SSC-N-521

# RESULTS OF MINIMUM PROPAGATING ZONE COMPUTATION


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This is a preliminary report on the computation of the minimum propagating zone (MPZ) of the superconducting cable in the SSC dipoles (the C358A Cross Section).

The computation is based on the analytic solution of the steady-state one dimension heat flow equation with heat conductivity along the cable length as well as cooling around the cable perimeter. Cooling is denoted by a heat transfer coefficient $H$ per unit surface area.

In general, the MPZ can be divided into three zones: The inner zone where the temperature exceeds the critical $T_L$ when the superconductor becomes completely normal with the critical current equal to zero. In this region, the generation is a constant. The adjacent zone starts from the temperature $T_G$ on critical thermodynamic surface to $T_L$. The equation of the critical surface was given by Morgan and detailed by Jackson in SSC-N-371. In this region, the generation is assumed to be linear with respect to temperature. The outer zone has a temperature ranging from the bath temperature $T_0$ to $T_G$. Here, there is no generation and there is only purely cooling at the perimeter.

Numerical data used include

$$\begin{aligned} \text{volume specific heat of Cu at 4.2 K} &= 1.6 \times 10^3 \text{ J/m}^3\text{K} \\ \text{volume specific heat of NbTi at 4.2 K} &= 6.8 \times 10^3 \text{ J/m}^3\text{K} \\ \text{thermal conductivity of Cu} &= 350 \text{ W/mK} \\ \text{cross sectional area of cable strand} &= 5.13 \times 10^{-7} \text{ m}^2 \end{aligned}$$

The electric resistivity of copper $\rho$ below $\sim$ 10 K is assumed to follow the empirical formula

$$\rho(T, B) = \left(0.0032B + \frac{1}{\text{RRR}}\right) 1.7 \times 10^{-8} \ \Omega\text{m} ,$$

where $B$ is the magnetic flux density in Tesla and RRR the residual resistivity ratio. Except for Fig. 7, a RRR of 100 has been assumed. In the computation, the specific heat of copper and NbTi are assumed directly proportional to the cube of the absolute temperature. To simplify the solution, the thermal conductivity of copper has been assumed to be temperature independent. This assumption is not so bad since the temperature excursion is small. A degradation of 95% is assumed throughout.

Solution of MPZ does not exist when the operating current is too high because the critical temperature $T_G$ may fall below the bath temperature $T_0$. Solution also does not exist when the surface cooling is too large, because any heat deposited on the cable will be carried away through heat transfer at the strand surface providing that the bath temperature $T_0$ is maintained. Once a stable heated zone exists, there are general infinitely many solutions. We choose the one that can be established with the minimum amount of energy and call it the MPZ.

Figures 1 and 2 show the temperature excursion for the MPZ as a function of copper to superconductor ratio $R$ in the strand for bath temperature $T_0 = 4.2$ K and 4.3 K respectively. Cooling has been set to zero. Here, temperature excursion implies the difference between the peak temperature $T_P$ at the center of the MPZ and the bath temperature $T_0$. Note that $T_P$ can be bigger than $T_L$. When $T_P$ is less than $T_L$, the inner zone does not exist. It is hard to compare these two graphs with those by Quigg and Tigner because they plotted $T_G - T_0$ instead.

Figures 3 and 4 show the half width of the MPZ as a function of $R$ for bath temperature $T_0 = 4.2$ K and 4.3 K respectively. Cooling has been set to zero. The half widths computed by Quigg and Tigner are much smaller. This is because they have used a wrong heating rate that is proportional to the square of the operating current $I_0$. The correct heating rate is proportional to $I_0 I_{cu}$, where $I_{cu}$ is the current spilled over to the copper. This correct quantity is definitely smaller when the temperature is less than $T_L$.

Figures 5 and 6 show the energy required to set up the MPZ *vs* $R$ at bath temperature $T_0 = 4.2$ K and 4.3 K respectively. This energy can be considered as the minimum energy required to trigger a quench if transient effects can be neglected. Cooling has been set to zero here. Again, our values are bigger than those computed by Quigg and Tigner because a smaller generation has been used.

Figure 7 shows the variation of the residual resistivity ratio (RRR) of copper to the minimum energy required to trigger a quench with no cooling assumed. In this plot, the bath temperature is held at 4.2 K and the operating current is 6.5 kAmp. A higher RRR lowers the electric field produced by the current spilled over in the copper and therefore less heat will be generated in the superconductor filaments. Thus, the energy required to set up the MPZ will increase. The plot also shows that there is not much advantage to increase RRR because magnetoresistivity begins to dominate when RRR exceeds $\sim 30$.

Figure 8 shows the effects of cooling by heat transfer at the perimeter. The bath temperature is at 4.2 K and operating current is fixed at 6.5 kAmp. We see that cooling effects are hardly visible when the heat transfer coefficient $H$ is less than $\sim 1000$ $\mathrm{Wm^{-2}K^{-1}}$. Even when $H$ rises to $1 \times 10^4$ $\mathrm{Wm^{-2}K^{-1}}$ the increase in minimum energy to trigger a quench is still rather small. For comparison, $H \approx 5 \times 10^4$ $\mathrm{Wm^{-2}K^{-1}}$ when the bare superconducting cable strand is in contact with liquid helium, The superconducting strands in the SSC dipoles are wrapped with insulator and are not in direct contact with liquid helium. Therefore $H$ should be far below $5 \times 10^4$ $\mathrm{Wm^{-2}K^{-1}}$. This may explain why in the quench-measuring experiments the results are not sensitive to the way the strands are cooled.

More details of the computation and the analyses of results will be presented elsewhere.

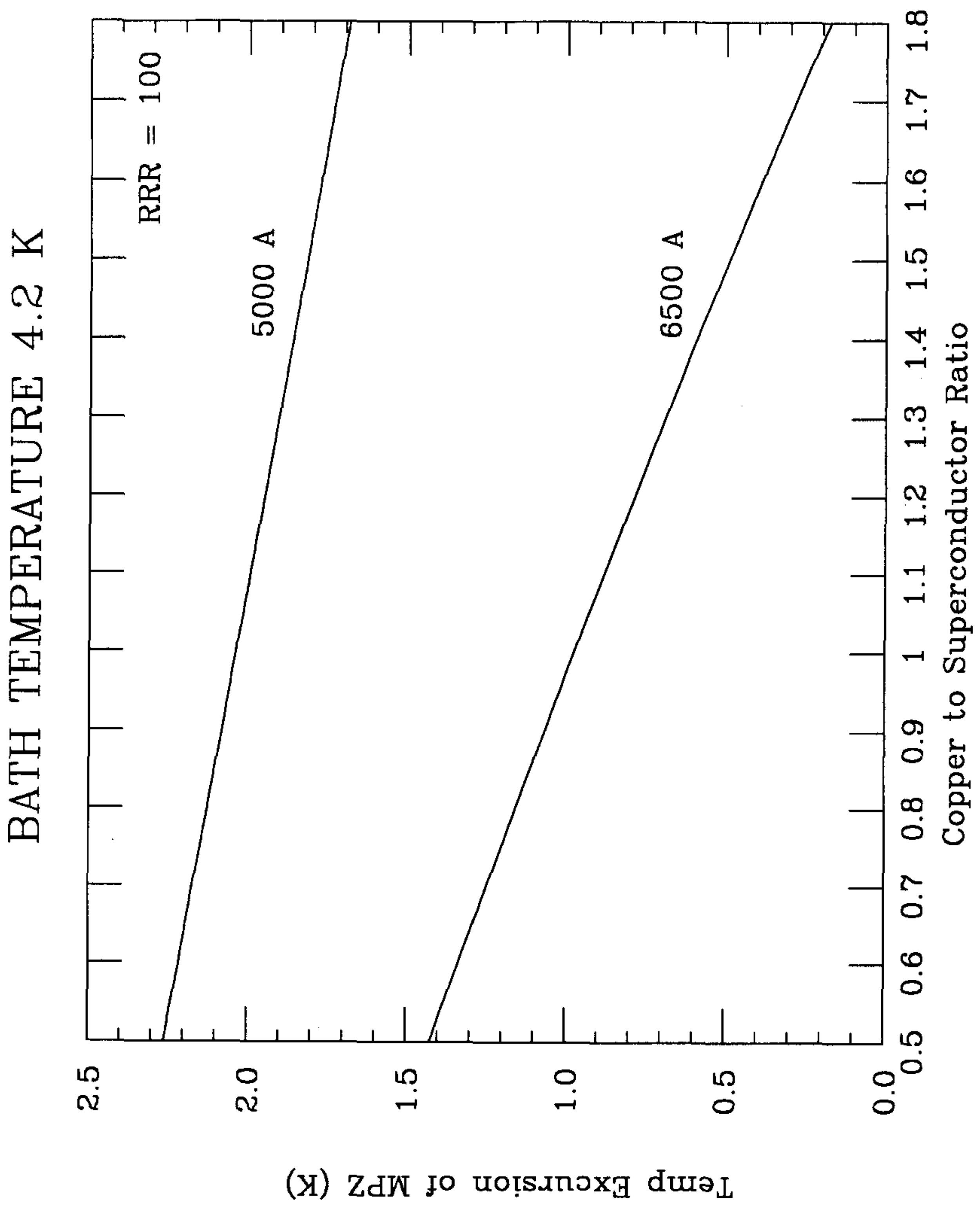

BATH TEMPERATURE 4.2 K
RRR = 100
5000 A
6500 A
Temp Excursion of MPZ (K)
Copper to Superconductor Ratio
0.0
0.5
1.0
1.5
2.0
2.5
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

Figure 1.

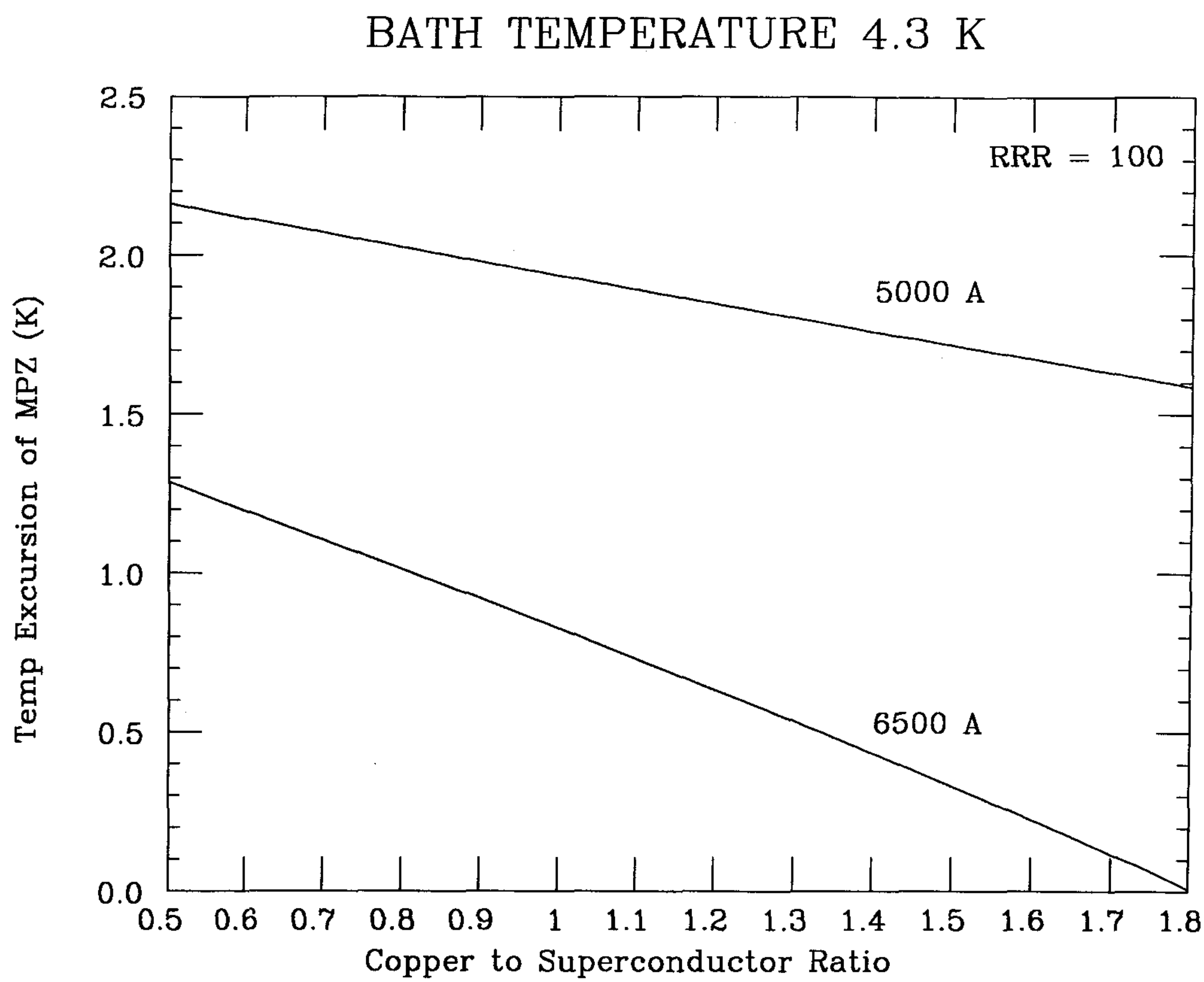

BATH TEMPERATURE 4.3 K
RRR = 100
5000 A
6500 A
Temp Excursion of MPZ (K)
Copper to Superconductor Ratio
2.5
2.0
1.5
1.0
0.5
0.0
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

Figure 2.

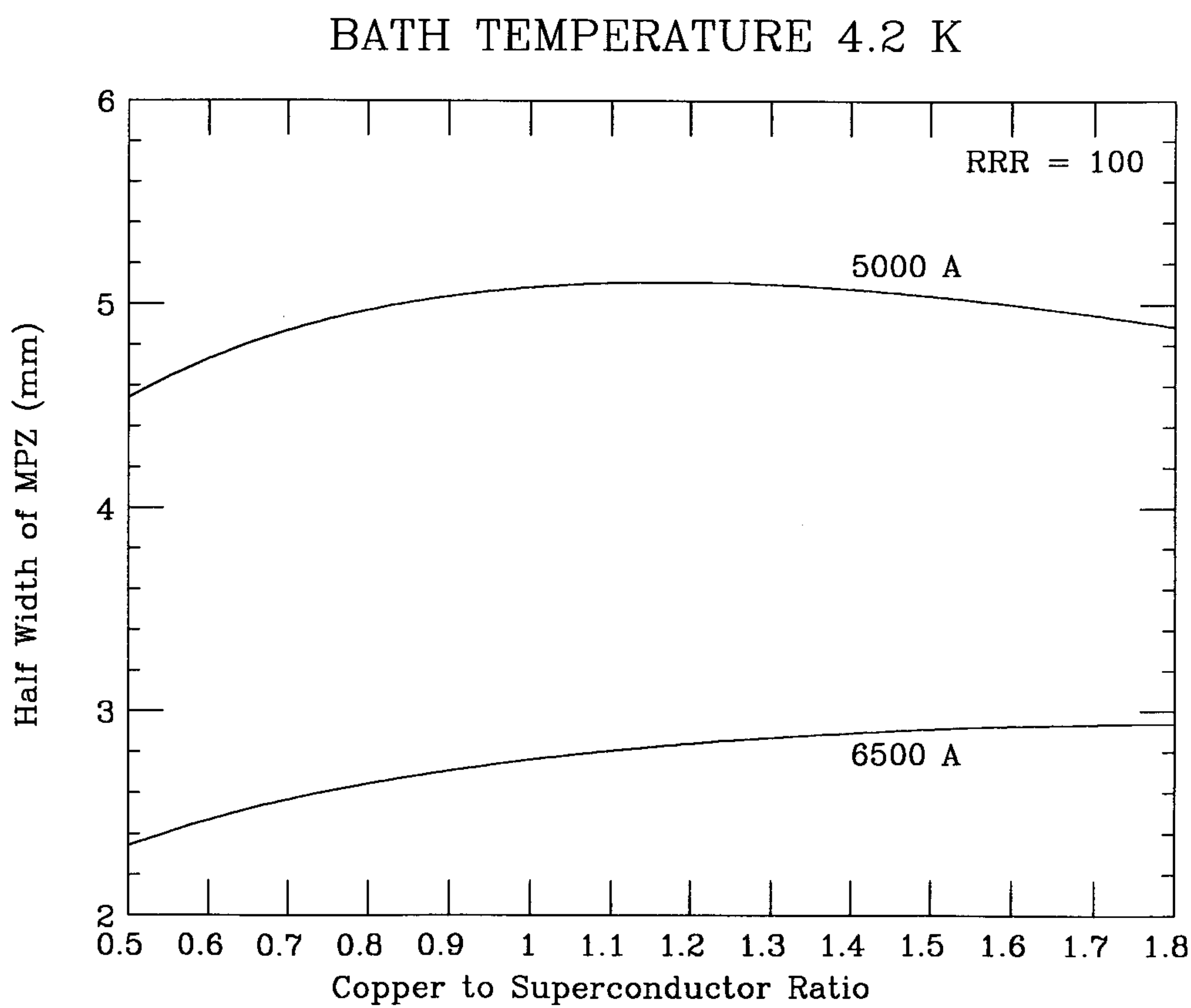
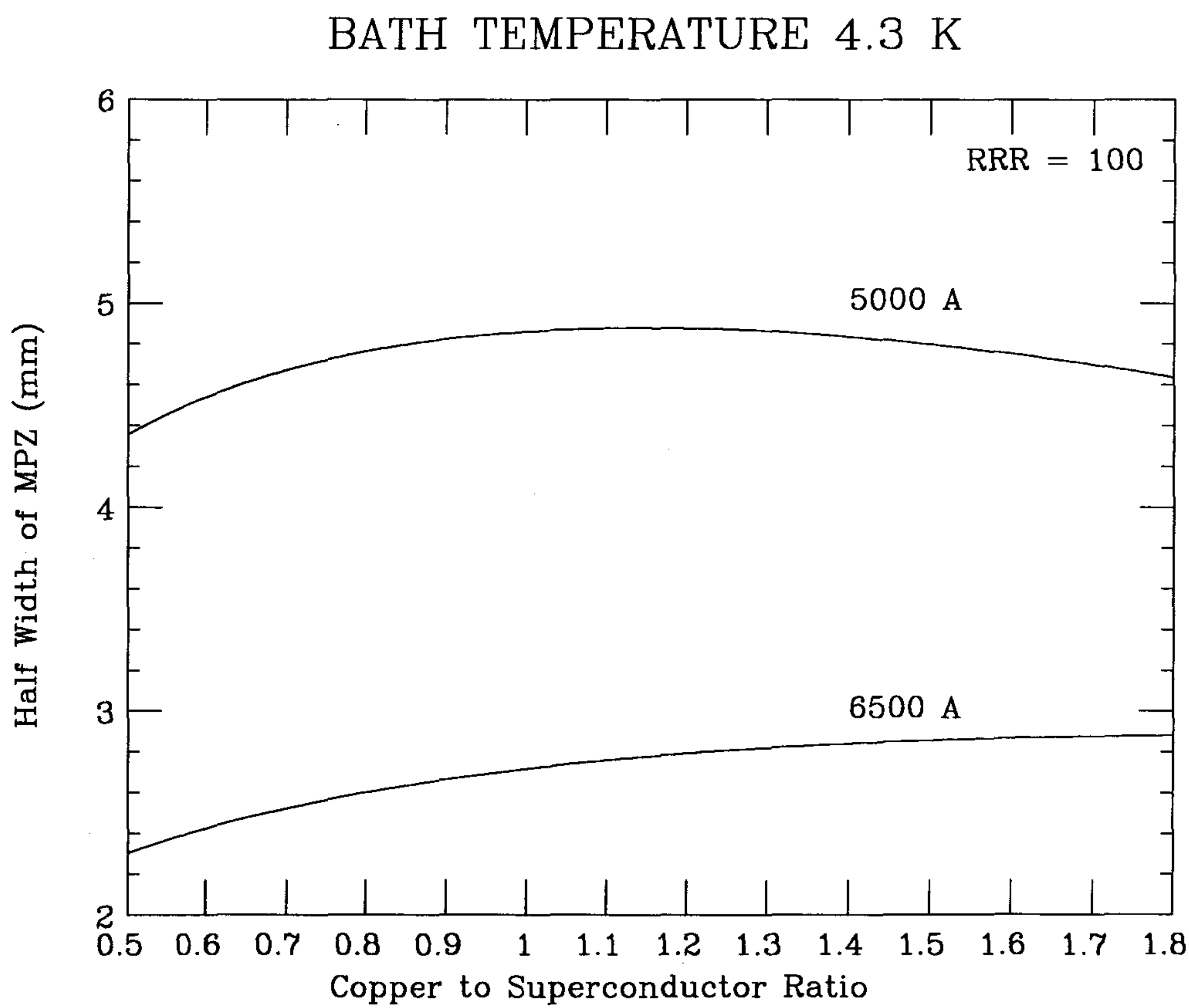

BATH TEMPERATURE 4.2 K
RRR = 100
5000 A
6500 A
Half Width of MPZ (mm)
Copper to Superconductor Ratio
6
5
4
3
2
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

Figure 3.



BATH TEMPERATURE 4.3 K
RRR = 100
5000 A
6500 A
Half Width of MPZ (mm)
Copper to Superconductor Ratio
6
5
4
3
2
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8


Figure 4.

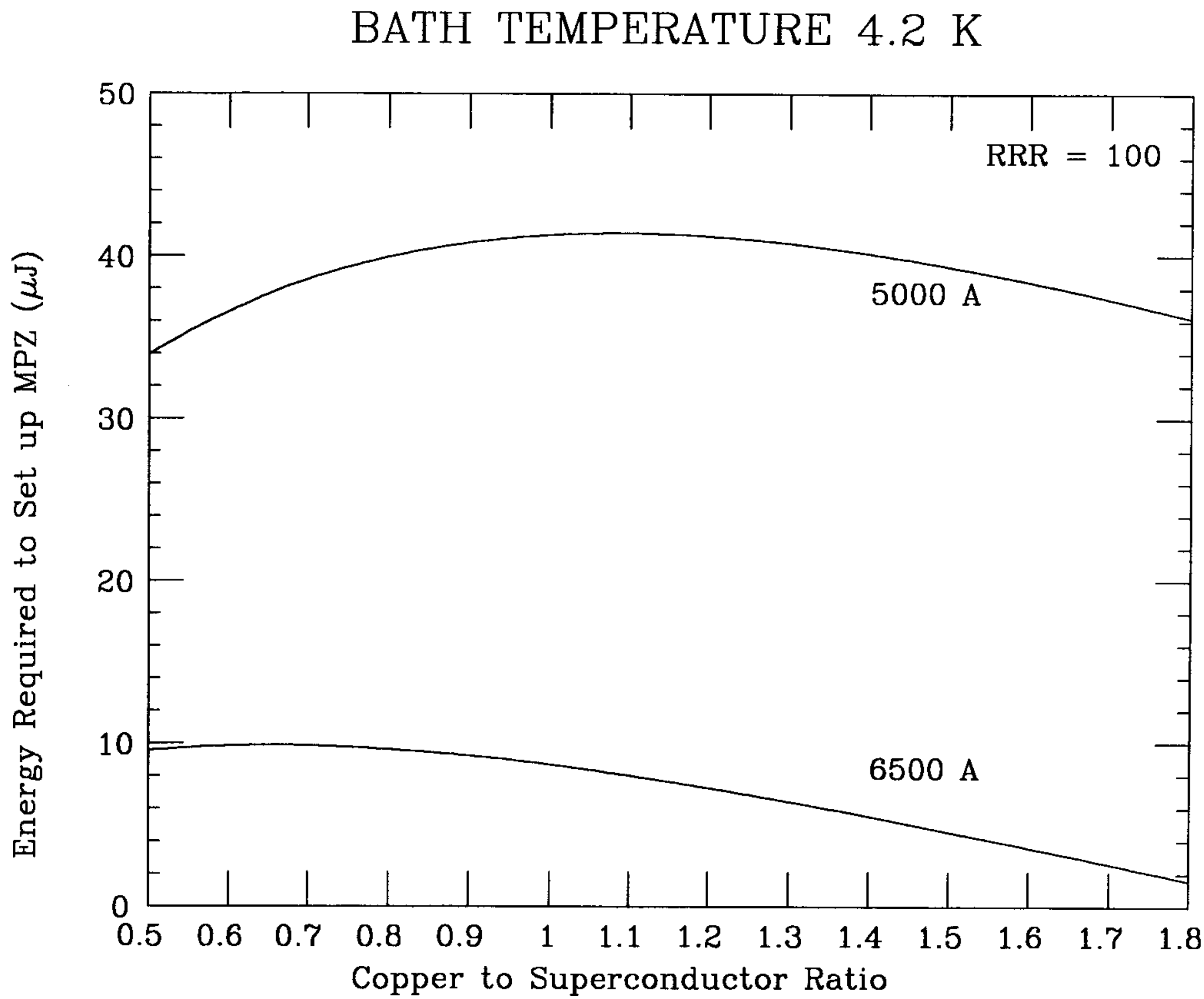

BATH TEMPERATURE 4.2 K
RRR = 100
5000 A
6500 A
Energy Required to Set up MPZ (μJ)
Copper to Superconductor Ratio
0
10
20
30
40
50
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

Figure 5.

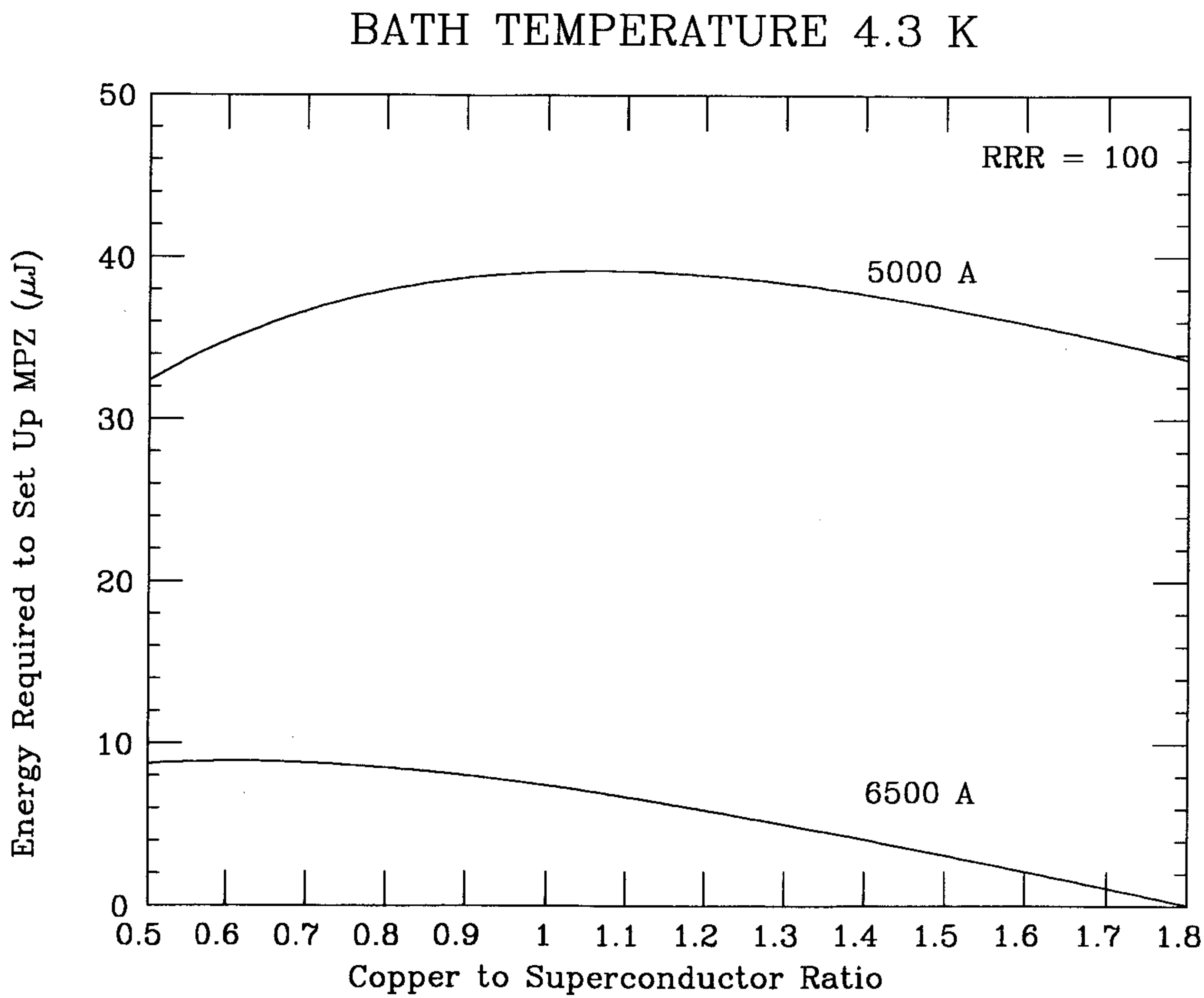

BATH TEMPERATURE 4.3 K
RRR = 100
5000 A
6500 A
Energy Required to Set Up MPZ (μJ)
Copper to Superconductor Ratio
0
10
20
30
40
50
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

Figure 6.

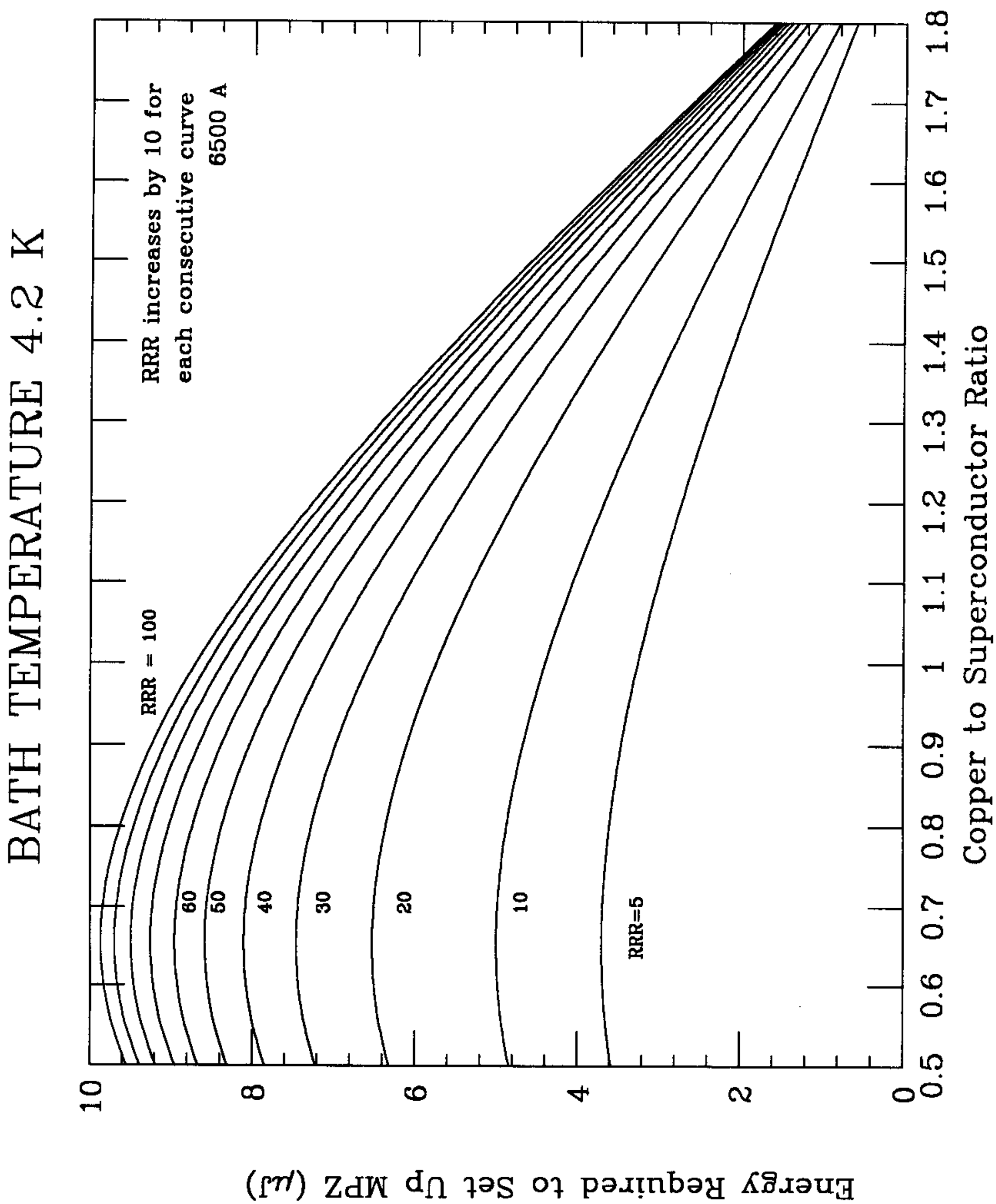
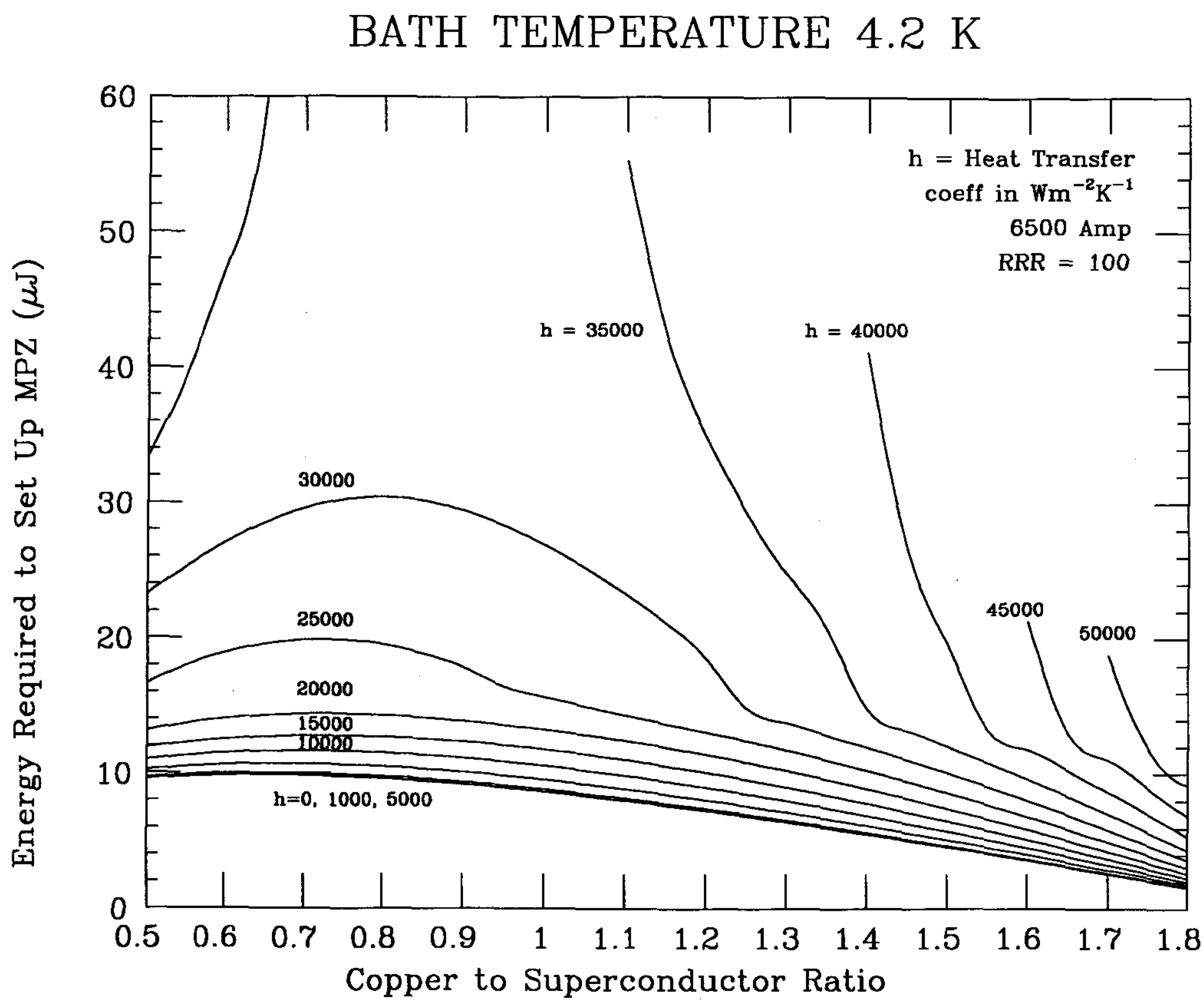

BATH TEMPERATURE 4.2 K
RRR increases by 10 for
each consecutive curve
6500 A
RRR = 100
60
50
40
30
20
10
RRR=5
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8
Copper to Superconductor Ratio
0 2 4 6 8 10
Energy Required to Set Up MPZ (μJ)

Figure 7.



BATH TEMPERATURE 4.2 K
h = Heat Transfer
coeff in Wm$^{-2}$K$^{-1}$
6500 Amp
RRR = 100
h = 35000
h = 40000
30000
25000
20000
15000
10000
h=0, 1000, 5000
45000
50000
Energy Required to Set Up MPZ (μJ)
Copper to Superconductor Ratio
0
10
20
30
40
50
60
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8


Figure 8.