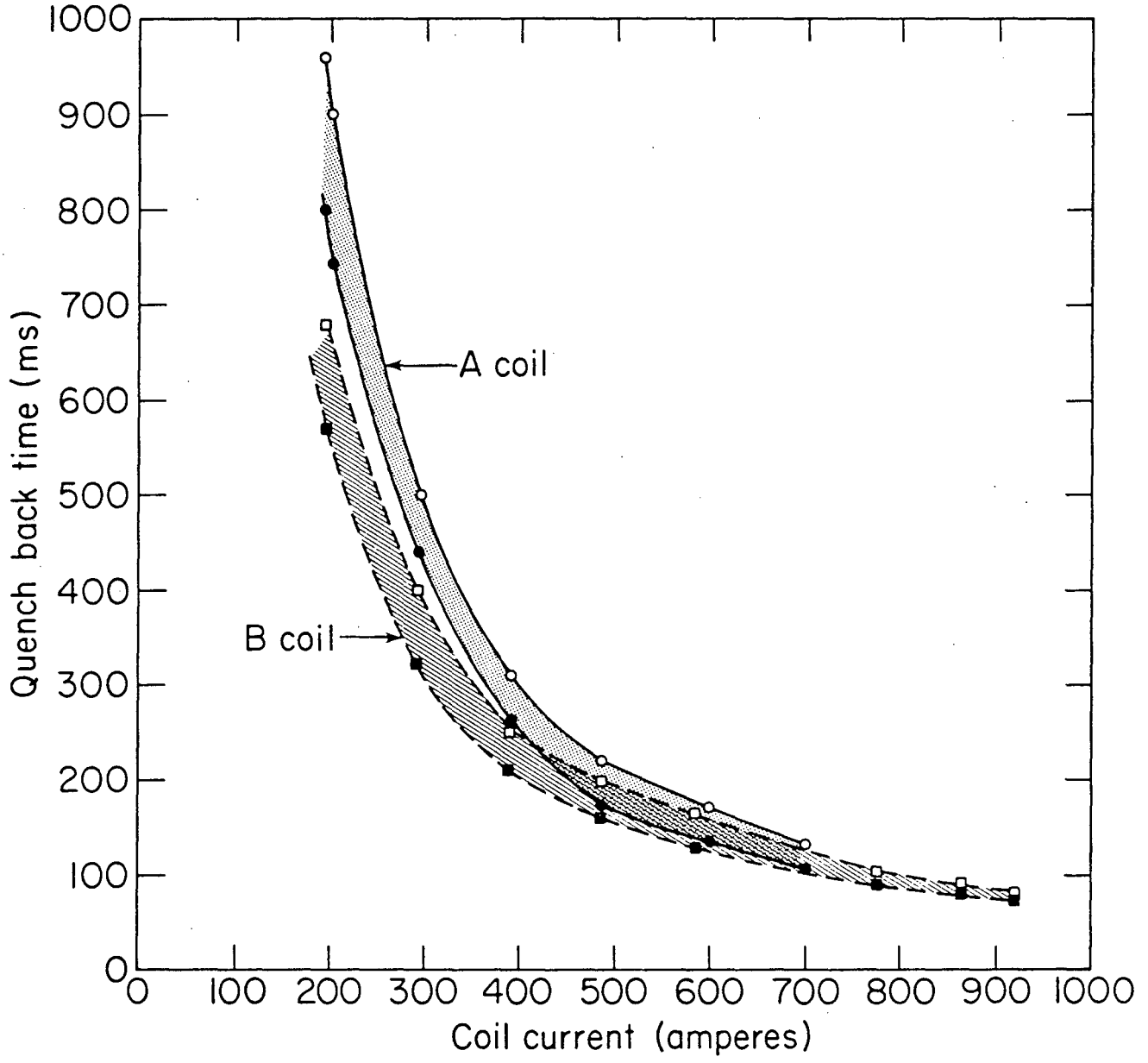
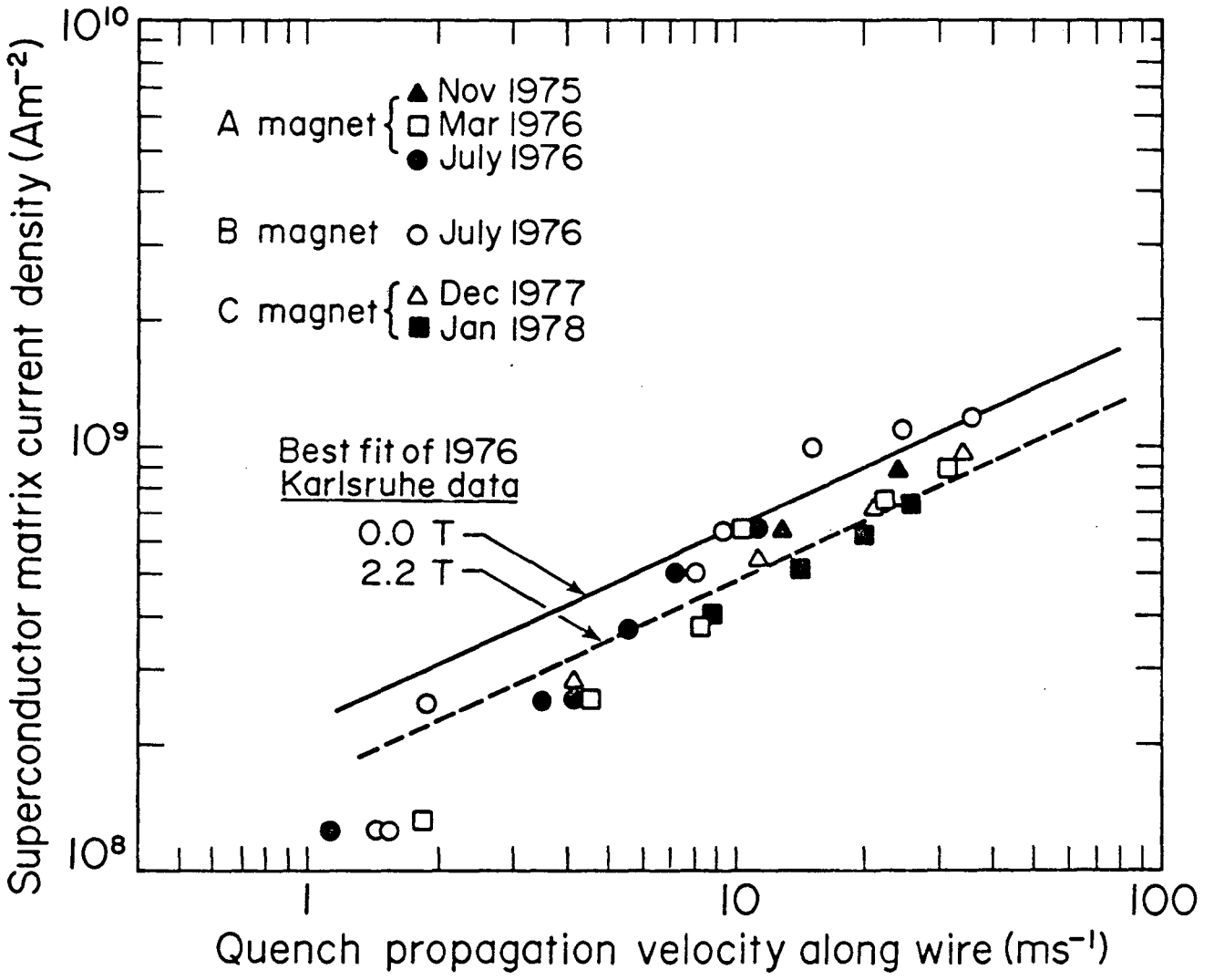

Normalized current I / I₀
1
0.5
0.2
0.1
0.05
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10.0
Time after start of quench (s)
100A
195A
390A
585A
780A
920A
Quench back start
Quench back end
XBL 769-4081

Figure 6



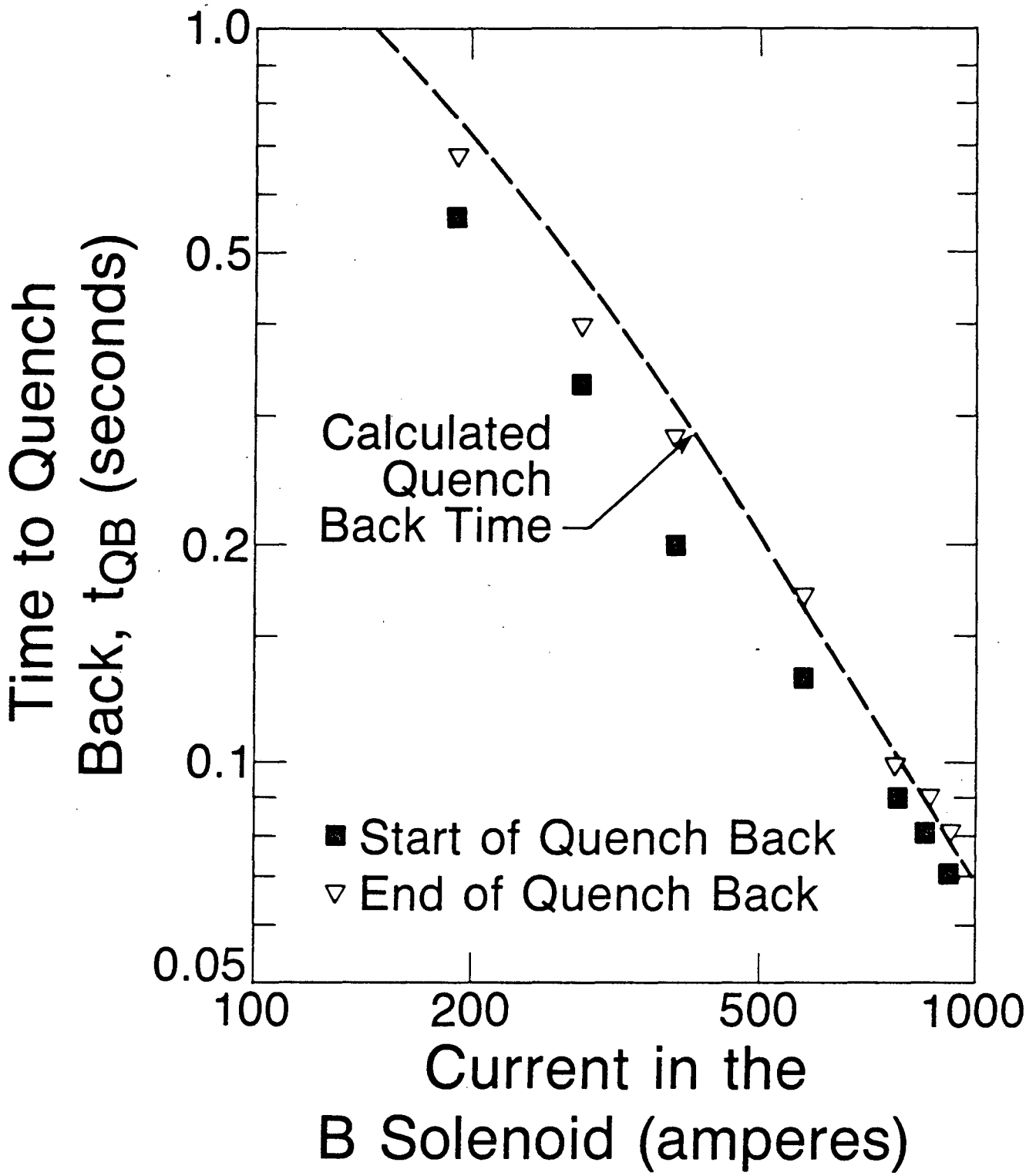
XBL768-3252

Figure 7



XBL 785-9000

Figure 8



XBL 836-2714

Figure 9

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