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OF AN SSC MODEL-DIPOLE

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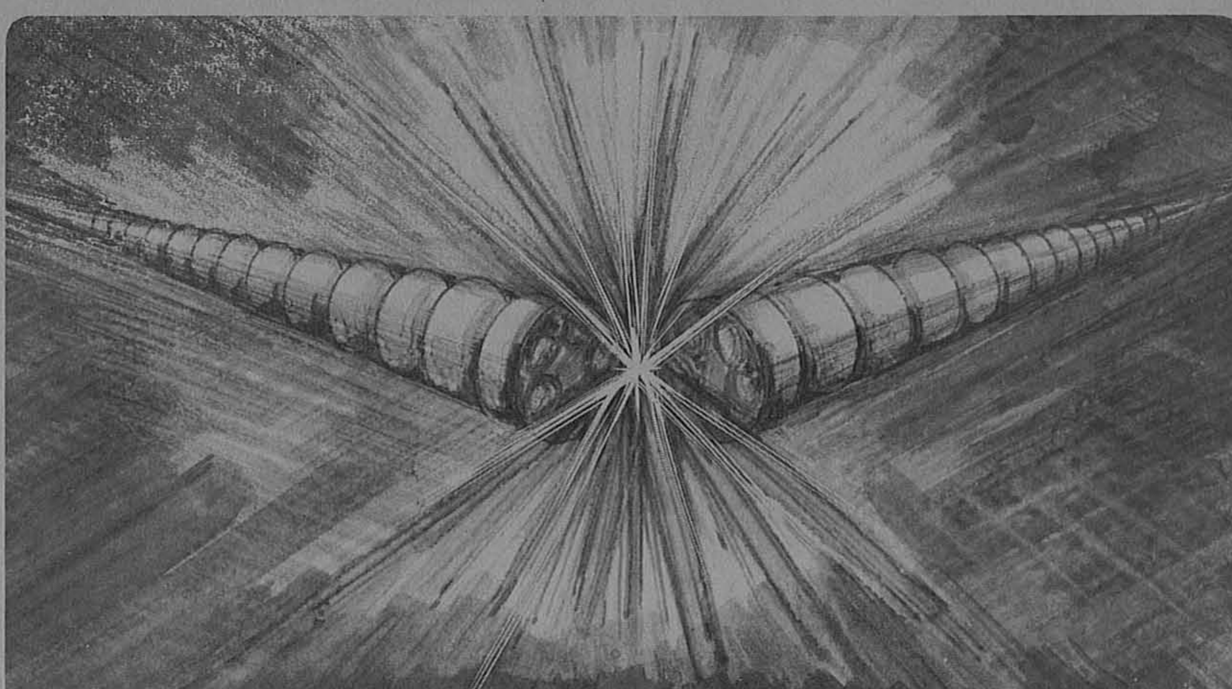

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Introduction

The quench behavior of SSC dipoles is of interest for several reasons. First, the quench characteristics of the conductor will affect the design of the magnet windings. Second, if excessiv. temperatures are reached in a passive protection mode then additional accelerator components such as fast quench detection circuits, heater firing units, and heaters will be required. Third, machine operation, percent downtime, ramp rate, acceptable beam loss, etc. will depend somewhat on the quench characteristics of the various superconducting magnets in the machine. Of course all these factors influence the ultimate cost of the accelerator.

As a consequence it is desirable to understand very early on the detailed quench behavior of the SSC dipole windings. In the absence of experimental data on the magnets themselves we will attempt here to estimate the characteristics of quenches, in particular the hot spot temperature, in the SSC Reference Design A dipoles. The quenches are analyzed using the computer program QUENCH. Input data, material characterstics, are similar to those for other accelerator dipoles. We have compared calculations from the program QUENCH with actual data on quenches in the CBA magnets and the LBL model dipoles in the D-7, D-8, D-9, and D-12 series. Two "parameters", the copper resistivity at low temperatures and the effective enthalpy of the liquid helium contained in the windings were adjusted to make the temperatures and velocities calculated by QUENCH correlate with those in the actual magnets. Where

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good data on the actual copper resistivity were available, the measured residual resistivity ratio was used, and only the helium fraction was adjusted. Good agreement was obtained with the available test results in all these comparisons.

These calculations are expected to be representative of quenches in the real SSC magnets, at least to the extent that they will correspond to other similar dipoles. We believe this correspondence is quite good. However, these calculations are not substitutes for hard data. Thus we recommend that as much data as possible be obtained on quenches in SSC model dipoles.

Program QUENCH

The calculations described here used the computer program QUENCH, it was first written by M.N. Wilson(1) and later modified and documented by W. Hassenzahl(2). The specific heats of copper and superconductor and the resistivity of copper that we used are given in Figs. 1 and 2.

Because of the low copper-to-superconductor ratio in the proposed cable the windings heat up very quickly. There is no pool boiling heat transfer. Though the program would permit some of the heat from the conductor to be deposited in the helium bath, this feature is not used in these calculations. From fundamental experiments,(3) it is known that there is some transient heat transfer from the rapidly heating conductor to the small volume of helium with which it is in direct contact, which is a fraction of the helium within the insulation. This transient characteristic is taken into account by ascribing a constant specific heat Cp to helium between 4.4 and 15 K. The value used is determined by the integral $\int_{4.4K}^{15K} C_p dT$ = heat of vaporization. The maximum temperature of 15 K is used because we know that by the time the surface temperature of the conductor reaches this temperature there is essentially zero heat transfer (the film boiling limit is reached at about 5 or 6 K) to liquid helium that started at either 1.8 or 4.2 K.

Quench Velocities

The program QUENCH can calculate the quench propagation velocity or the velocity can be set by the user. If the velocity is calculated, the formula used is:

$$v_c = \frac{I(\Theta_m - 2\Theta_c)}{C} \sqrt{\frac{LT_m}{\Theta_c \, \Theta_m (\Theta_m - \Theta_c)}}$$

where:

I = operating current (A/m^2)

C = specific heat (J/m^3K)

Θ_m = $(T_m - T_b)$ temperature difference between the maximum temperature of the conductor and the bath temperature

Θ_c = $(T_c - T_b)$ temperature difference between the critical temperature of the conductor and the bath temperature

L = 2.45×10^{-8} (V^2/K^2) = (Lorenz ratio)

T_c is calculated by

$$T_c = T_{cmax} - \frac{T_{cmax} - T_b}{I_c} I/I_c$$

where:

T_{cmax} - maximum critical temperature for $B = 0$

I_c - critical current at the bath temperature (A)

Conductor and Windings

We ran quench calculations for the conductor in both the inner and outer layer of the proposed SSC-dipole. The conductors are slightly key-stoned, "Rutherford type" cables wrapped with two overlapping layers of Kapton. The Kapton has a thin layer of B-stage epoxy on one surface. The cable data for an LBL model dipole are given in Table I and those from the SSC reference design are displayed in Table II.

The coil geometry evaluated by the program QUENCH is rectangular. For small bore dipoles this approximation is not perfect, but the results of interest, namely temperature, do not depend strongly on slight variations in the overall coil dimensions. We have taken the circumferential extent of the winding at the mean radius of the conductor for one dimension, the height of the conductor for another dimension and twice the length of the coil for the other. These dimensions are also given in Tables I and II. The presently proposed geometry for the SSC model A magnet includes wedges in both layers. These may have an effect on circumferential quench propagation but the specific effect is unknown at present so these have not been included at all in the calculation.

Calculations

The program QUENCH allows the user to restrict the total normal going volume (the maximum extent of the quench) to certain regions of the coil. In our calculations the worst cases were those where only one layer, either the inner or the outer goes normal starting at the pole. The quench moves circumferentially in only one direction. For some other calculations we chose the innermost point of the inner layer in the midplane of the magnet as the point of quench initiation, i.e. B = B central. The length of the magnet is assumed to be 16 m unless otherwise specified, and no external dump resistor is used. Though some of the heat from the conductor will end up in the helium bath while the quench is in progress, the event is over so fast in general that very little

Table I

Characteristics of the D-12 Cable and Windings

	Inner Layer	Outer Layer
Bare Cable Dimension Average (in)	.371 x .0557	.383 x .0470
Insulation Thickness (in) (before squeezing)	.0022	.0022
Insulation Thickness (in) (after squeezing)	.0015	.0015
Number of Strands	23	30
Strand Diameter (in)	.0310	.0255
Copper to Superconductor Ratio	1.1	1.79
Percent of Unit Cell (%) in squeezed conductor		
Copper	44.6	52.7
Superconductors	40.5	29.5
Insulation	7.3	8.3
Void (He)	7.7	9.5
Winding Height (cm (in))	5.03 (1.98)	5.50 (2.17)
Width (cm (in))	0.93 (.37)	0.99 (.39)
Length (cm (in))	220 (87)	220 (87)

Table II

Characteristics of the SSC Reference Design Study Cable and Windings

		Inner Layer	Outer Layer
Bare Cable Dimension Average (in)		.371 x .0571	.383 x .0470
Insulation Thickness (in) (before squeezing)		.0022	.0022
Insulation Thickness (in) (after squeezing)		.0015	.0015
Number of Strands		23	30
Strand Diameter (in)		.0318	.0255
Copper to Superconductor Ratio		1.3	1.8
Percent of Unit Cell (%) in squeezed conductor			
Copper		48.1	54.0
Superconductors		37.0	30.0
Insulation		6.9	8.0
Void (He)		8.0	8.0
Winding Height	(cm (in))	5.03 (1.98)	5.50 (2.17)
Width	(cm (in))	0.93 (.37)	0.99 (.39)
Length	(cm (in))	3220 (1268)	3320 (1268)

heat has a chance to be transferred out of the coil volume. Thus, in keeping with making a pessimistic estimate, no heat transfer to helium or any of the coil structure is taken into account.

One output of the program that is of major interest here is the time dependence of the highest temperature in the windings. The temperature increases with time and reaches its final value after 0.5 to 0.7 seconds. The final temperature depends strongly on the effective specific heat C_p of the helium in the windings through the effect of this parameter on the propagation velocity. For example, for a quench in the outer layer at the pole, the quench propagation velocity was calculated to be 13, 18, 27 and 35 m/s respectively for 7, 5, 3 and 2 percent helium, as shown in Fig. 3. To check this assumption we carried out another calculation with quench velocity as direct input to QUENCH and a helium fraction of 7 percent. In this case the enthalpy of the helium affects the temperature rise up to 15 K but not the quench velocity. These results are shown in Fig. 4. The final temperatures of this calculation are in good agreement with the results displayed in Fig. 3.

It is interesting to note, that the geometrically calculated fraction of about 7 percent helium does not give the quench velocity measured in other magnets with almost identical conductor geometry.(4) Instead, much lower percentages, about 2 percent for our model, give the experimentally observed velocity. This same effect appears to have been observed at BNL ,(5) where they measured lower velocities in "forced-flow" than in "pool-boiling" experiments. The explanation was that only a small amount of helium boils and the rest is simply forced out of the conductor with the result that the quench front "sees" only a limited volume of liquid helium. On this basis we use the percentage of helium as a knob to adjust the quench propagation velocity in the calculation so it will agree with the few known experimental values.

Figure 5 shows the final hot spot temperature for the inner and outer layers of the 1 m long D-12 magnet as a function of the operating current. A maximum is observed at about 5000 Amps. For higher currents the stored energy increases, but the quench velocity increases even faster (Figure 6). A similar effect was observed in the CBA coils.

The predicted temperatures are well under the damage level, which we assume to be below 700 K.

Improved Superconductor

In recent months there has been a successful effort to improve the critical current density of the NbTi superconductor used in the SSC dipoles. Improved superconductor has several effects on the SSC. First, it can reduce costs. Second, it may improve accelerator reliability if a greater operating margin (ΔT) is allowed. Third, on the negative side, this increased margin will increase hysteretic losses, and induced multipoles. Fourth, the increased margin will cause the quench propagation velocity to decrease, and thereby increase the ultimate peak temperature in the windings. Figure 7 shows the critical currents of three cables; the middle curve is the quoted SSC RDS performance curve, not the design curve. The other two are actual conductors. The lower is for the conductor used in the D-12C series of magnets and the upper curve is for the most recent billets of high homogeneity conductor. Also shown in this figure is the short sample performance of the high homogeneity wire alone. In Figure 8 we see the peak magnet temperature to be expected for quenches at the layer 1 pole for 16 m SSC dipoles made of these conductors. No active protection system is used. By keeping the copper to superconductor ratio constant the improved conductor to some extent reduces the likelihood of a possibly safe coil.

Effect of Magnet Length on Temperature

The SSC coil length of 16 m, which was set rather arbitrarily for the reference design study, may be changed for a variety of reasons before the SSC is actually constructed. One reason for shortening the coils would be the desirability of a passively safe magnet system. The peak temperature predicted in Fig. 8 occurs at about 5000 A for all the different superconductor characteristics. Using the Reference Design Study Nb-Ti critical current characteristics, and 5000 A, the effect of magnet length on peak temperature is shown in Fig. 9.

Conclusions

Preliminary calculations of the quench behavior in SSC-dipoles show that the magnets could be self-protecting and that a heater may not be necessary, depending on the conductor used. Nevertheless, in order to get more accurate results, it is necessary to measure quench propagation velocities in the model magnets and the cable temperature as a function of "MIITS" in the model magnets or in short sample experiments. Furthermore, we must pay attention to the difference between "pool-boiling" and "forced flow" cooling as this may also affect the ultimate temperature rise in the conductor. As a separate issue, not discussed above, improving the residual resistivity of the copper in the conductor will have a major effect on the final temperature.

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(4) S. Caspi, W.V. Hassenzahl, "The source, origin and propagation of quenches measured in superconducting dipole magnets," IEEE Transactions on Magnetics, Vol. MAG-19, No. 3, May 1983.

(5) A.J. Stevens, "Quench Studies on CBA in Forced Flow Cooling", BNL, ISABELLE Technical Note No. 381 (1982).

(6) A.J. Stevens et al, "Quench Protection Studies on CBA Magnets", IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, Aug. 1983.

(7) P.S. Martin (FNAL), Private communication.

Figure Captions

1. Specific heat of copper and NbTi superconductor used for the calculations in this report.

2. Resistivity of copper based on measurements of LBL conductor #280 used in the D12A magnet. The residual resistivity ratio is 60.

3. Quench propagation velocity affects the final quench temperature more than any other factor. In this study the effective helium content in the windings was varied to control the velocity. The initiation point of the quenches for this figure were at the inner layer midplane. No external energy dump is assumed.

4. Quench propagation velocity was a fixed input to QUENCH for this set of curves. Note that the helium content has little effect on the final temperature compared with the previous figure.

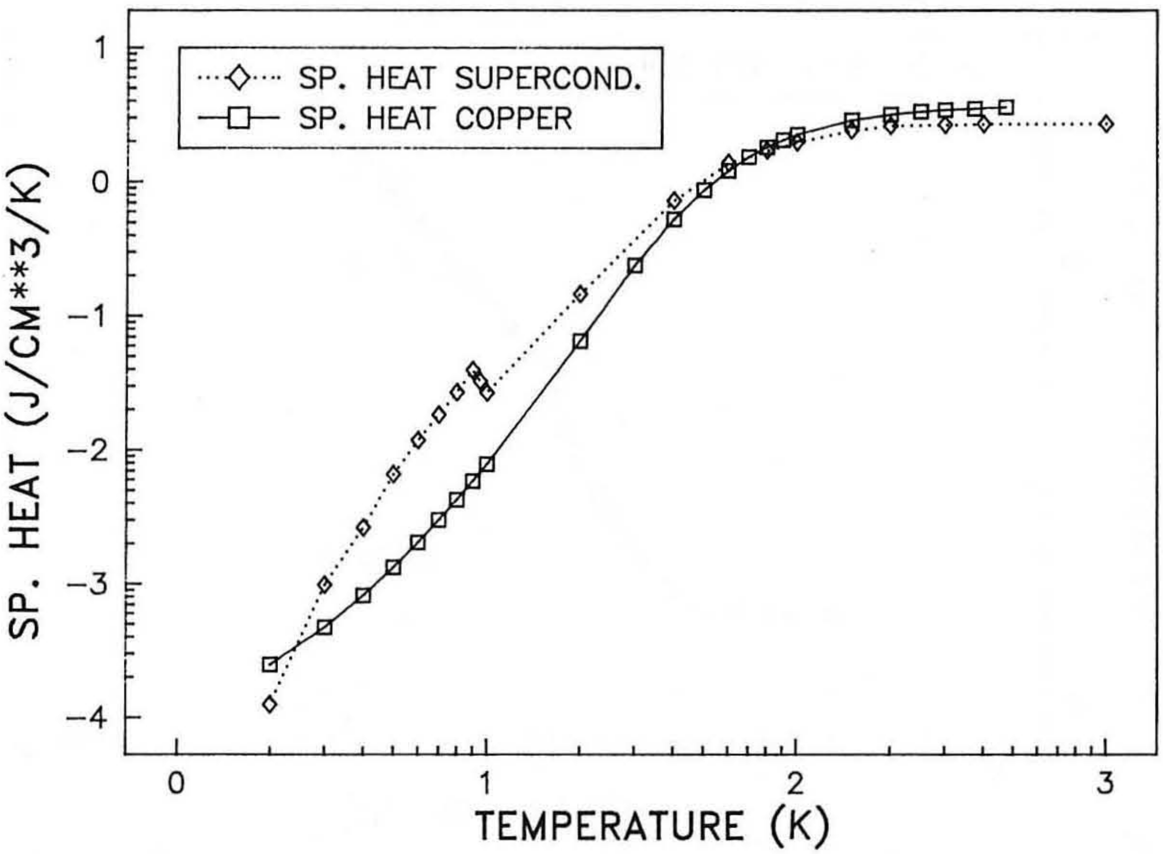
5. Estimates of maximum quench temperature for a 1-meter model magnet with graded conductor from the inner to the outer layer.

6. Estimates of quench propagation velocity as a function of current and the effective helium content within the windings.

7. Load line and critical current curves for the C-5 magnet design and three conductors. The parameters for these conductors are used to estimate the temperatures in Fig. 8.

8. Peak temperatures in a quench in an SSC dipole for different conductors. Note that the magnet made with the best conductor has the highest final temperature.

9. At the observed propagation velocities only about 5 to 7 meters of an SSC-dipole will go normal during a quench in which no heaters are used. Thus final temperature will depend on magnet length as shown here. This curve is for a 5000A quench, the highest temperature for the Reference Design Conductor of the previous figure.



XBL 845-1735

Fig. 1

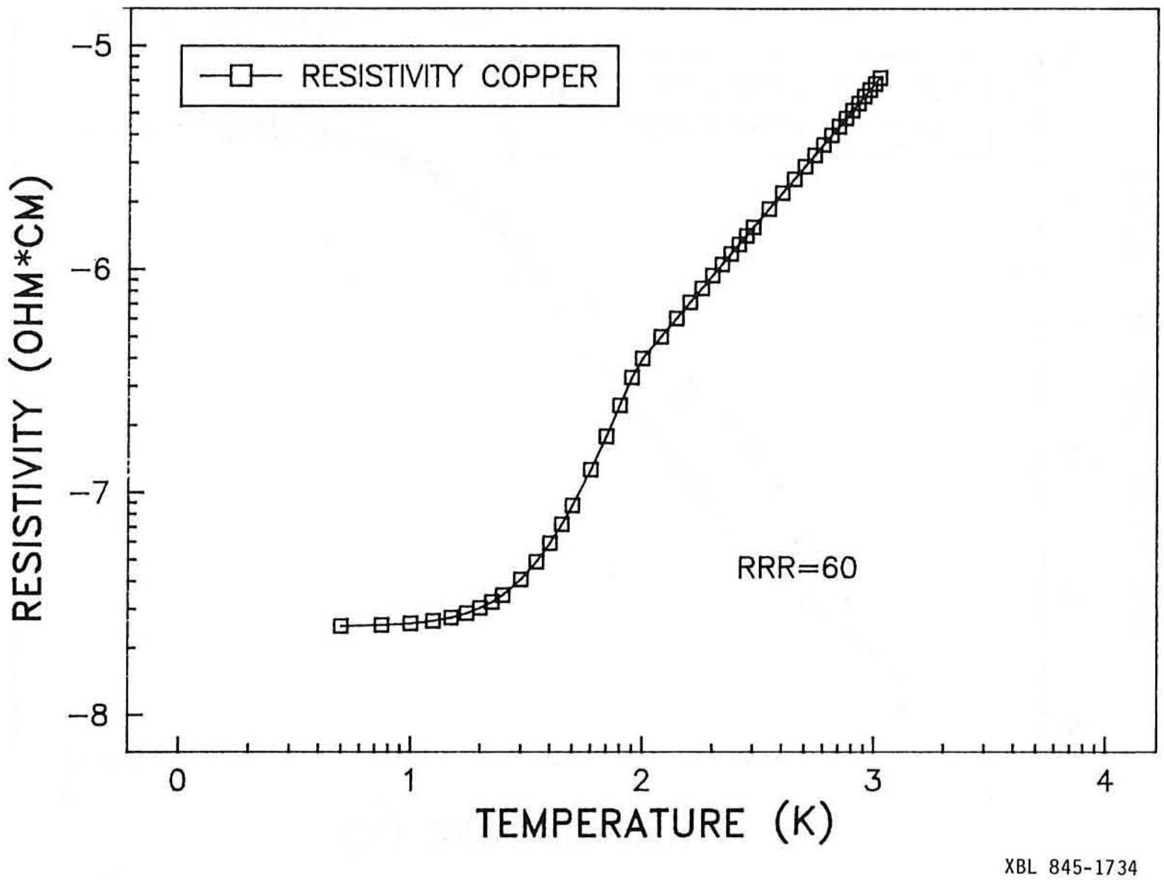

RESISTIVITY COPPER
RRR=60
RESISTIVITY (OHM*CM)
-5
-6
-7
-8
0
1
2
3
4
TEMPERATURE (K)
XBL 845-1734

Fig. 2

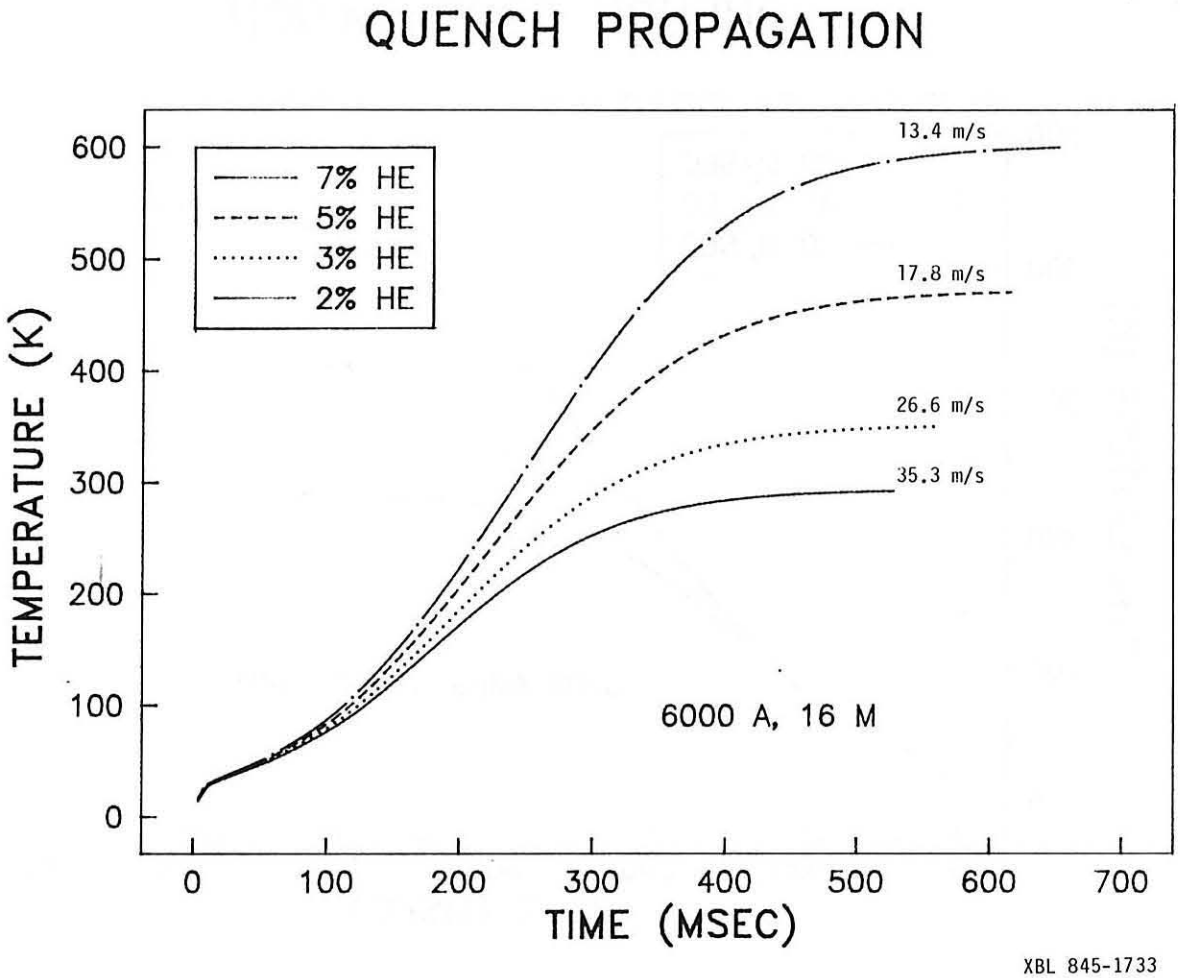
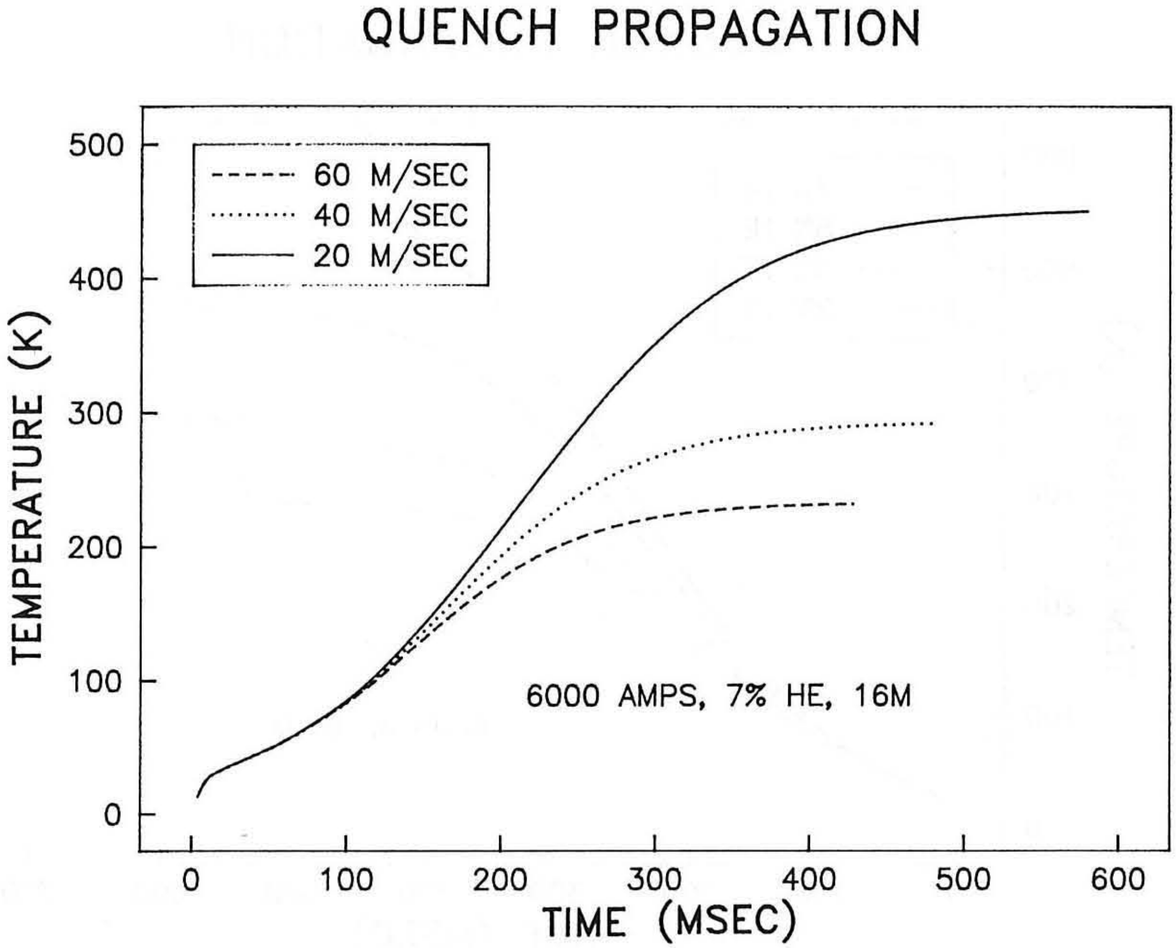
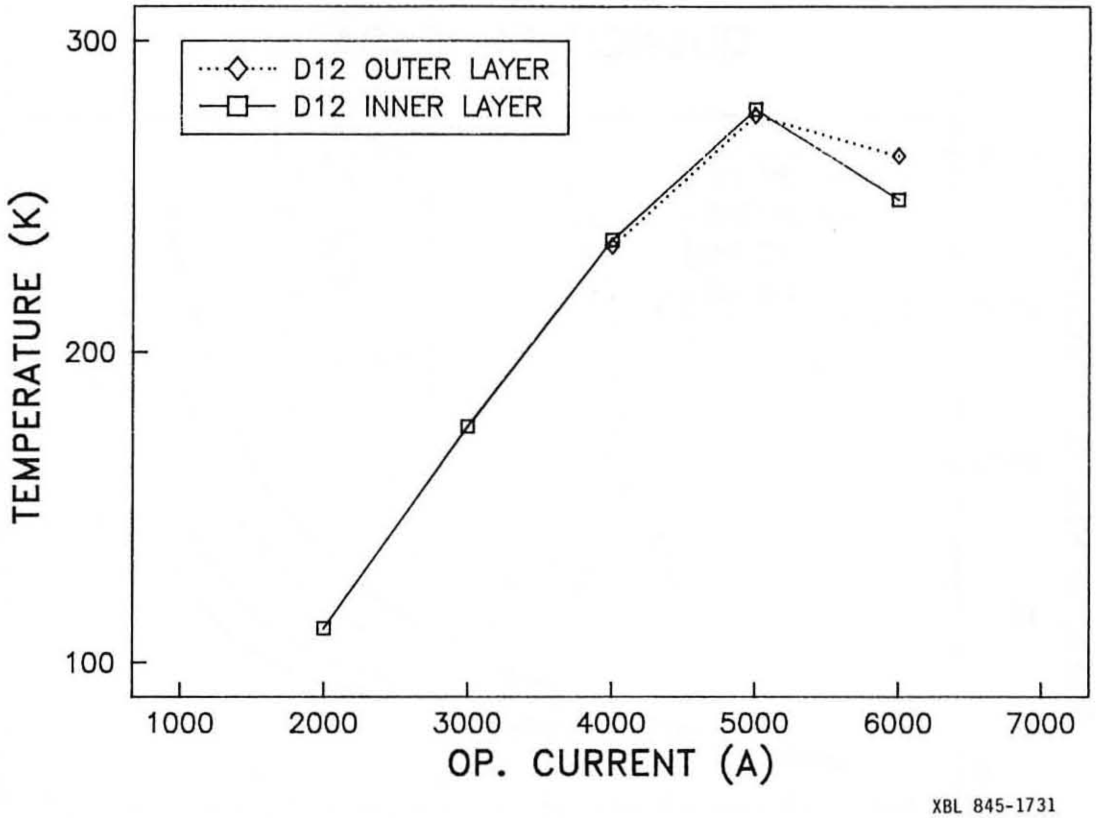

QUENCH PROPAGATION
7% HE
5% HE
3% HE
2% HE
13.4 m/s
17.8 m/s
26.6 m/s
35.3 m/s
6000 A, 16 M
TEMPERATURE (K)
TIME (MSEC)
0
100
200
300
400
500
600
700
XBL 845-1733

Fig. 3



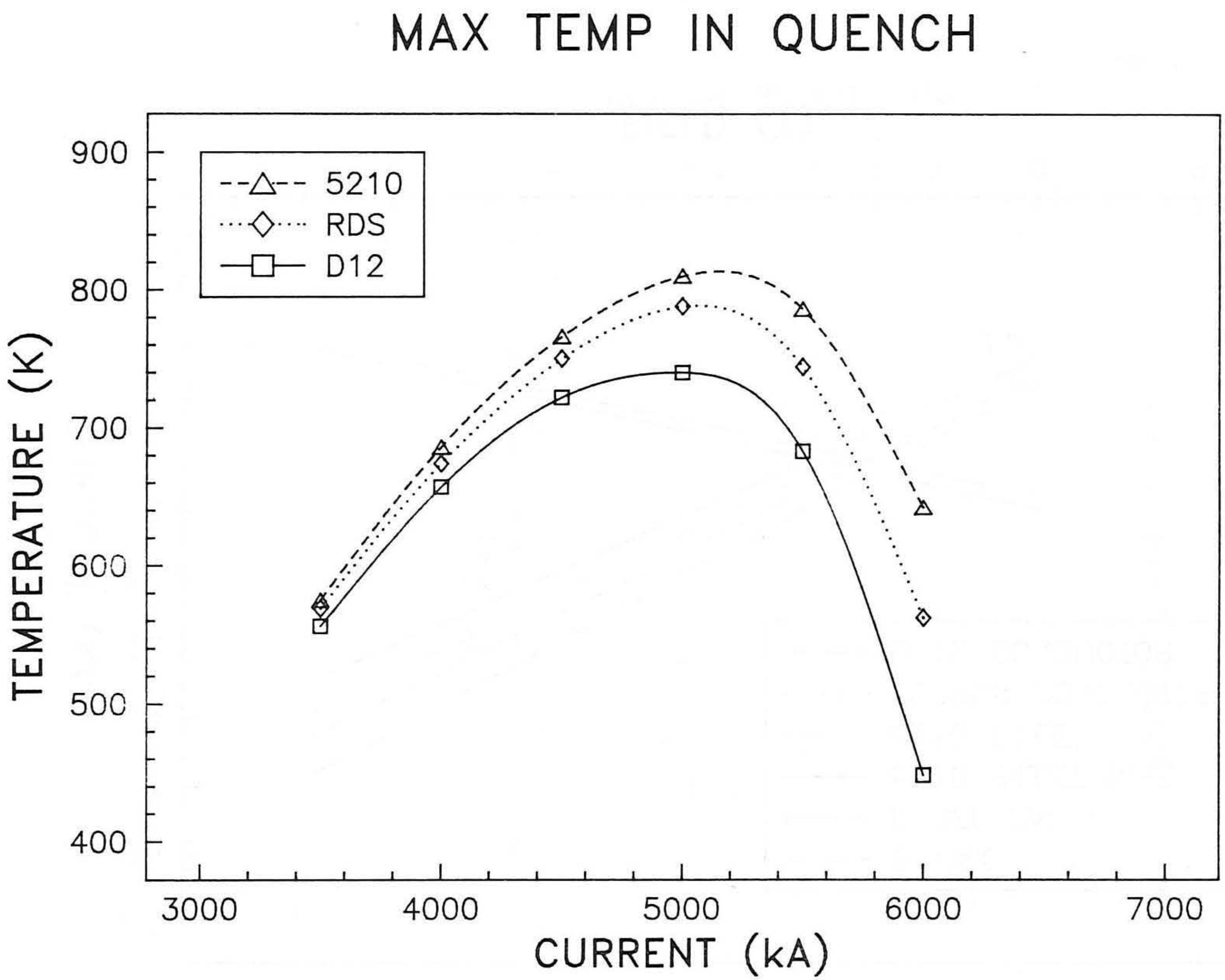
XBL 845-1730

Fig. 4



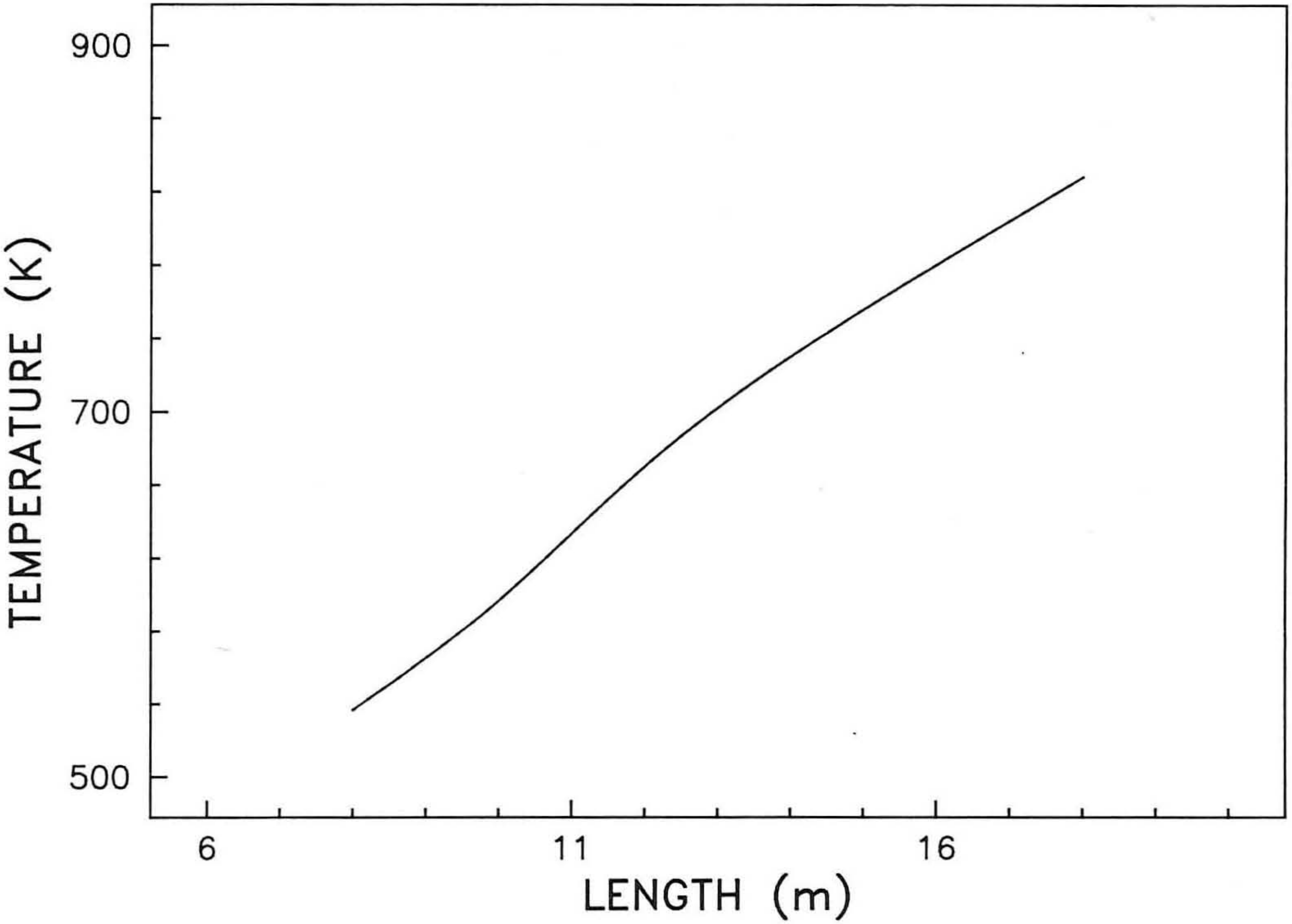
300
200
100
TEMPERATURE (K)
D12 OUTER LAYER
D12 INNER LAYER
1000
2000
3000
4000
5000
6000
7000
OP. CURRENT (A)
XBL 845-1731

Fig. 5



XBL 852-1275

Fig. 8



XBL 852-1277

Fig. 9