High Energy Facilities

Accelerator Development Branch

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QUENCH PERFORMANCE OF THE 16.6 m SSC MAGNET COMPUTED FROM MEASURED DATA

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If the quench developed resistance as a function of time is known, then all of the electrical properties of the quench event can be computed including the integral I^2dt and the internal I X R voltage product. Various models have been used to help study magnet quenching events. K. Koepke [1], A. Stevens, William Hassenzahl [2], and myself have studied models based on quench velocities measured on sample pieces of cable by William Sampson, BNL. These models can be adjusted to fit the observed I^2dt integral, but the time function of the quench resistance is never reproduced well. The shape of the measured resistance-time function has suggested that the quench front is being accelerated and this has led to various speculations. Analytical work by R. Shutt [3] and D. Hagedorn[4] based on solutions of the diffusion equations have shown acceleration of the quench front, particularly the quench front in the second and later turns tend to accelerate and approach the quench front traveling in the first turn.

The possibility that this type of acceleration of the quench front might occur, led the BNL team to heavily instrument magnet SLN-012, one of the 4.5 cm 4.5 m SSC magnets, and examine the motion of the quench front in the first and subsequent quenching turns. Detail results of this experiment will be reported by A. Prodell in another note but typical results are shown in Figure 1. The vertical axis of Figure 1 is distance in inches and the horizontal axis displays time. To my surprise there are three important observations that can be made by studying this figure.

1. Indeed, the quench in the second and third turn accelerates and tends to catch up with the quench front in the first turn qualitatively confirming the diffusion equation analysis by Shutt and Hagedorn.

2. The quench front in the first quenching turn also accelerates and the change in velocity is sizable. The initial velocity at 5000 amps is 8.8 m/sec. and after it travels 40 inches it has accelerated to a velocity of 16.5 m/sec. Clearly, heat is being transported ahead of the quench front possibly by thermal conduction or by extrusion of "hot" gas from the quenching zone.

3. The motion of the quench zone azimuthally is also accelerated. It took 26 m sec to induce a quench in the second turn, an additional 9 m sec to reach the third turn but in another 7 1/2 m sec the quench front reached the fifth turn. (The fourth turn was not instrumented.)

These accelerations of the quench front motion go a long way in explaining the pessimestic results given by the models which did not contain this action. It is not, at present clear how to quantify these acceleration terms and further study is required.

However, the quench resistance-time function can be extrapolated from measured data. The resistance developed in each magnet half is measured by measuring the current and voltage associated with that half and solving for the resistance using the equation

$$E = L \frac{di}{dt} + IR$$

The results are shown in Figure 2. The data out to 0.24 sec. can be approximated by three line segments on the semilog plane. Beyond that time the resistance curve falls from the straight line because the current in the magnets are falling. The full length (16.6 m) SSC magnet will have more inductance than the 4.5 m model under test and as a result the current will decay more slowly. If the current did not decay, then the resistance-time function would continue to follow the last line segment of the approximation. To estimate the decay in the resistance-time function for the full length SSC magnet the rate of change of resistance with time is examined. For constant current the resistance is given by

$$R = e^{(At+B)}$$

where A and B are constants determined by data fit and t is time.

$$\frac{dR}{dt} = Ae^{(At+B)}$$

For varying current this derivative function is modified by a form factor F. Figure 3 is a plot of this modifying factor versus time. The dots represent the data and the line an approximation.

Also shown is the ratio of current to starting current and lines proportional to the square and 2.5 power of this ratio. The line that approximates the correction factor runs parallel to the line that represents the 2.5 power of the current ratio. Thus the time derivative of resistance can be approximated by,

$$\frac{dR}{dt} = \left(\frac{I}{Io} \right)^{2.5} Ae^{(At+B)}$$

where I = current, Io = starting current.

From this derivative the resistance-time function can be generated by numerical integration and the current commutation process can be computed for various assumed circuit configurations.

I have chosen to analyze three conditions,

1. The SSC magnet passively protected by a single diode and the quench is confined to one magnet half.

2. The SSC magnet is protected by a "double diode" system and the quench is also confined to only one magnet half. This case makes the best use of the "double diode" action.

3. The SSC magnet is protected by a "double diode" system and there exists two identical quenches one in each half of the magnet. This type of quench receives no help from the "double diode" system but the total resistance has been doubled.

The analysis was performed for five starting currents and the results are shown in Figure 4. For each starting current the experimental data was plotted and the A and B constants were determined for each line segment. The full length SSC magnet inductance was assumed to be 0.0546 henries and the half magnet self-inductance to be 0.017 henries.

Because of the quench propagation acceleration the current was commutated out of the magnet quickly even in the single diode case. The peak I^2dt integral reaches only 11.3 x $10^6 A^2$sec., a long way from the "burnout" point for the inner cable, 15.27 x $10^6 A^2$sec.[5] All of the measurements were made on the inner coil since this was the coil that was instrumented with the necessary potential taps. In CBA magnets quenches were slower in the outer coil than in the inner but with the graded conductor used in the SSC magnets, this speed difference should be reduced and the quench properties made similar. If this is true, these results may also represent the quench characteristics of the outer coil. Certainly, this is the best approximation yet. The "burnout" point in the outer coil conductor is lower, 12.16 x $10^6 A^2$sec.[5] This leaves little margin for error and unit variation, if the single diode passive protection system is used. The action of the "double diode" protection system falls between the two other cases analyzed and at worst gives another 1.3 x $10^6 A^2$sec. of margin often more.

When a quench occurs at a current near the short sample value the quench front travels very fast. Under these conditions the current is commutated out of the magnet rapidly and the "hot spot" temperature is low, but this process develops high internal I x R products. Figure 5 shows these potentials as a function of time and starting current. A peak potential of 4350 volts was reached and approximately half of this potential (2175 volts) can appear on the mid-tap. The potential to ground is this potential plus any system voltage this is driving this magnet off ground.

The "double diode" protection system does not develop such high internal I X R voltages. In case 3 with two symmetrical quench, no voltage appears on the terminals since the I X R potential is bucked in place by an opposing L di/dt term. In Case 2 where the quench is confined to only one magnet half a small I X R product is developed and that is shown in Figure 6. This voltage will appear across the other magnet half modified by the top to bottom magnetic coupling coefficient, 0.588. The internal I X R peak is 1380 volts thus only 811 volts will appear on the magnet terminals to add to the system voltages. While this is small it is not negligible and the insulation and helium pressures must be engineered to handle this additional terminal voltage. The single diode case creates very high voltages which produce insulating problems that have not been addressed and may be difficult to solve even in 5 atmospheric helium.

From these experimental results I believe that we can now expect to be able to passively protect the 16.6 meter SSC magnet and that we should actively engineer the necessary diodes and their assemblies into the magnet end configuration. I would recommend that the "double diode" protection system be adopted because of its extra burnout margin and reduced voltage characteristics.

1) TM 1316-SSC20, SSC-N-12, K. Koepke, "A Simulation of Quenches in SSC Magnets with Passive Quench Protection".

2) LBL-19004, SSC Mag. Note 29, G. Moritz, W. Hassenzahl, "Computer Studies of the Quench Behavior of an SSC Model-Dipole.

3) Unpublished computer analysis, R. P. Shutt, BNL.

4) Private communication P. Hagedorn, CERN

5) SSC Technical Note 27, G. Cottingham, "Passive Quench Protection for SSC Magnet Design D.

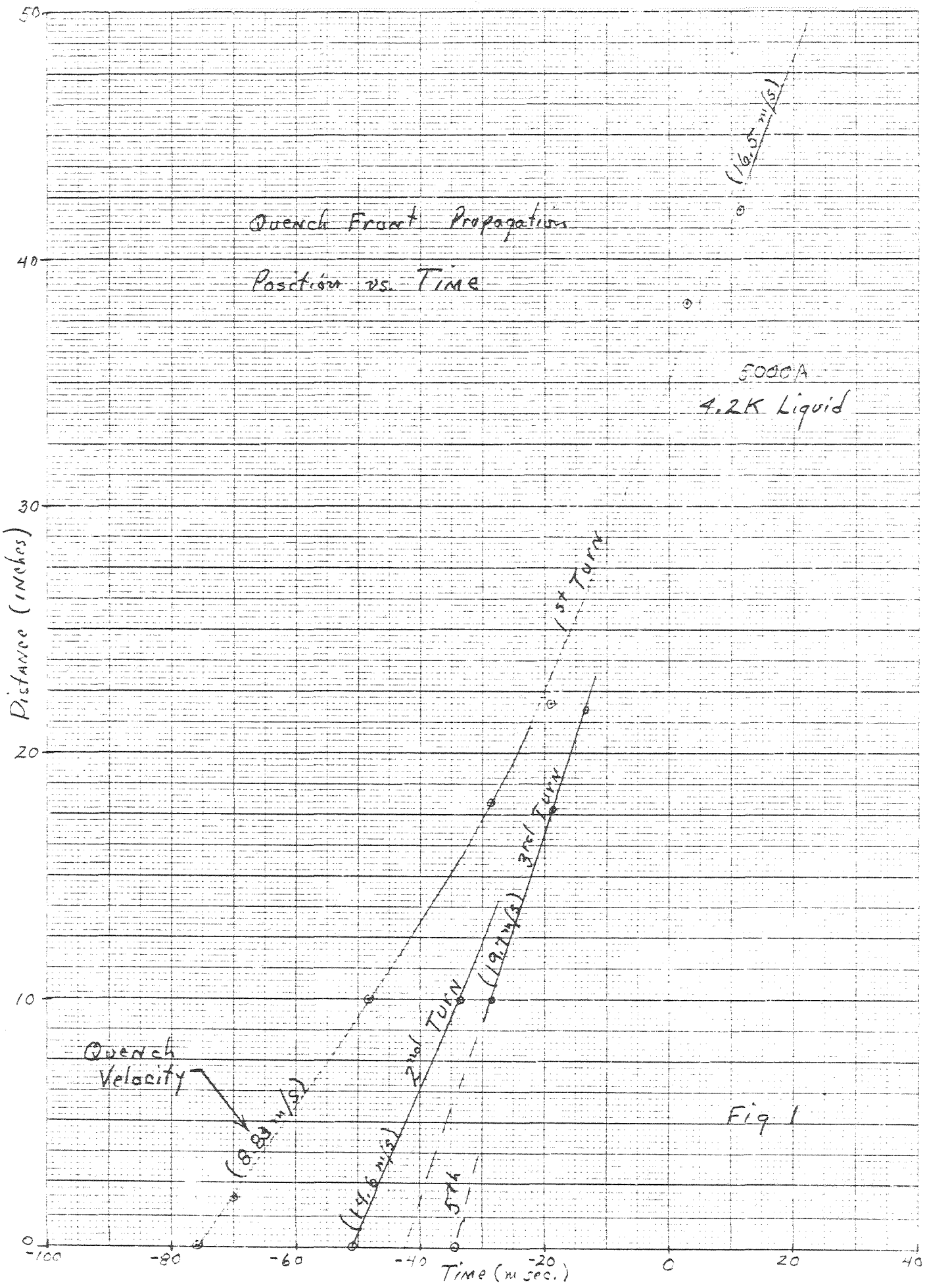
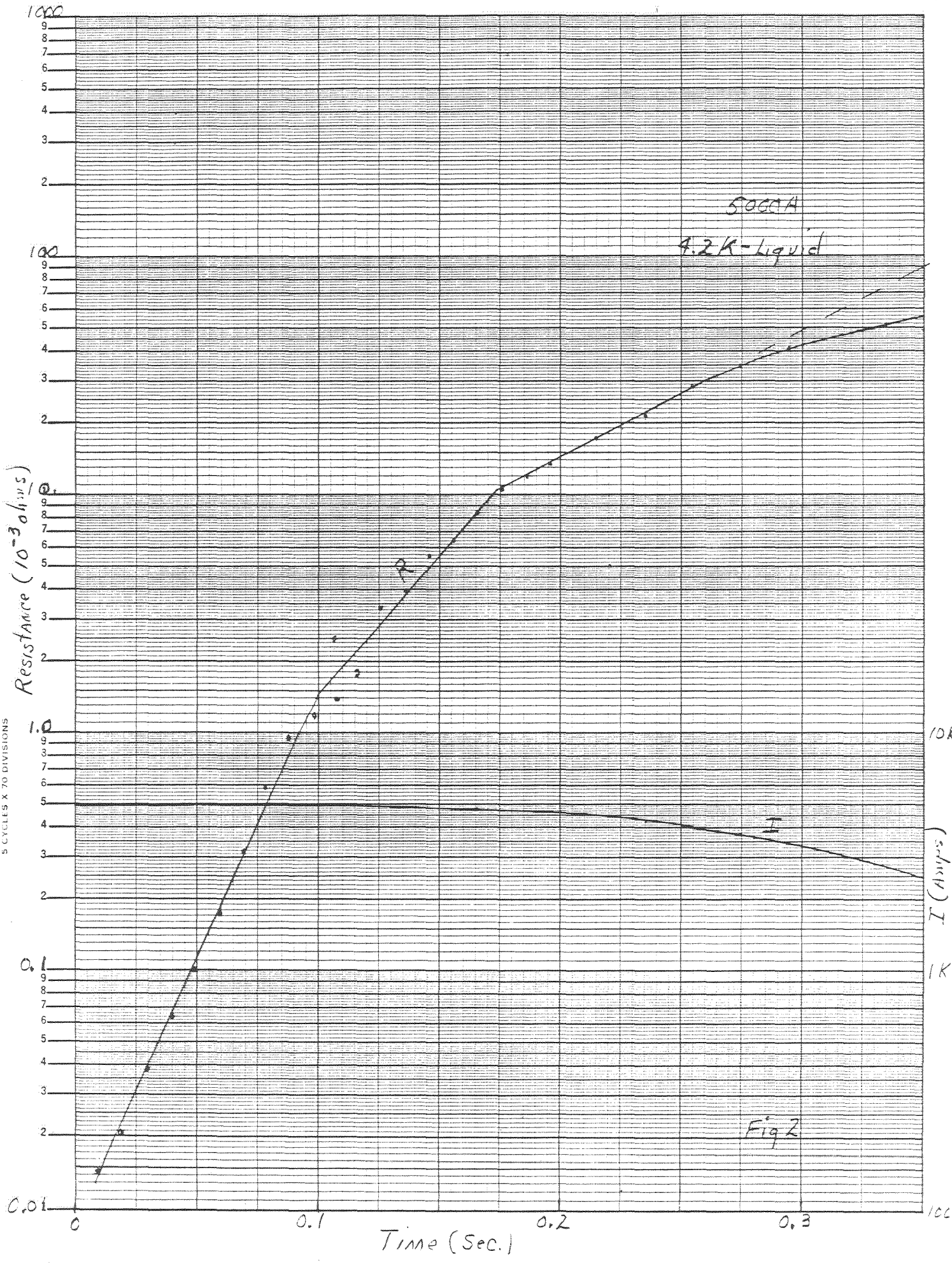

Quench Front Propagation
Position vs. Time
5000A
4.2K Liquid
Distance (inches)
Time (m sec.)
Quench Velocity
(8.83 m/s)
(14.6 m/s)
(19.7 m/s)
(16.5 m/s)
1st Turn
2nd Turn
3rd Turn
5th
0
10
20
30
40
50
-100
-80
-60
-40
-20
0
20
40

Fig 1


500A
4.2K-Liquid
R
I
Resistance (10^{-3} ohms)
I (Amps)
Time (Sec.)
1000
100
10
1.0
0.1
0.01
10K
1K
100
0
0.1
0.2
0.3
Fig 2
SEMI-LOGARITHMIC 358-91
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS

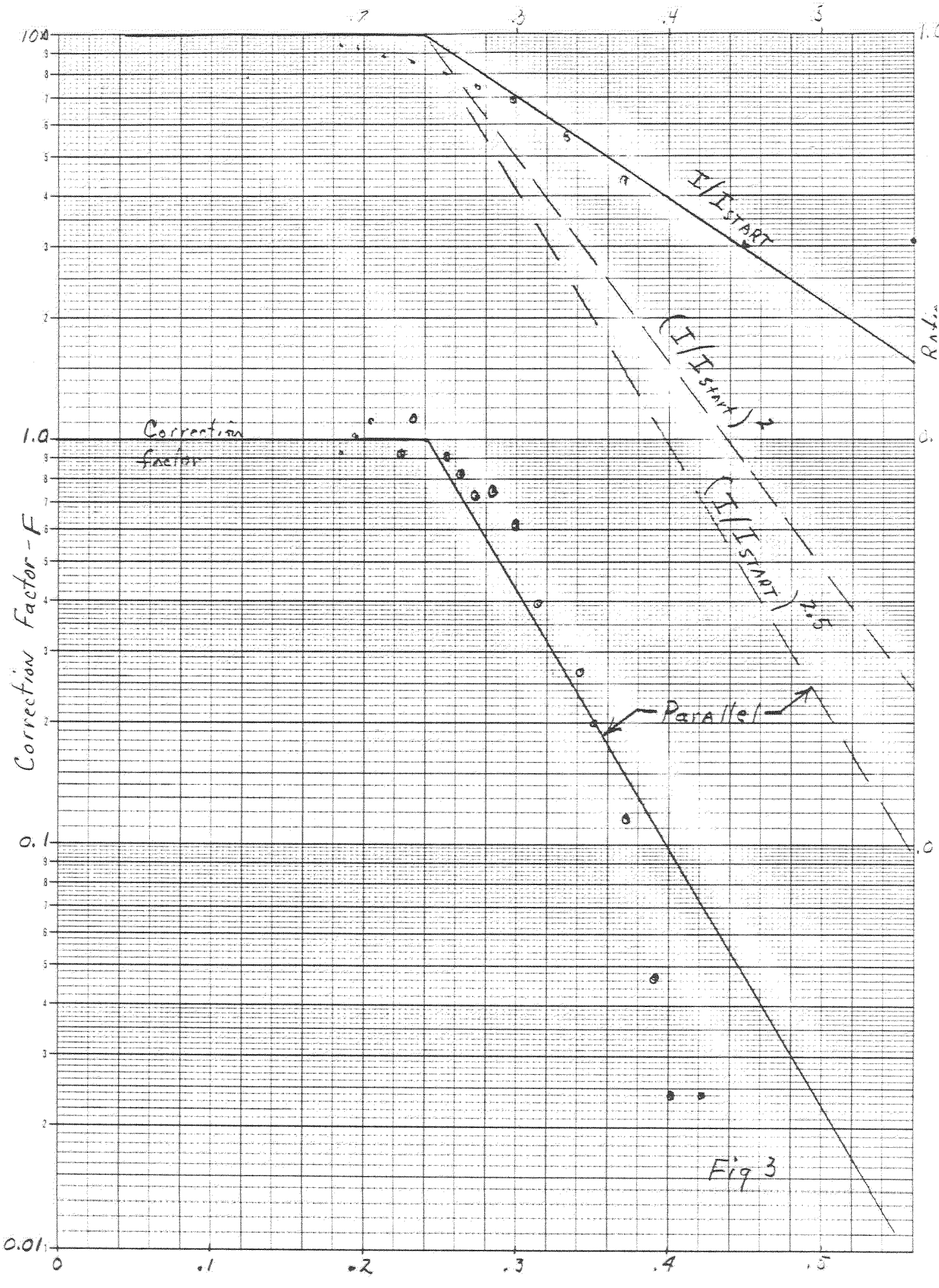


Fig 3

SEMI LOGARITHMIC 3 CYCLES X 140 DIVISIONS AD 0840 - 60

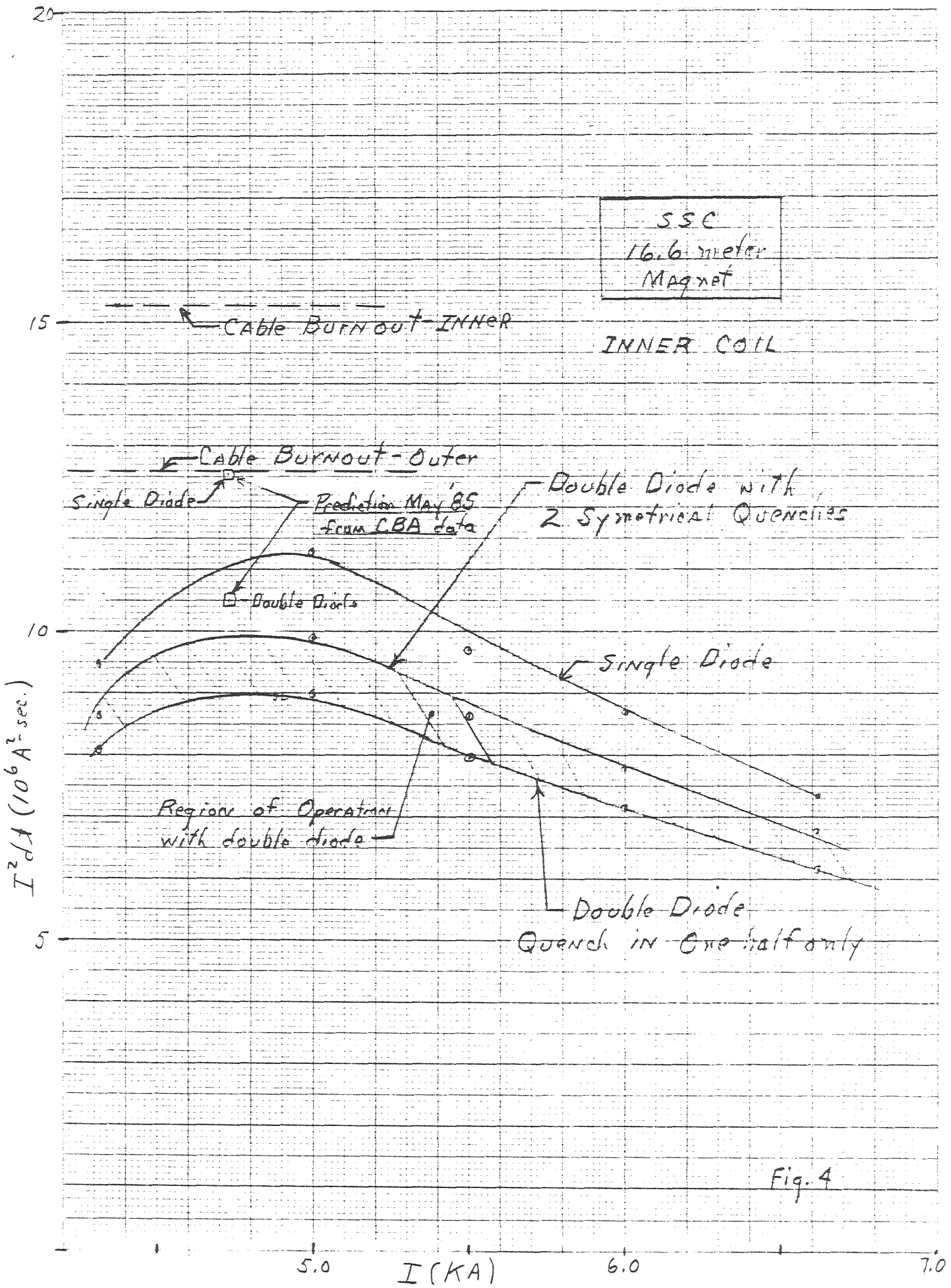

SSC
16.6 meter
Magnet
INNER COIL
Cable Burnout - INNER
Cable Burnout - Outer
Single Diode
Prediction May '85
from CBA data
Double Diode with
2 Symmetrical Quenches
Double Diode
Single Diode
Region of Operation
with double diode
Double Diode
Quench in One half only
$I^2 dt$ ($10^6 A^2$-sec.)
I (KA)
20
15
10
5
5.0
6.0
7.0

Fig. 4

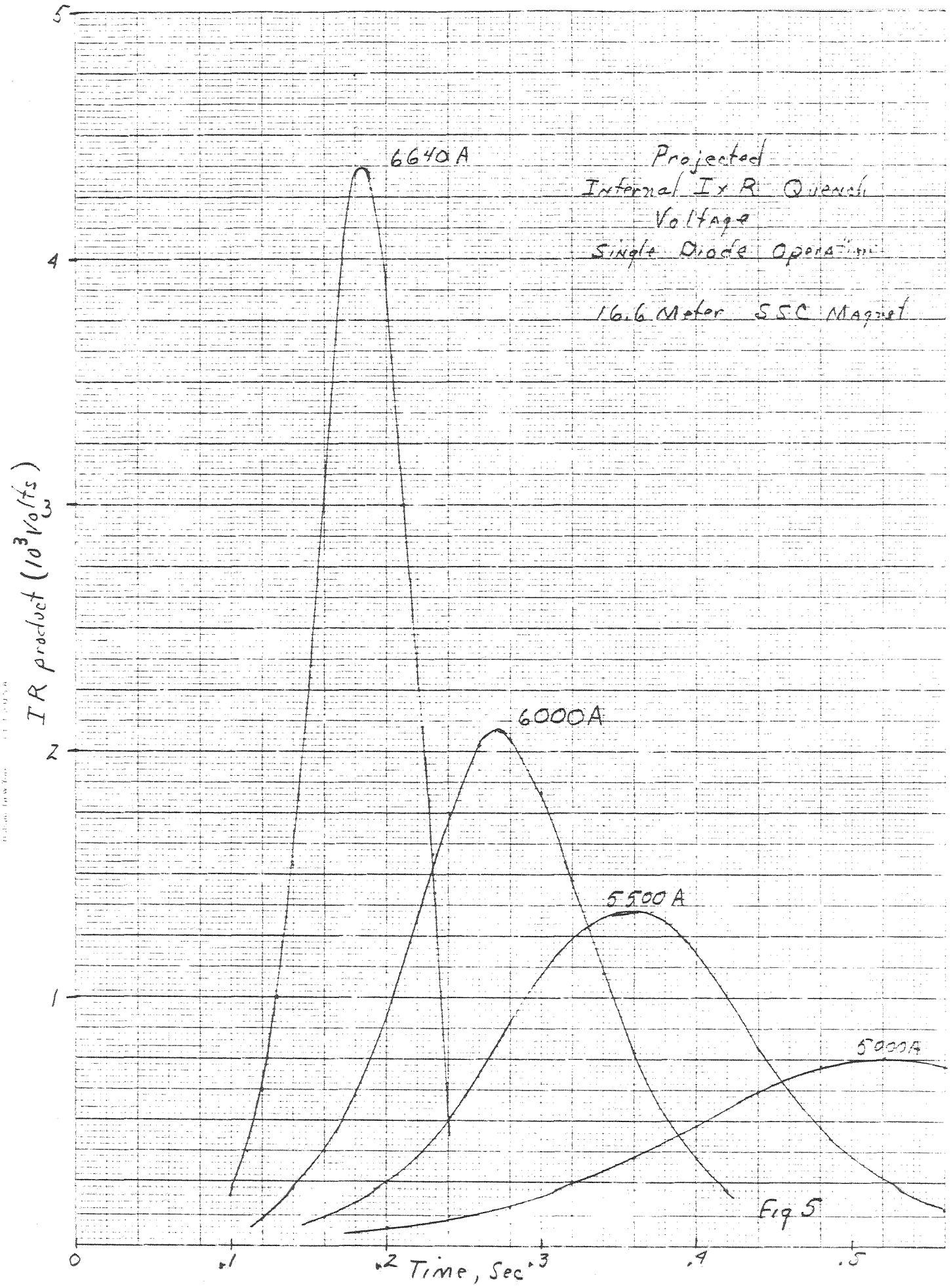

Projected
Internal I x R Quench
Voltage
Single Diode Operation
16.6 Meter SSC Magnet
6640 A
6000 A
5500 A
5000 A
IR product (10^3 Volts)
Time, Sec
0
.1
.2
.3
.4
.5
1
2
3
4
5

Fig 5

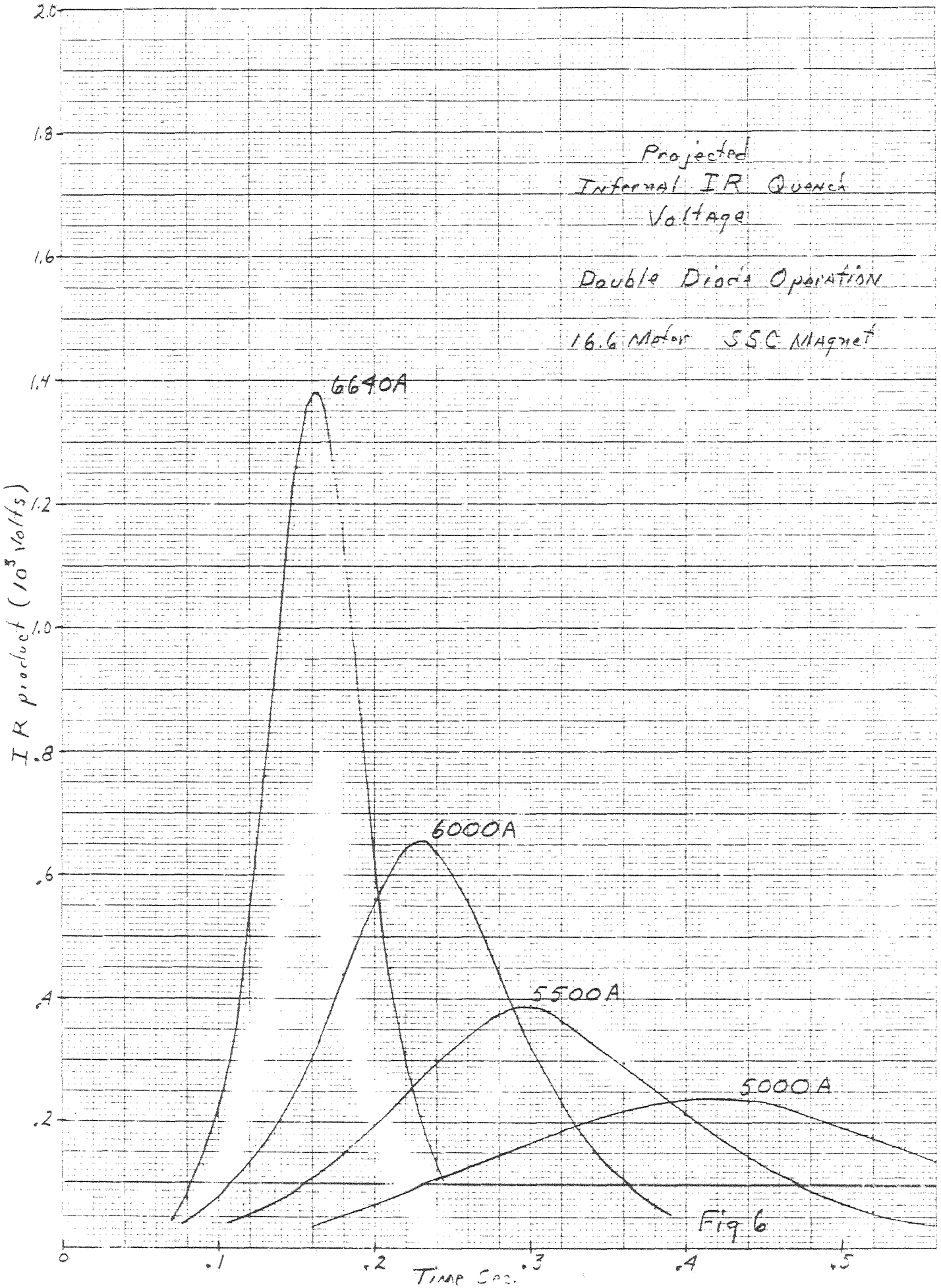

Projected
Internal IR Quench
Voltage
Double Diode Operation
16.6 Meter SSC Magnet
6640A
6000A
5500A
5000A
IR product (10^3 Volts)
Time Sec.
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
.1
.2
.3
.4
.5

Fig 6

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