Summary of the Tohoku Magnet
Stability, Burnout Protection, and
General Electrical Integrity

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April 2, 1985

Introduction

The superconducting wire wound into the Tohoku Bubble Chamber Magnet coils is a 14 strand solder filled cable wrapped around a 0.042" x 0.131" copper core. Most of the conductor for this project was unwound from the Chicago Cyclotron Magnet after being severely damaged through overheating and mishandling. This cable was made with six Energy Doubler strands and eight copper strands each with a 0.0268" diameter. New conductor was purchased, however, for the inner 26 layers. This cable was made in the same fashion except that seven Energy Doubler and seven copper strands were used. Most of the Energy Doubler wire used in this new batch was substandard I_c surplus. The soldering job on this wire was vastly improved from the original batch.

Notched G-10 strips, 1-1/4" wide, provide the layer to layer insulation and also the cooling channels. Because layer to layer shorts developed from damaged conductor during winding, the following peculiar winding scheme was eventually used.

Layer #'s	G-10 Spacer Thickness	Mylar Between Layers
1 - 8	0.050"	perforated mylar
9 - 26	0.034"	perforated mylar
27 - 63	0.050"	solid dimpled mylar

Coil number two had 1/2" x 0.020" G-10 strips bonded to the perforated mylar for further protection against layer to layer shorts. The solid mylar sheets were dimpled to prevent complete contact with the conductor. I would estimate the dimple height to be 0.010".

Figure 1 is a plot of the magnitude of the magnetic field through the coil windings. The peak field is found to be 54.1 kG at 704 amps when the muon notches have been completely filled with iron. The initial residual resistivity ratio of the 6 superconductor strand cable was measured to be RRR = 107. After thousands of cycles, the RRR of the cable can still be expected to be greater than 100. At 4.2 K a sample of cable was cycled 640 times to 645 lbs (40.5 ksi for 0.0159 in^2 total cross section) with $\Delta\varepsilon = 0.31\%$ and $\varepsilon_{max} = 0.91\%$. The critical current was reduced by 8%, and the initial RRR was reduced by 12%. Ramping the magnet up to 700 amps produces only a maximum tension of 180 lbs on the inner layer.

Stability

Conductor stability is extremely difficult to predict for this coil because of the wide range of conditions. In this magnet we have

1. Two grades of conductor.

2. Two different channel widths.

3. Conductor in the horizontal channels sits face up to exactly vertical.

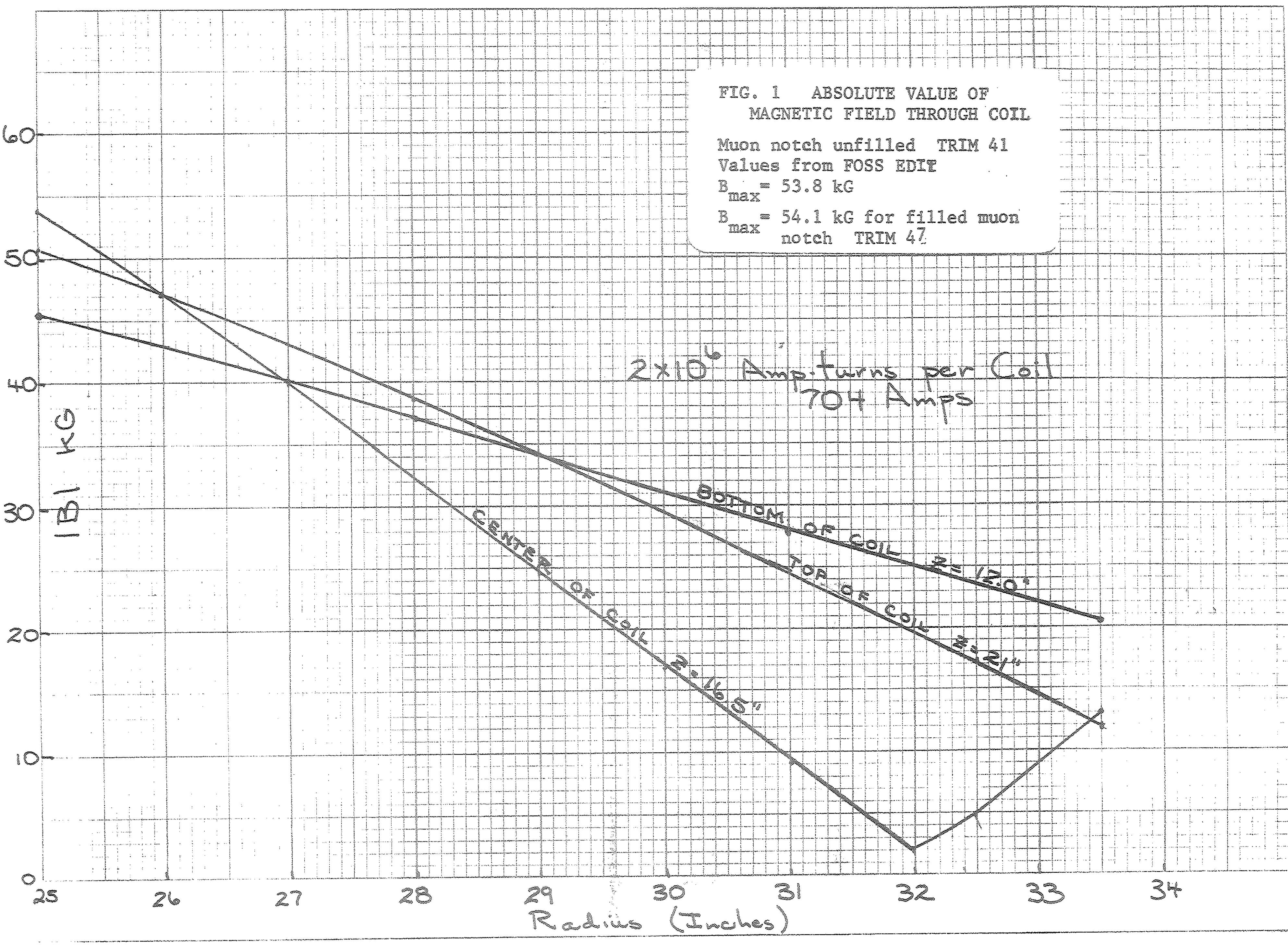


FIG. 1 ABSOLUTE VALUE OF MAGNETIC FIELD THROUGH COIL
Muon notch unfilled TRIM 41
Values from FOSS EDIT
B max = 53.8 kG
B max = 54.1 kG for filled muon notch TRIM 47
2×10⁶ Amp-turns per Coil
704 Amps
|B| kG
Radius (Inches)
BOTTOM OF COIL z = 12.0"
TOP OF COIL z = 21"
CENTER OF COIL z = 16.5"
0
10
20
30
40
50
60
25
26
27
28
29
30
31
32
33
34

4. Solid mylar is in some layers and perforated mylar in the other layers. The effective channel width is extremely dependent upon how the mylar lies on the conductor.

5. The connecting cooling channels to the horizontal layer to layer cooling channels form a complicated path.

Vapor locking of the channels is a possibility. Simple stability criteria are presented, and experimental stability studies are reproduced in Appendix 1 and Appendix 2.

With a 0.042" x 0.131" copper core the total cross sectional area of the conductor is 0.0134 in^2 (0.0865 cm^2) where the area is calculated by summing the cable component rather than using the overall dimensions. The following copper to superconducting ratios are obtained

Cu/S.C. =8.5 for the 7 superconductor strand cables
Cu/S.C. =10.1 for the 6 superconductor strand cables.

The typical measured conductor size is ~ 0.091" x 0.183". The I.G.C. wire spec. size is 0.088" x 0.178".

Only the wide face of the conductor is available for cooling or 2 x (0.183 x 2.54) x 1 = 0.93 cm^2/cm. For copper with a RRR = 100 the magnetoresistivity at 4°K is approximately $\rho = 1.57 \times 10^{-8} (1 + 0.31\ B)\ \Omega$-cm where B is the magnetic field in Tesla. Figure 2 is the measured resistance of the 6 superconductor strand cable. Included on this same plot is the theoretical resistance for RRR = 100 and B = 0. Also included are two data points based on overall coil resistance. The total length of cable in each coil is 43,700 feet.

$$R = 29.7\ \Omega = 2.23 \times 10^{-5}\ \Omega/\text{cm at } 293^\circ K$$

$$4.2\ \Omega = 3.15 \times 10^{-6}\ \Omega/\text{cm at } 80^\circ K$$

Overall Cryostability:

Rather than use the Stekly stability parameter, the unit heat flux will be compared with measured critical heat flux numbers.

$$Q = \frac{I^2 \rho}{AP} = 0.40 \text{ watts/cm}^2$$

where $I = 700$ Amps

$\rho = 4.2 \times 10^{-8}\ \Omega$/cm (B = 5.4 T)

$A = 0.0865 \times 8.5/9.5 = 0.0774\ cm^2$

$P = 0.93 \text{ cm} \times 0.716 = 0.67$

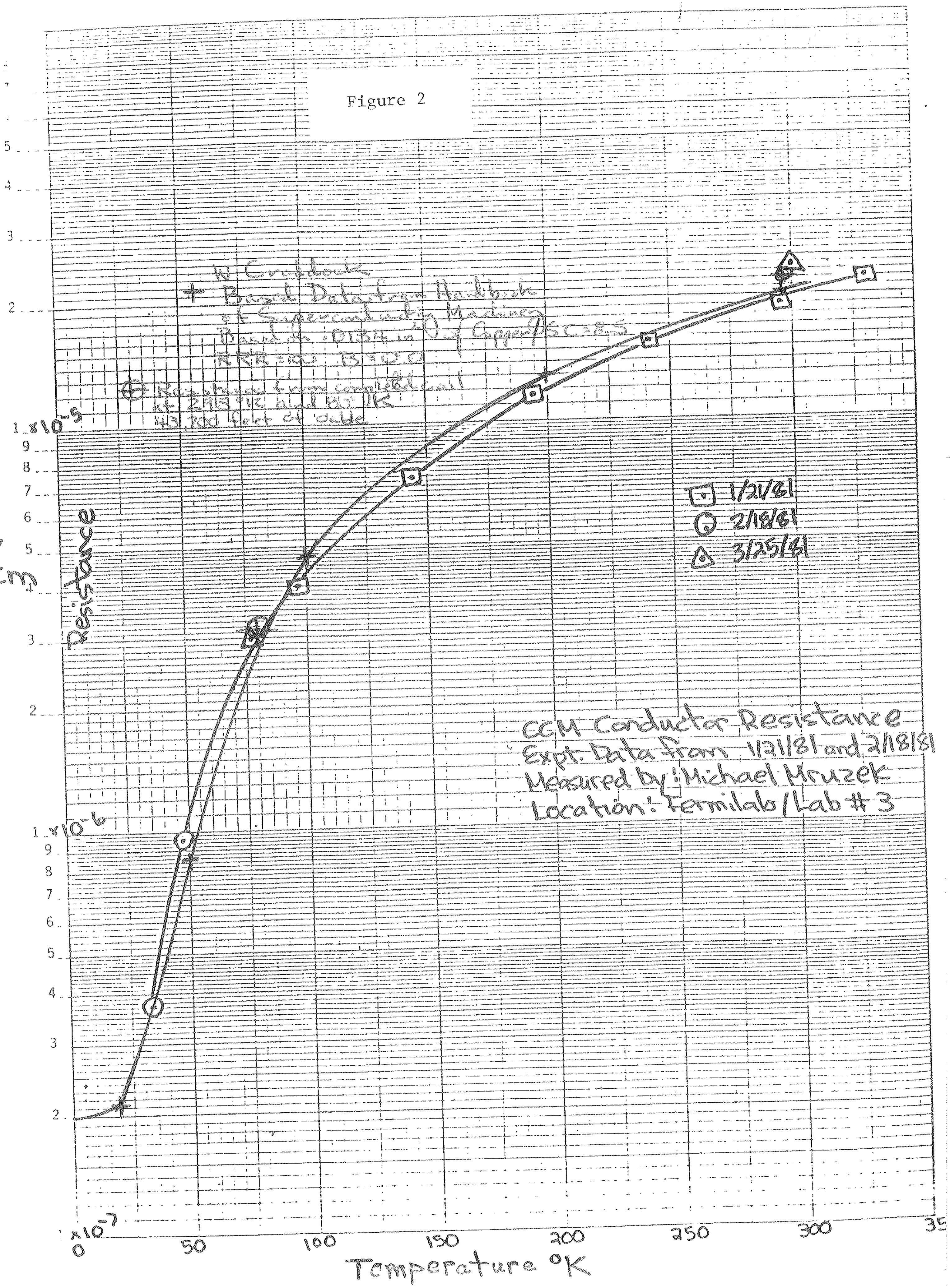


Figure 2
CCM Conductor Resistance
Expt. Data from 1/21/81 and 2/18/81
Measured by: Michael Mruzek
Location: Fermilab/Lab #3
1/21/81
2/18/81
3/25/81
Ω/cm
Resistance
Temperature °K
0
50
100
150
200
250
300
1 x10⁻⁵
1 x10⁻⁶
x10⁻⁷
46 5492

where 0.716 is the fraction of area not covered by G-10 spacers on the inner layers.

A design number of 0.40 watts/cm^2 is reasonable for open channel cooling. This number is several times greater than an allowable steady state heat flux for narrow horizontal channels, however.

Thermal Temperature Reserve:

This is a useful concept for magnets which are not fully cryostable. It gives a feel for the likelihood of a quench. Our worse case conductor on the inner layer has a 4.2 K short sample limit of

1140 Amps at 6 T
1560 Amps at 5 T
1390 Amps at 5.4 (interpolated value)

The critical current is reduced by ~10% for a 4.5^{O}K (4 psig) temperature. Thus we will normaly operate at 56% of short sample. Two points are known for the thermal temperature reserve concept: critical current at 4.2 K and critical temperature at B = 0. The thermal margin is an interpolation between these two points. Figure 3 demonstrates that we have a 2.3^{O}K temperature margin at 700 Amps. This is a relatively large value.

Experimental Studies:

Appendix 1 is an experimental model of our coil package. Appendix 2 is the CCM coil model test data and is included for comparison. The Tohoku (30-Inch) model is only a fair representation to our actual coil windings. The results of this test are:

1. 700 Amps is below the cold end recovery current.

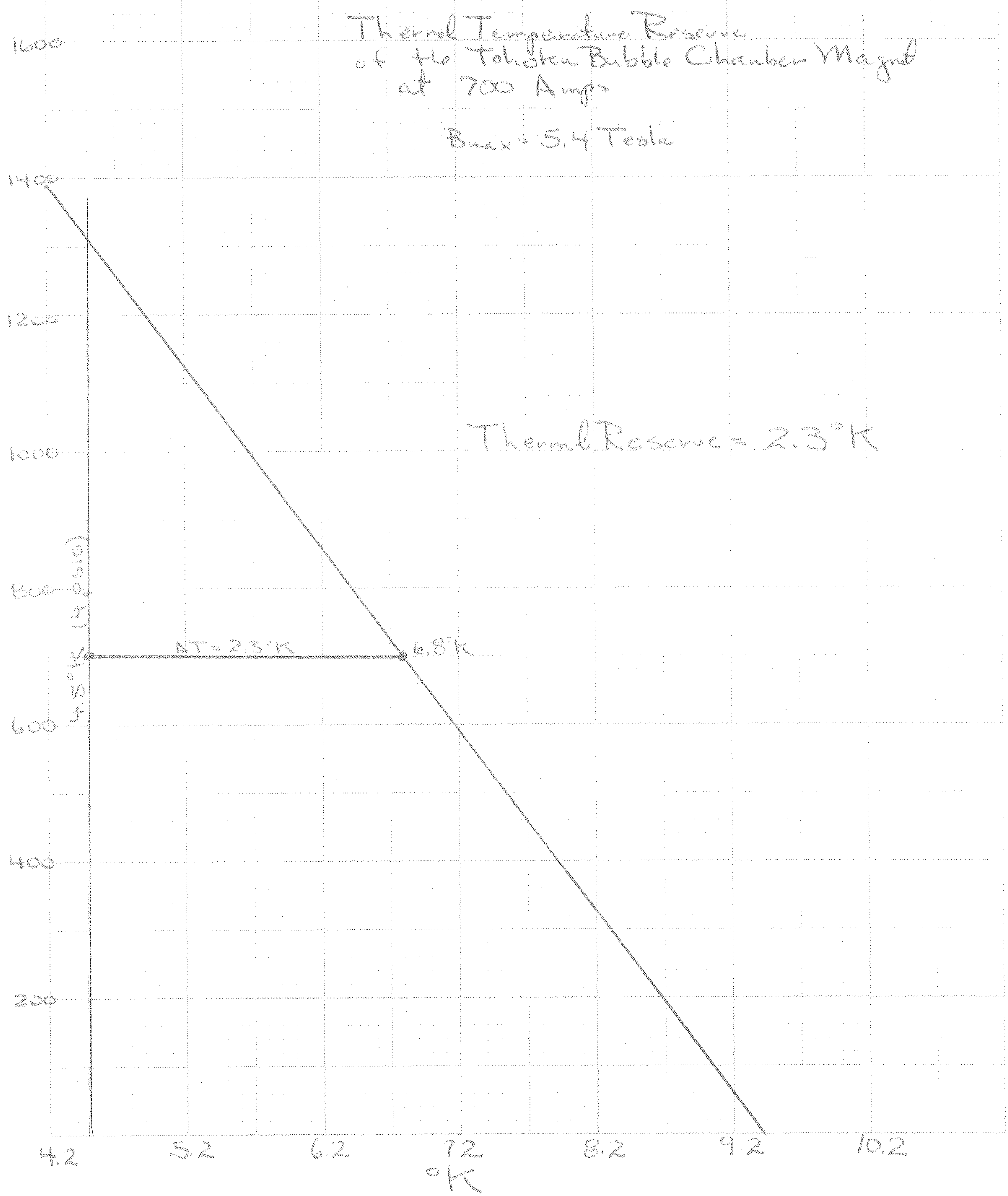
2. The coil can recover at 635 Amps when a heater inducing a quench at 700 Amps remains on.

3. Details not given in the report show that the test set up began to recover at 710 with an approximate 10 cm long normal region. The quench inducing heater was turned off.

Conclusion:

Although we have no where near a fully cryostable magnet, the coil is never expected to quench. Large thermal margin, high values of transient heat transfer, and cold end recover will keep the magnet stable.

Figure 3



Thermal Temperature Reserve
of the Tohoku Bubble Chamber Magnet
at 700 Amps
Bmax = 5.4 Tesla
Thermal Reserve = 2.3°K
ΔT = 2.3°K
6.8°K
4.5°K (4 PSIG)
1600
1400
1200
1000
800
600
400
200
4.2
5.2
6.2
7.2
8.2
9.2
10.2
°K

Conductor Burnout and Energy Removal

Worse case conductor temperature can be estimated from an adiabatic heating of the conductor once it is driven normal. The basic equality is

$$\int_0^t \rho J^2 = \int_{T_c}^{T_{max}} C_p(T)\, dT$$

where

ρ = resistivity
J = current density
C_p = specific heat per unit volume.

With superconductor present ρ is modified by the factor $(1 + r)/r$ = 1/copper fraction where r is the copper/superconductor ratio.

Rearranging

$$\frac{r+1}{r} \int_0^t J^2\, dt = \int_{T_c}^{T_{max}} C_p(T)/\rho(T) = {}^*F(T)$$

These integrals were calculated using the most accurate data available and are plotted in Fig. 4 for various RRR values. If the maximum conductor temperature is allowed to be 350^oK, we can permit 1.52×10^9 Amp^2-cm^{-4}-sec. With a 500^oK upper temperature bound, the maximum heating limit rises to only 1.75×10^9 Amp^2-cm^{-4}-sec. With the 350^oK limit the $\int I^2\, dt$ limit for our conductor is

$$1.52 \times 10^9 \times (0.0865 \text{ cm}^2)^2\ (8.5/8.5 + 1)$$

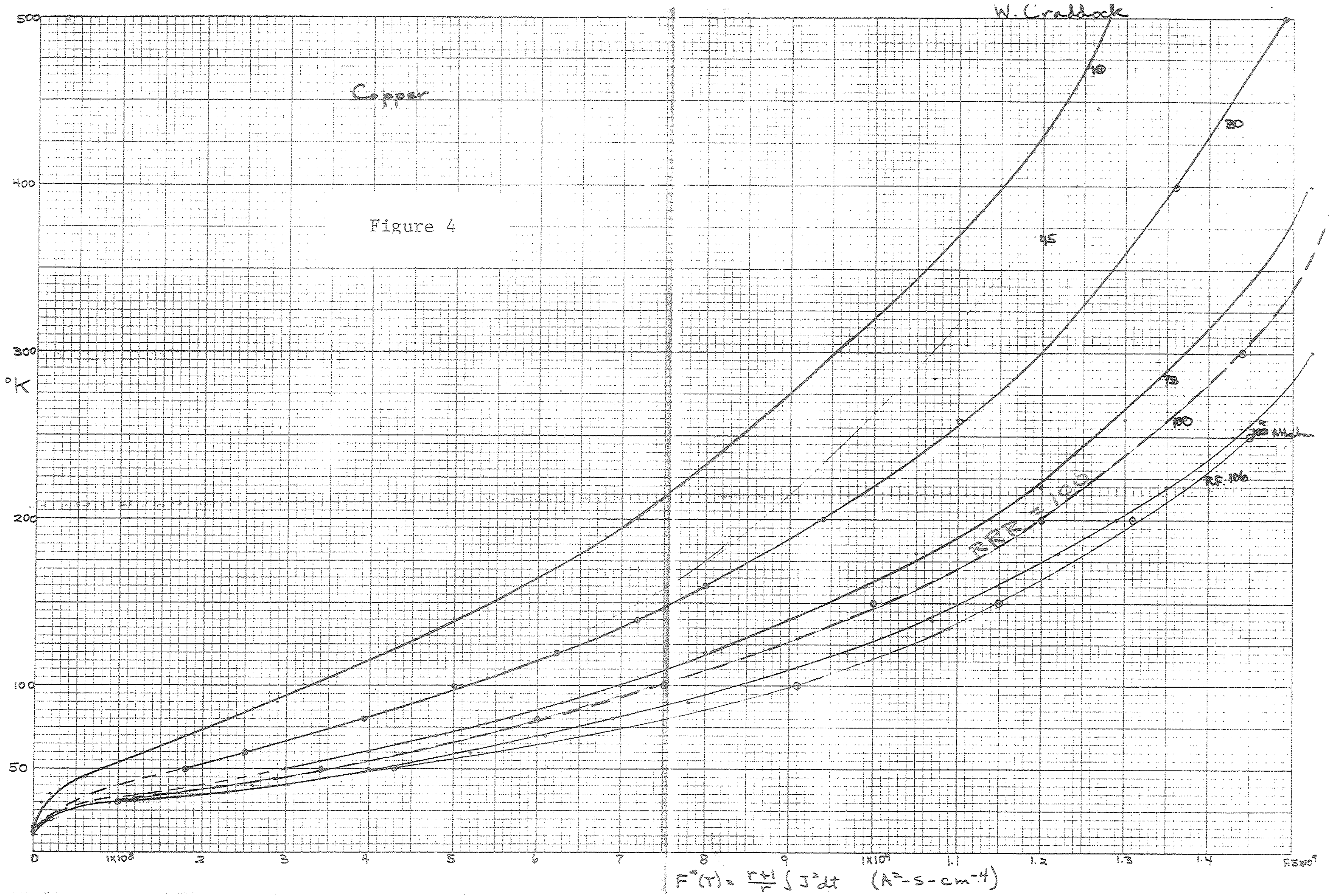
$$= 1.02 \times 10^7 \text{ Amp}^2\text{-sec}$$

$$(1.17 \times 10^7 \text{ Amp}^2\text{-sec for } 500^oK)$$

Figure 5 plots our specific conductor temperature limits.

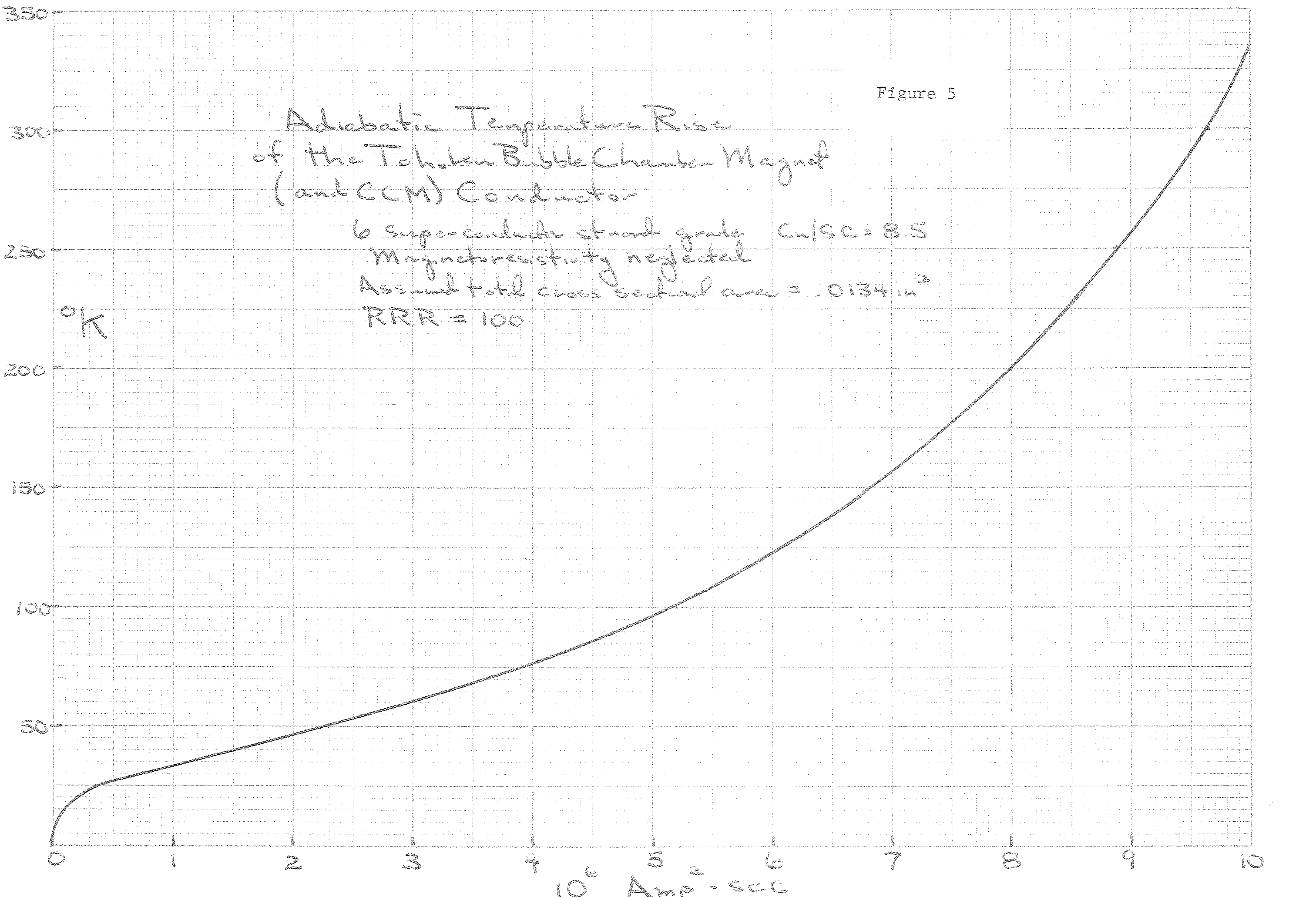
M. Mruzek has predicted a steady state 700 Amp conductor warm-up from both experiment and from a computer program he wrote. See Appendix 3. My values are plotted on one of his curves and reproduced in Fig. 6. Figure 7 is his theoretical predication of conductor warm-up using 1 atm helium gas in between 0.040" layer to layer cooling channels. The volume available for cooling is one half of an inner layer and one half an outer layer or 0.047 cm^3 per cm of length. Note that the warm-up time to 300^oK has doubled from his theoretical adiabatic warm-up time. Thus we can expect that our conductor hot spot temperatures are substantially overestimated.

Protection of the coil depends upon the dump resistor's ability to discharge the coil quickly enough that the conductor $\int I^2\, dt$ limit is not reached. The resistor is a special design using Balco (Ni 30% Fe) which has a large



W. Craddock
Copper
Figure 4
°K
500
400
300
200
100
50
10
30
45
75
100
RRR = 100
RF 106
0
1X10^8
2
3
4
5
6
7
8
9
1X10^9
1.1
1.2
1.3
1.4
1.5X10^9
F*(T) = (r+1)/r ∫ J²dt (A²-s-cm^-4)

Figure 5


Adiabatic Temperature Rise
of the Tohoku Bubble Chamber Magnet
(and CCM) Conductor
6 superconductor strand grade Cu/SC = 8.5
Magnetoresistivity neglected
Assumed total cross sectional area = .0134 in²
RRR = 100
°K
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
10⁶ Amp² - sec

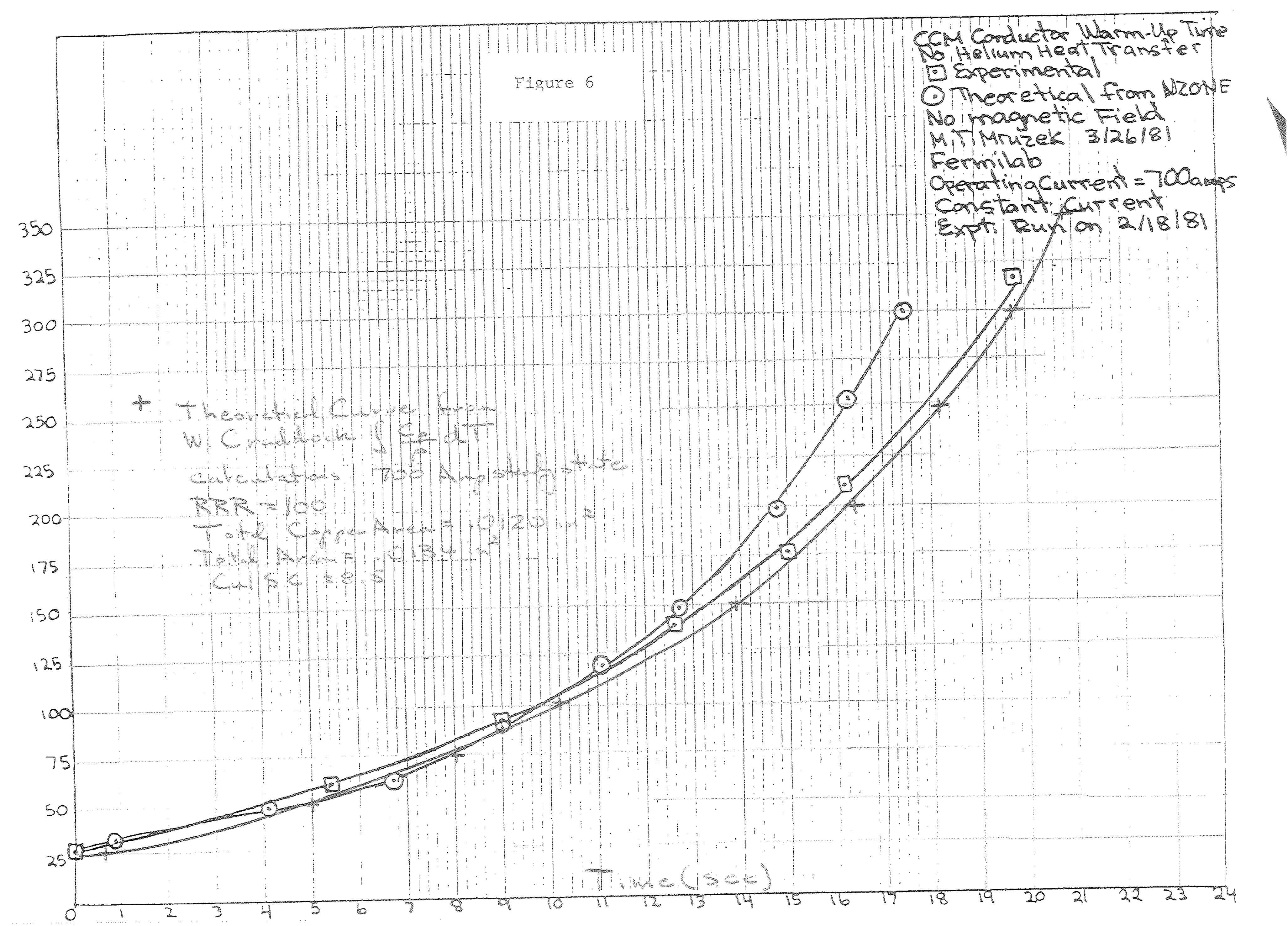


Figure 6
CCM Conductor Warm-Up Time
No Helium Heat Transfer
Experimental
Theoretical from NZONE
No magnetic Field
M.T. Mruzek 3/26/81
Fermilab
Operating Current = 700 amps
Constant Current
Expt. Run on 2/18/81
Theoretical Curve from W. Craddock ∫ Cp dT calculations 700 Amps
RRR = 100
Time (sec)

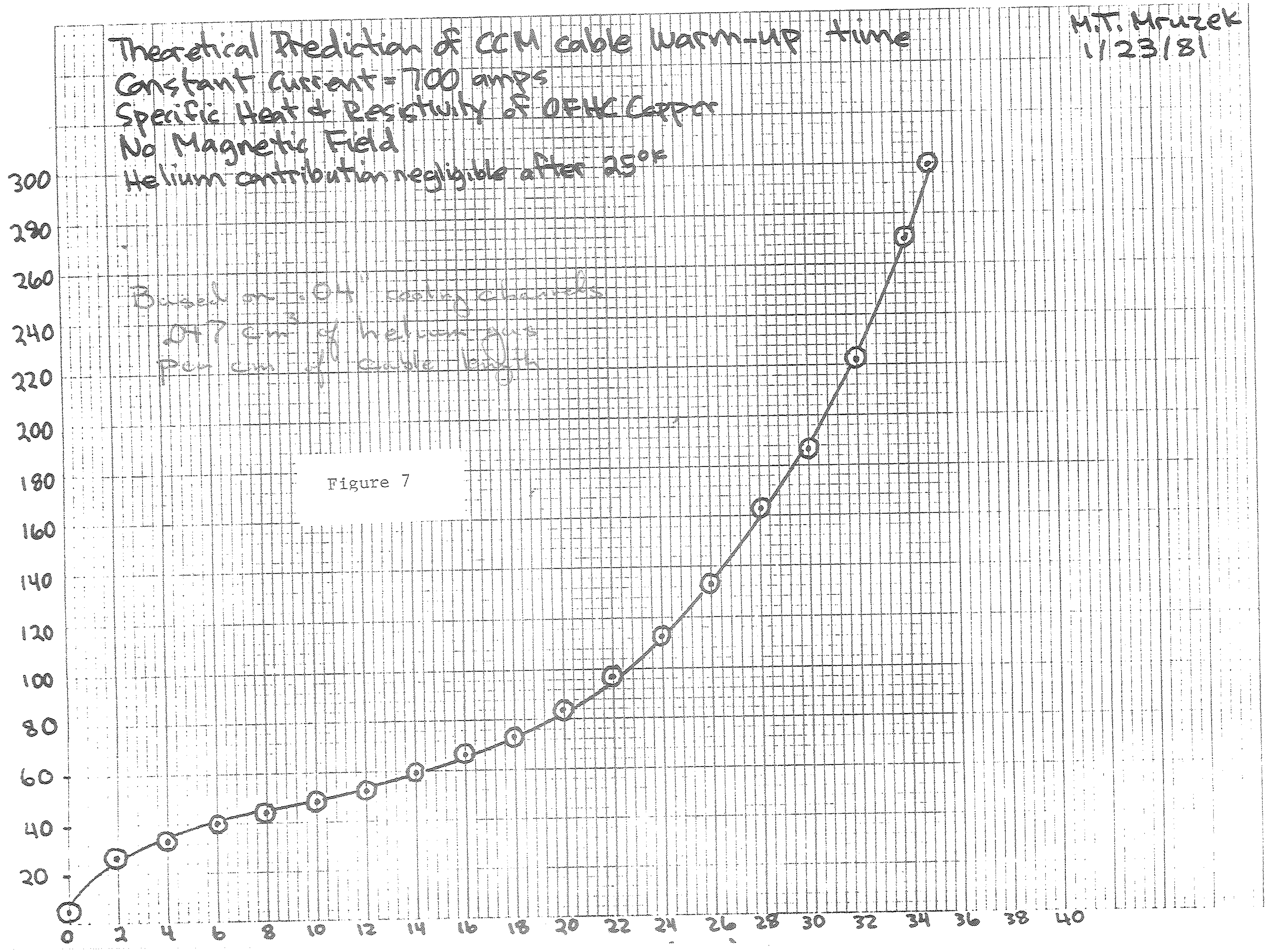

Theoretical Prediction of CCM cable warm-up time
Constant Current = 700 amps
Specific Heat & Resistivity of OFHC Copper
No Magnetic Field
Helium contribution negligible after 25°K
M.T. Mruzek
1/23/81
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40

Figure 7

coefficient of resistivity such that an approximate constant voltage discharge is obtained. The constant voltage discharge has a lower peak voltage than an exponential discharge. M. Mruzek note (Appendix 3) calculates the discharge parameters. His second note (Appendix 4) demonstrates that the resistor behaves as was assumed in the first note. Mruzek's note does not state his computer calculated maximum temperature. Performing the integration gives 7.67×10^6 Amp^2 sec or 185°K.

One can also get a feel for the wire burnout danger by comparing the operating current to the fusing or melting current. An expression for this is given by the Reference Data for Radio Engineers as

$$I_m = 10244\ d^{3/2} = 445 \text{ Amps}$$

where d = 0.124" is the equivalent round wire diameter. At 700 amps we are 2-1/2 times above the open air fusing current power limit.

Quench Detection

In case a small portion of the conductor were to go normal, it is important to be able to detect this event and extract the energy from the magnet. It is possible although very unlikely that only a small region could become increasingly hot without propagating a quench down the wire. This is conceivable for the outermost and innermost layers were vapor locking is not possible. However, these layers should be cryostable. Figure 2 is a graph of conductor resistance from M. Mruzek's report on dump resistor requirements. See Appendix 3. Included on this figure are cable resistance values based on overall magnet resistance values and a theoretical curve assuming RRR = 100 and area = $0.0865\ cm^2 \times 8.5/9.5 = 0.07739\ cm^2$.

The maximum sensitivity is approximately 15 mV which can be expected with our quench imbalance circuit. The following are lengths of conductor required at specific temperature and current levels to initiate a dump. Magnetoresistivity effects are included for low temperature values, and the conductor is assumed to be in the high field inner layers. The appropriate magnetic field for a given current is used.

Amps	Temperature °K	R Ω/cm	Required Length for 15 mV (cm)
700	10	5.4×10^{-7}	40
600	10	4.9×10^{-7}	51
700	50	9×10^{-7}	24
700	100	4.5×10^{-6}	4.8

Only small lengths of conductor becoming normal should trigger our quench imbalance circuit. If, for example, a 2" length became normal and reached 100°K for a magnet dump, the energy could be extracted quickly enough to prevent conductor burn up.

Dump resistor "takes" 7.7×10^6 Amp^2-sec

Conductor "loses" 5×10^6 Amp^2-sec starting at 100^oK

Sum = 1.27×10^7 Amp^2-sec

~ 500^oK conductor temperature = 1.17×10^7 Amp^2-sec.

Note also that 700 Amp x 0.015 volt = 10.5 watt. This more than doubles our normal boil off and would cause a current lead overflow trip.

High Voltage Testing

The coils and the wires leading out of the dewars have been high voltage tested to ground many times. The following is a summary of the final HiPot tests.

Date	Item	Volts	Leakage Current μA	Condition
5-17-84	Coils and Inter-connecting Wire	1250	0.05	Dry N_2
5-17-84	Wires in Dewar to ground	2000	0.05	Dry N_2
5-17-84	Wires in Dewar to each other	2000	0.05	Dry N_2
3-12-85	Complete Magnet & Dewar A	400	0.05	Warm 2 psig He gas
3-13-85	Complete Magnet & Dewar B	400	0.1	Warm 2 psig He gas
3-17-85	Complete Magnet & Dewar A	740	0.1	*Cold 2 psig He gas
3-17-85	Complete Magnet & Dewar B	750	0.1	*Cold 2 psig He gas
3-30-85	Entire System up to Dump Switch	700	2.7	*LHe in both dewar ~1.5 psig
3-30-85	Entire System up to Dump Switch	600	1.5	*LHe in both dewar ~1.5 psig

3-30-85	Entire System up to Dump Switch	700	1.85	*LHe in both dewars. All instrumentation disconnected

Note: In all cases only conductor positive polarity was tested.

*No attempt was made to eliminate frost and moisture around the current lead flags.

Since our maximum voltage to ground from either coil is 350 volts we have a safety factor of two in our system. LHe normally provides a huge insulating safety factor.

Current Leads

All four 1000 Amp current leads were x-rayed and then tested by Al McInturff. Both x-rays and testing showed that the leads were satisfactory. A summary data sheet for 500 Amp and 1000 Amp testing is provided. Note that two of the leads require ~50% more flow than the other two. As per Al McInturff's suggestion we will at least initially run these leads with less than a total 50 mV voltage drop. This should provide very safe and reliable operation. Many minutes of operation at full current with no flow are possible ensuring that the magnet can be easily powered down in the event that one of the leads should become plugged.

For the worse case lead the requirement for totally stable operation is

1.0 liter per hr at 500 Amps
2.5 liter per hr at 1000 Amps

A 500 Amp increase uses 1.5 liter/hr more helium. This extra boiloff is necessary because of I^2R heating.

$K(1000/500)^2 \times 1.5 \qquad K = 0.375$

Then

$0.375\ (700/500)^2 = 0.74$ liter per hr

The flow requirement at 700 Amps is

$1.0 + 0.74 = 1.75$ liter/hr = 46 SCFH

Lead #	Date	recommended Liquid Lite per hr	kA	Liters/hr	mV	Time to reach 1 mV/min (min)	mV at 1 mV/min	exit gas Temp	mV	mV/min	
68	830811	7.5	4.5	6.0	34				80	5	11.5
				7.0	25	5.0	40	-5			
				8.0	23	2.0	30				
69	830811	7.5	4.5	6.0	39				80	8	4.5
				7.0	30	4.5	48	2	Non stable conditions		
				8.0	27	2.0	35				
205	830527	1.2	0.5	0.65	22.5				39.5	0.75	8.5
				0.8	22.5				34.5	0.75	9.5
				1.0	22.5	7.5	31	14			
				1.2	22.5	6.0	28				
				1.4	22.5	5.5	26				
				1.6	22.5	1.0	24				
			1.0	2.2	33.5				27	1	5
				2.5	33.5	1.2	37	3			
				3.0	33.5	0.6	29				
206	830527	1.2	0.5	0.65	21				39	0.75	8.5
				0.8	21				34	1	9.5
				1.0	21	7.5	30	15			
				1.2	21	6.0	27				
				1.4	21	5.5	24				
				1.6	21	1.0	22				
			1.0	2.2	31.5				24.5	1.2	5
				2.5	31.5	1.2	34	5			
				3.0	31.5	0.6	26				
207	830521	.8	0.5	0.6	19.5	11.0	38	18			
				0.8	19.5	14.0	33				
				1.0	19.5	7.6	28				
				1.2	19.5	9.4	26				
				1.4	19.5	9.0	24				
				1.5	19.5	8.5	22				
				1.6	19.5	4.0	20				
			1.0	2.25	38.5	4.5	35	5			
				2.5	38.5	3.8	32				
				3.0	38.5	1.0	28				
208	830521	.8	0.5	0.6	19	11.0	38	20			
				0.8	19	15.4	33				
				1.0	19	8.0	27				
				1.2	19	8.6	25				
				1.4	19	9.0	23				
				1.5	19	8.5	22				
				1.6	19	4.0	20				
			1.0	2.25	38	4.4	35	10			
				2.5	38	3.8	32				
				3.0	38	1.0	27				
H 281	821221	7.5	4.5	6.0	36				68	6	5.2
				6.0	40				72	6	5.2
				7.0	36	2.0	44				
				7.0	40	1.0	48				
H 282	830226	5.5	4.5	4.5	36				52	1.2	14
				4.5	36				51	1.2	14
				5.0	30	11.0	36				
				5.0	30	11.0	36				
				6.0	37	6.0	74				

about a 50% dif in flow

MAC

Appendix 1

EXPERIMENTAL DETERMINATION OF STABILITY IN A 30" BUBBLE CHAMBER SIMULATION COIL

Experiment Report: M.T. Mruzek
Experiment Leader: Mineo Kobayashi

Space limitations imposed by the magnet iron from the original normal coil in the 30" Bubble Chamber have influenced the replacement coil's design. In particular the coil's cooling channels have been kept as small as possible to conserve space and provide a higher field. Concern about the stability of this dense configuration prompted the experimental investigation now being reported.

The superconducting braid for the 30" magnet is the same wire used in the Chicago Cyclotron magnet. The approximate dimensions are 0.091" x 0.183". There are six energy doubler strands, 8 copper strands and a copper core measuring 0.037" x 0.128". The copper/superconductor ratio is 9.8. The operating field in the magnet is approximately 5T. The short sample critical current measured at this field and a ramp rate of 50 amp/sec is 1950 amps. The design value of operating current is 700 amps. Hence the magnet will be operating at 36% of short sample.

There are two types of layer to layer spacers. Both are made of sheet G-10, however, the inner spacers on the actual coil are 0.05" thick, the outer spacers are only 0.03" thick. The wider spacers on the inside of the coil provide a larger cooling channel in the high field region. The larger spacers also reduce the possibility of a layer to layer short because of the smaller winding radius.

As an added precaution against layer to layer shorts 5 and 7 mil mylar, with holes punched in it, was included in the voids between the

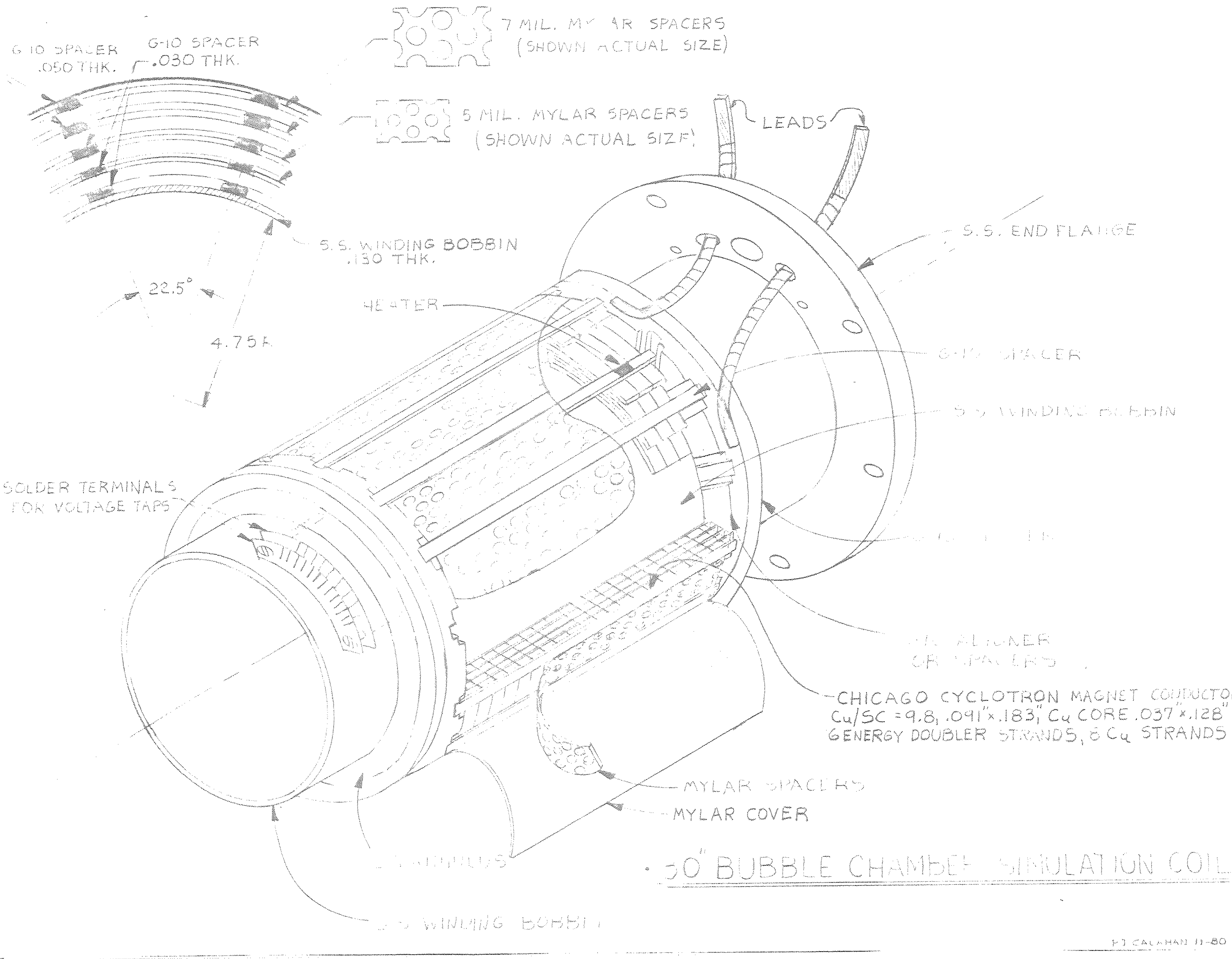
G-10 spacers. The mylar spacers are an option in the actual coil, but were included in the simulation coil to verify they didn't seriously affect stability. The simulation coil and layer arrangement are shown in Fig. #1.

The coil consisted of 4 layers of superconducting braid. Heaters and voltage taps were included on every layer. The heaters were fabricated with 2.5 mil thick BeCu wire wound on a thin piece of mylar. Both of the heaters used in this experiment were located at the bottom of the model coil. The punched mylar sheets were arranged as depicted in Fig. #1. The coil was wound with a winding tension of 60 lbs. The turn-to-turn insulation consisted of 2 mil thick yellow mylar tape, which was applied to the edges with a special fixture. The outermost layer was protected from dust and damage with a mylar cover taped in place. The end flange on the model coil is designed to fit snugly into the bias magnet.

The bias field magnet was fabricated especially for this experiment. Its overall length was limited by the size of a conveniently available helium dewar. The magnet was wound with 7600 ft of 0.040" diameter monolithic conductor. The stored energy is 79 kJoules and the inductance of the solenoid is calculated to be 1.76 H (assuming the thin coil method). The charging rate of the coil later indicated the inductance was closer to 1 H. In all, 22 layers were wound on the 6-5/8" OD stainless steel bobbin. Sheet mylar 5 mils thick was used for additional layer to layer insulation.

The field produced by the bias magnet was calculated from the winding dimensions. The field at the midpoint of the centerline is

$$B_o = (0.0190 \text{ Tesla/amp})(I \text{ amp})$$



30" BUBBLE CHAMBER SIMULATION COIL

where B_0 is the field in Tesla, and I is the bias coil current in amps. The field at layers 3 and 4 of the test coil was approximately 7% higher. The coil typically operated at 250 amps.

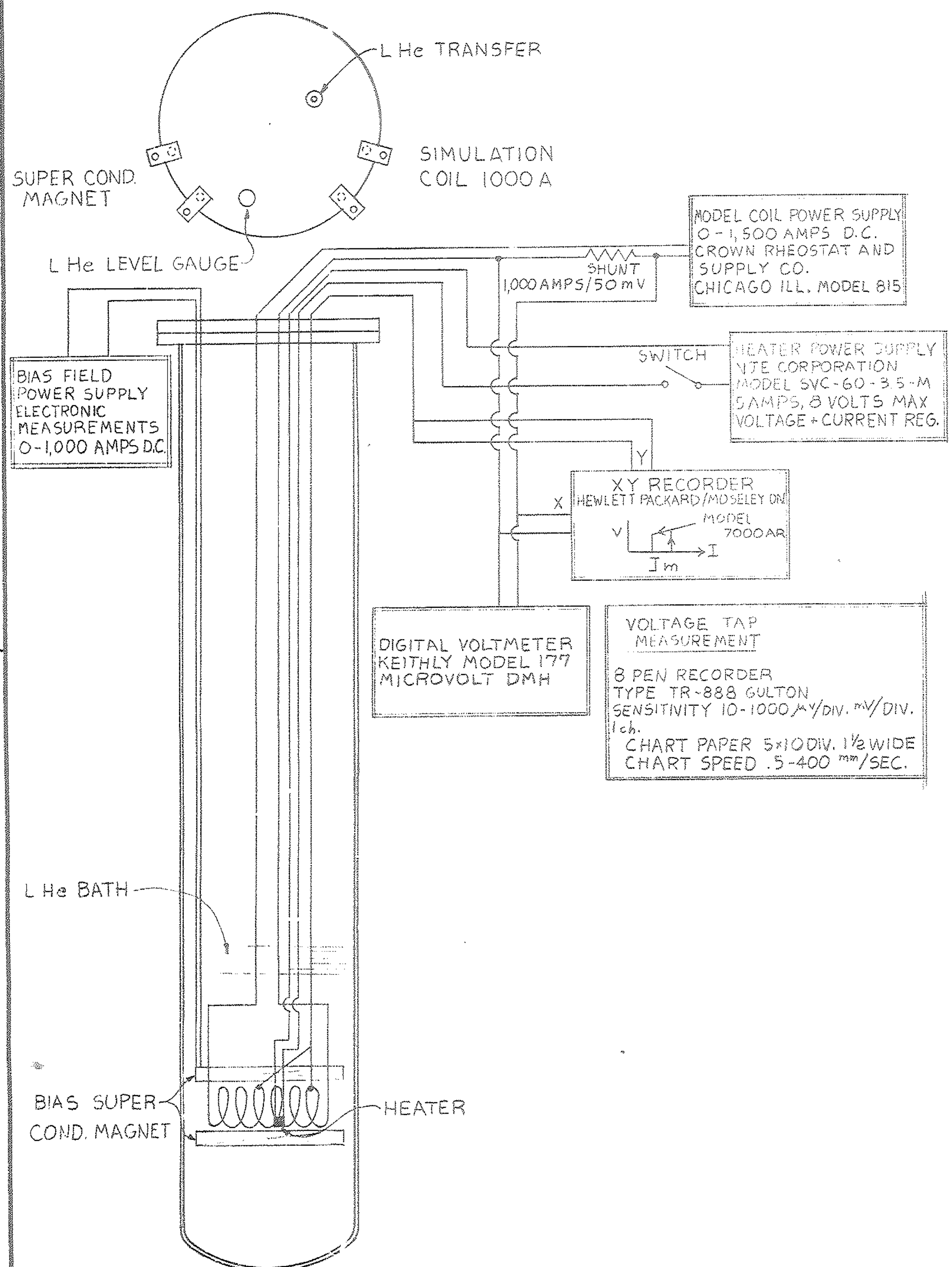
EXPERIMENTAL DESCRIPTION

The general configuration of the experiment's equipment arrangement is shown in Fig. 2. The heater power supply was used to produce a normal zone in the superconducting braid. Significant variables in the experiment were the test coil current, the background field of the solenoid, the power and duration of the heater signal, and the rate of increase or decrease of the test coil's current. During every experimental run, voltage taps in the vicinity of the heater were monitored on an 8 channel pen recorder.

Two sets of data were obtained, but the first set is considered inaccurate because there was a short in the leads of the background field magnet. Although a partial field was obtained, its exact magnitude is not known. The total amount of data, which is considered reliable for analysis consists of 26 experimental runs.

ANALYSIS

The stability of a superconducting magnet can be classified into three distinct regimes. These three are: 1) stable, 2) quasi-stable, and 3) unstable. Figure 3 qualitatively depicts these concepts of stability. In the fully stable region a superconductor will always recover from a normal zone transition. In the quasi-stable region a superconductor may or may not recover. The quasi-stable region can be divided into two distinct areas. Below the dashed line of cold end recovery, a magnet will recover



REV.	DESCRIPTION	DRAWN	DATE
		APPD.	DATE

ITEM NO.	PART NO.	DESCRIPTION OR SIZE	QTY. REQ.

PARTS LIST

UNLESS OTHERWISE SPECIFIED			ORIGINATOR	KOBAYASHI/KRUZEK
FRACTIONS	DECIMALS	ANGLES	DRAWN	P.J. CALAHAN
±	±	±	CHECKED	
			APPROVED	

1. BREAK ALL SHARP EDGES 1/64 MAX.
2. DO NOT SCALE DWG.
3. DIMENSIONING IN ACCORD WITH ANSI Y14.5 STD's.
√ MAX. ALL MACHINED SURFACES

USED ON

MATERIAL-

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

SCALE	FILMED	DRAWING NUMBER	REV.

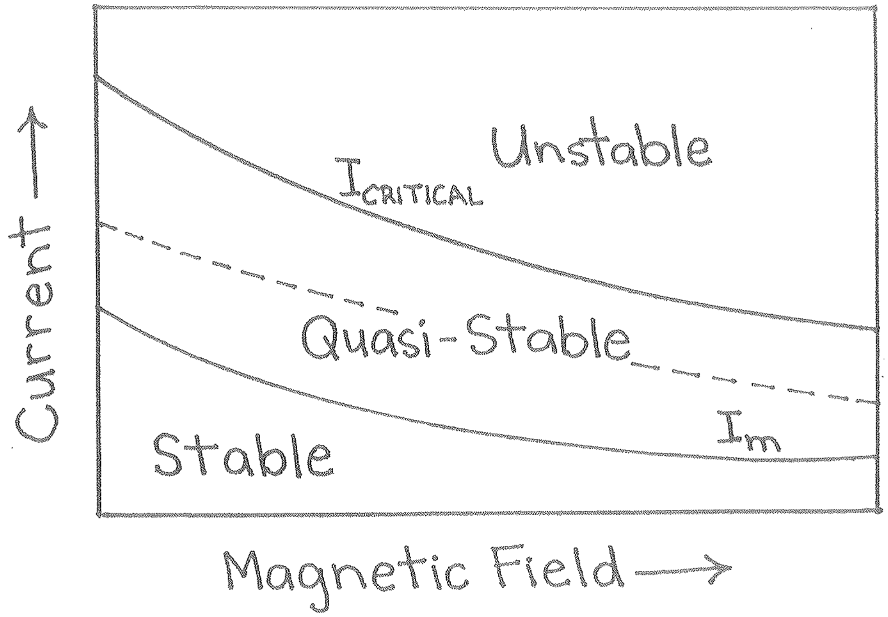


Figure 3
Degrees of Stability for a Superconducting Magnet

from a normal zone transition if at least one end of the conductor is kept cold. Above the line, a normal zone will propagate if initiated. In the unstable region a normal zone will always initiate and propagate, because the critical current has been exceeded. Naturally, the designer should try to operate as close as possible to the fully-stable region, to reduce the likelihood of a disastrous quench. In Figure 3 the symbol for the value of current where recovery instantly occurs is I_m. The purpose of this experiment is to determine the value of the recovery currents for our cooling configuration, operating current, and operating field.

The measured value of cold end recovery current is subject to experimental procedure. The duration and amplitude of the heater pulse used to initiate the normal zone has a profound effect on recovery. The exact nature of a frictional disturbance in a superconducting magnet is not known. It is likely to be a short pulse of energy with a high power density. After the disturbance occurs, the magnet's normal zone recovery will probably not be hindered by additional frictional energy. The cold end recovery current measured with the heater off is the best simulation of an actual disturbance. The cold end recovery with the heater on is a worse case value.

THE CONCEPT OF CRITICAL POWER

Runs 14b, 15, 16, 19, 20, 21, 22, 23, 24

Before the recovery current data can be analyzed, it is important to understand the effect heater pulse power and energy have on stability. In this series of runs the transport current in the model coil was kept constant, and the heater power slowly increased, until the normal zone showed a rapid advance. The concept of vapor locking suggests there is some critical heater power level where the vapor will accumulate faster than it can be carried away. At this power level the temperature of the heater begins to increase, and it is likely the heater has induced a normal zone in the wire layer on the other side of the G-10 strip. This power level likely corresponds to the transition point from nucleate boiling to film boiling in the liquid helium.

Two heat transfer crises are possible in the liquid helium heat transfer. The total energy of the heat pulse can be large enough to boil away all the liquid helium, or the power can be high enough to cause the boiling mechanism to switch from nucleate boiling to film boiling. It is important to remember the concept of critical power must be thought of on a per area basis. In this case the important area is the heater's, which is approximately 1 cm^2.

Table 1 is a summary of the critical power and energy delivered in 9 different runs. Figure 4 is a graph of the 700 and 800 amp data for the two layers. As expected, the layer with better cooling requires either a higher total energy or power to propagate the quench. Note that for large values of energy only the heater power determines if a normal zone exists.

FIGU^E 4

Heater Power and Energy required for Quench Propagation

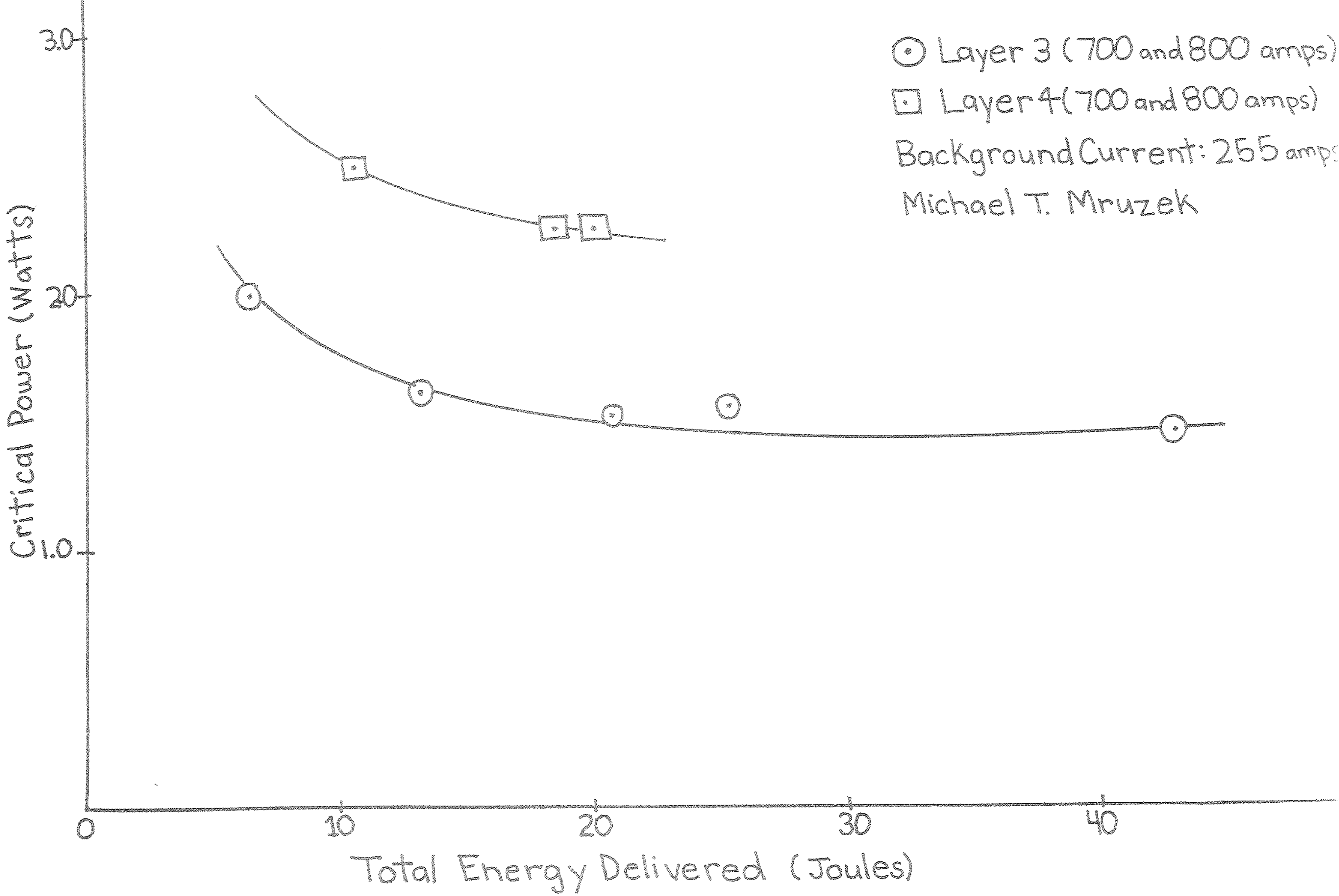


Table 1

	Run #	Operating Current (amps)	Background Current	Bias Field Tesla	Total Energy	Critical Power
layer 4	14b	700	255 amps	5.2	20.0 joules	2.25 ω
	15	800	255 amps	5.2	10.5 joules	2.50 ω
	16	800	255 amps	5.2	18.4 joules	2.25 ω
layer 3	19	700	255 amps	5.2	13.1 joules	1.62 ω
	20	700	255 amps	5.2	6.4 joules	2.00 ω
	21	700	255 amps	5.2	20.6 joules	1.52 ω
	22	800	255 amps	5.2	42.8 joules	1.47 ω
	23	800	255 amps	5.2	25.1 joules	1.57 ω
	24	600	255 amps	5.2	21.9 joules	2.00 ω

Figure 4 dramatically illustrates the effect of reduced channel size. Neither line in the graph illustrates the very worst case of a 30 mil spacer both inside and outside the layer. I expect the lower case to be close to worst, because the vapor locking mechanism occurs in the 30 mil inside layer. The conclusion is 1) Reducing the channel size also reduces the cooling effectiveness and 2) for high values of deposited energy there is a critical power level where a large normal zone will always exist.

COLD END RECOVERY CURRENT

Runs 18, 21, 14b, 24, 14a; Heater ON

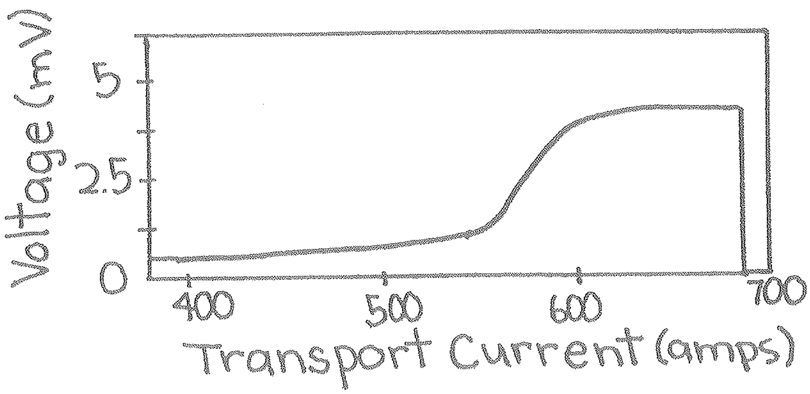
The cold end recovery current is the value of current where the propagation velocity of the normal zone becomes negative. It is measured by inducing a normal zone in the conductor with a heater while transport current is flowing. The transport current is then slowly reduced until the normal zone begins to shrink. As previously discussed, the heater can be either on or off during this process. The data in Table 2 underestimates the cold end recovery current because the heater power remained on. Note that in all cases the power exceeds the critical power of Fig. 6,

Run	Max. Transport Current	Constant Watts Heater Power	amps/sec $\frac{dI}{dt}$	amps I_m
18	595	1.72	-29.0	495
21	700	1.52	-93.0	450
14b*	685	2.02	-70.0	550
24	600	2.50	-143.0	430
14a*	665	3.00	-18.5	500

*data is from layer 4, all other data from layer 3.

for large values of deposited energy. Hence recovery at 700 amps was precluded by the power of the heater pulse. Another important parameter is the rate at which the transport current was decreased. A high current decrease rate raises the possibility the coil was recovering, but the current was needlessly still being reduced. The collapse of the normal zone occurs at a finite rate. It requires time to retrace its path.

Figure 5 is a tracing of the actual X-Y plot of run #14b, which corresponds to the highest measured recovery current. The X axis is the transport current in the model coil, the Y axis is the resistive voltage across half a turn with the heater. The recovery occurs when the voltage disappears as the current is reduced. The voltage does not disappear completely because there is always a small normal zone near the heater when it is operating. A direct extrapolation of the curve yields a recovery current of 550 amps. The normal zone first began to shrink when the current was 635 amps. Because the current was reduced quickly, and the heater was on, the normal zone didn't disappear until 550 amps. The conclusion is 3) the cold end recovery current with the heater exceeding the critical power for 700 amps is at least 635 amps, and is probably higher.



DISCUSSION OF OBSERVED QUENCH

The model coil was first operated at 700 amps in Run #7. The background field was 5 Tesla. The heater in layer four was fired at a power level of 13 watts and for a duration of 2.25 sec. The critical power level given in Fig. 4 for an energy of 29.25 joules is 2.2 watts. Hence, the critical power was exceeded by a factor of nearly 6. The model coil quenched in this run approximately 4 seconds after the heater pulse has ended. Before the quench occurred, the normal zone in layer four (the same layer as the heater) had recovered. I concluded the normal zone responsible for the quench propagated in layer 3. Figure 6 depicts my hypotheses of vapor locking in the helium cooling channel. The heater pulse dumped sufficient energy to vapor 1.5 grams of helium. The vapor, under the influence of gravity, floats to the top of the channel

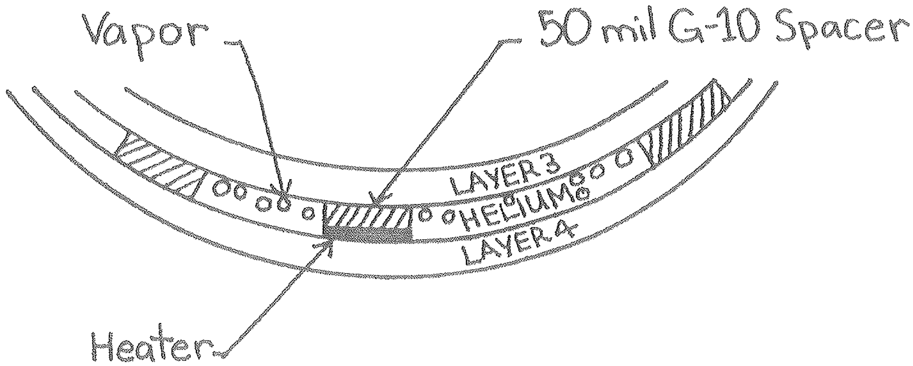


Figure 6
Vapor Locking of Layer 3 By Layer 4

and reduces the effective cooling on the layer above. The bubbles were undoubtedly hindered from floating away by the punched mylar and G-10 spacers. The normal zone in layer 4 also creates additional vapor. With the cooling to layer 3 reduced, the normal zone easily propagates there. The conclusion is 2) the current of 700 amps lies below the cold end recovery line with the heater off, but vapor generated by large energy pulses can comprise the cooling on the layer above and makes a layer to layer normal zone transition disastrous.

SYNOPSIS OF CONCLUSIONS

1) Reducing the channel size also reduces the cooling effectiveness. The results of this experiment indicate there is an observable advantage in making the cooling channels larger (i.e., 50 mil G-10 is to be preferred over 30 mil G-10 in critical areas).

2) For high values of deposited energy there is a critical power level where a large normal zone will always exist. Although dependent on

the heater area, the critical power is a useful concept for interpreting quench data from the same heater's layer.

3) The cold end recovery current, with the heater exceeding the critical power for 700 amps, is at least 635 amps and is probably higher. When the critical power was exceeded for 700 amps, a normal zone propagated, reducing the current at a rate of 70 amps/sec caused the normal zone to begin retreating at 635 amps.

4) The current of 700 amps lies below the cold end recovery line with the heater off, but vapor generated by large energy pulses can compromise the cooling on the layer above, and make a layer to layer normal zone transition disastrous. In this case the critical power was exceeded by a factor of 6 and the quench propagated in the layer above the heater.

Appendix 2

CCM CONDUCTOR STABILITY EXPERIMENTAL MEASUREMENTS

R. Kephart, M. Mruzek and M. Binkley

February 9, 1981

At an excitation of 1000 amps (B_o = 1.5T), the CCM coil contains a stored energy of 32 MJ. Since its inductance is 65H and external dump resistor is 0.2 Ω (limited by maximum terminal voltages) these combine to give an L/R ratio of 300 seconds. In other words in 5 minutes 1/e of the total magnet energy (20MJ) is removed by heating the dump resistor leaving 12MJ still in the magnet. Clearly with such long energy removal times we must insure that if a quench is induced in the coil by release of mechanical energy (conductor motion, cracking epoxy, etc.) the conductor must receive sufficient cooling such that the quench will extinguish. The purpose of these calculations and tests is to determine for what CCM excitation current this is the case. At full magnet excitation B_o = 1.5T the peak field on the conductor is 2.85T. In this field, with the CCM coil geometry, one calculates a full recovery current of 880 amps using the STEKLY criterion. If one includes end cooling this number increases to 1080 amps. (See Appendix I). Since these calculated recovery currents depend on the details of film boiling in 50 mil vertical channels, they are subject to error due to the effective area for heat transfer as well as the heat transfer coefficient in the channels. We therefore attempted to model the coil geometry with a test sample and experimentally determine the recovery current. The CCM coil is insulated with 50 mil thick G-10 spacers 1" wide located on 2.5" centers. (See Fig. 1.) The height of the coil and thus the vertical channels is 4.6". We wished to perform the test in the Doubler short sample test facility. This facility has a solenoid (to provide the background field) that has an I.D. of 3". To simulate the CCM coil we formed 50 mil vertical channels 4.25" high and arranged the spacers and conductor in the cylindrical geometry shown in Fig. 2. The conductor was measured to have a short sample current of 2135 amps at B = 2.85 tesla with a ramp rate of 50 amps/sec ($\sim$ 2150 at 100 amp/sec measured also). For the first series of tests current was passed through the sample and a capacitor was discharged into a heater to drive $\sim$ 1 cm of the conductor normal. The circuit is shown in Fig. 3. The energy input to the heater $\left(E = \frac{1}{2} CV^2 \right)$ was delivered as an exponentially decaying pulse with $\tau = R_{heater} C \simeq 30$ milliseconds. The data from voltage taps 1-4 and 2-3 were recorded with a digital storage scope. Figure 4 shows a typical trace from a 1400 amp quench. The data are summarized in Table 1. From these data we reach the following conclusions. At a field of 2.85 tesla for currents $\geq$ 1400 amps if a quench is induced the conductor slowly heats ($\sim$ 12 sec) makes the transition from nucleate to film boiling and begins a thermal run away. For currents in the range 1300 $\leftrightarrow$ 940 amps. The conductor can be quenched with $\sim$ 1/2 joule (P_{ave} = 15 watts). The conductor in the sample remains normal but has sufficient cooling not to vapor lock the vertical channels and therefore is not overheated. (Note that this probably would not be the case for the full coil since as the quench propagated, the channels would eventually vapor lock). In this region we might be able to detect the quench and discharge the magnet to $\leq$ 930 amps before any damage was done, but operation at these currents is not recommended unless physics requirements justify the risk involved. Finally for currents $\leq$ 930 amps the conductor is fully stable and quenches recover quickly. If the field is raised to 3.0 tesla, the full recovery current is lowered to 910 amps.

The conductor recovers at 910 amps even with energy deposits as high as 7.2 joules (240 watts average power).

Conclusion

On the basis of these tests and calculations the magnets peak test current should be 900 amps (B_{max} = 2.54T) and suggested maximum operating current = 875 amps. This will give a central field of 14 Kg.

APPENDIX I

The Stekly parameter[1] α for our coil is defined to be:

$$\alpha = \frac{\rho I^2}{fA\ Ph\ e(T_c - T_o)}$$

where

- I = current in the conductor
- fA = area of conductor that is copper = 0.074 cm^2 *
- P = parameter in contact with helium = (0.183")2(2.54) = 0.93 cm
- e = effective fraction of area exposed to helium = 0.6 (spacers cover 40%)
- T_c = 6.4^oK at 2.85 Tesla
- T_o = 4.2^oK
- h = effective heat transfer = 0.25 $w/cm^2\ {}^oK$ (for 50 mil vertical channels ∿ 4.5" high)
- I_c = 2200 amps

for $\alpha \leq 1$ the magnet is below full recovery current and a quench will extinguish.

---

*NOTE: Cable contains 14 strands & copper core (RRR = 95)

{6 double strands Cu/SC = 1.8/1; 8 copper strands}

$$A_s = \frac{\pi d^2}{4} = \frac{\pi}{4}(0.0268)^2(2.54)^2$$

$$A_s = 0.00364\ cm^2$$

core = 0.037" x 0.128"

$$A_{core} = (0.037)(0.128)(2.54)^2 = 0.0305\ cm^2$$

$$A_{copper}/A_{sc} = \frac{9.8}{1} \begin{cases} A_{copper} = 0.0305 + 8(0.00364) + 6(0.00364)(\frac{1.8}{2.8}) = 0.074\ cm^2 \\ A_{sc} = (0.00364)(\frac{1}{2.8}) = 0.0078\ cm^2 \end{cases}$$

Thus $\alpha = 1$ defines critical full recovery current.

$$I_F = \left[\frac{fA\ P\ he(T_c - T_o)}{\rho}\right]^{1/2}$$

ρ = resistivity of copper

$\rho = \rho_o(1 + 0.3B)$

$\rho_o = \dfrac{1.5 \times 10^{-6}}{95}\ \ell\text{-cm} = 1.58 \times 10^{-6}$ (RRR = 95)

for $B_o = 1.5$ Tesla $\Rightarrow B_{MAX}$ in coil $= 2.85$ Tesla $\Rightarrow$

$\rho = 1.58 \times 10^{-8} (1 + 0.3\{2.85\}) = 2.93 \times 10^{-8}\ \Omega\text{-cm}$

which gives

$$I_F = \left[\frac{(0.074)(0.93)(0.25)(0.6)(6.4 - 4.2)}{2.93 \times 10^{-8}}\right]^{1/2}$$

$\boxed{I_F = 880 \text{ amps}}$ ← (Worst case since it neglects end cooling)

According to Turck[2] a more accurate expression that includes end cooling effects is given by:

$$I_{CE} = \left[\{-1 + \sqrt{1 + 8\alpha}\}/2\alpha\right] I_c$$

$$\alpha = \left(\frac{I_c^2}{I^2}\right) = \left(\frac{2200}{880}\right)^2 = 6.25$$

$\boxed{I_{CE} = 0.45\ I_c = 1080 \text{ amps}}$

REFERENCES

1. Stekly, Z.J.T., Zar, T.L., IEEE Trans. Nucl. Sc., NS12 (1965), p. 367.

2. Turck, B., Cryogenics, March (1980), p. 146.

Table 1

Trial #	B_o(Tesla)	I(amps)	Quench	Recovery	(1000 μf) Capacitor Voltage (volts)	Energy (Joules)	P_{AVE} (watts)
1	2.85	1400	Yes	No, thermal run away	30V	0.45	15
2	2.85	1300	Yes	No, but stable and resistive ⇒ nucleate boiling	30V	0.45	15
3	2.85	1200	Yes	No, but stable and resistive ⇒ nucleate boiling	30V	0.45	15
4	2.85	1000	Yes	No, but stable and resistive ⇒ nucleate boiling	30V	0.45	15
5	2.85	900	Yes (glitch)	Yes	30V	0.45	15
6	2.85	<900	No (small glitch?)	Yes	30V	0.45	15
7	Initiate quench at 1300 amps lower current until it recovers at 930 amps (see, e.g., Fig. 5)						
8	2.85	1400	No	---	10V	0.05	1.7
9	2.85	1400	No	---	20V	0.20	6.7
10	2.85	920	Yes (glitch)	Yes	40V	0.80	26.8
11	2.85	930	Yes (glitch)	Yes	40V	0.80	26.8
12	2.85	940	Yes (glitch)	Yes	40V	0.80	26.8
13	2.85	950	Yes	No, stable and resistive	40V	0.80	26.8
14	3.0	900	Yes	Yes	30V	0.45	15
15	3.0	1300	Yes	No, stable and resistive	30V	0.45	15

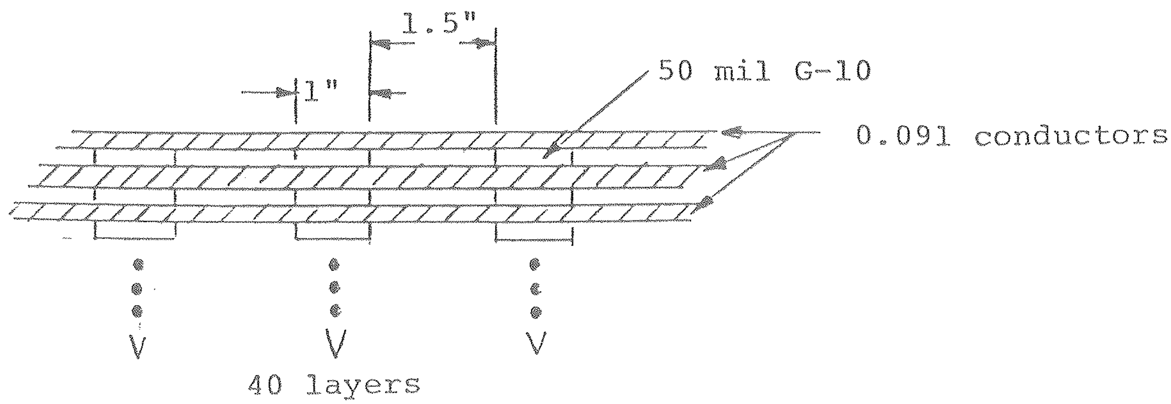
Table 1 (Contd.)

Trial #	B_0(Tesla)	I(amps)	Quench	Recovery	(1000 μf) Capacitor Voltage (volts)	Energy (Joules)	P_{AVE} (watts)
16	3.0	(Quench 15 recovers at 910 amps)					
17	3.0	1000	Yes (glitch)	Yes	30V	0.45	15
18	3.0	1050	Yes	No,stable	30V	0.45	15
19	3.0	1020	Yes (glitch)	Yes	30V	0.45	15
20	3.0	1020	Yes	No,stable	40V	0.80	26.8
21	3.0	1000	Yes	No,stable	40V	0.80	26.8
22	3.0	950	Yes	No,stable	40V	0.80	26.8
23	3.0	930	Yes	No,stable	40V	0.80	26.8
24	3.0	1050	No	---	10V*	0.80	6.7
25	3.0	900	Yes (glitch)	Yes	60V	1.8	60
26	3.0	930	Yes	No,stable	60V	1.8	60
27	3.0	920	Yes	No,stable	60V	1.8	60
28	3.0	910	Yes (glitch)	Yes	60V	1.8	60
29	3.0	910	Yes (glitch)	Yes	70V	2.45	82
30	3.0	910	Yes (glitch)	Yes	80V	3.20	107
31	3.0	910	Yes (glitch)	Yes	90V	4.05	135
32	3.0	910	Yes (glitch)	Yes	100V	5.0	167
33	3.0	910	Yes (glitch)	Yes	110V	6.0	201
					120V	7.2	240

*4000 μf.

Figure 1

CCM COIL TOP VIEW



CCM COIL SIDE VIEW

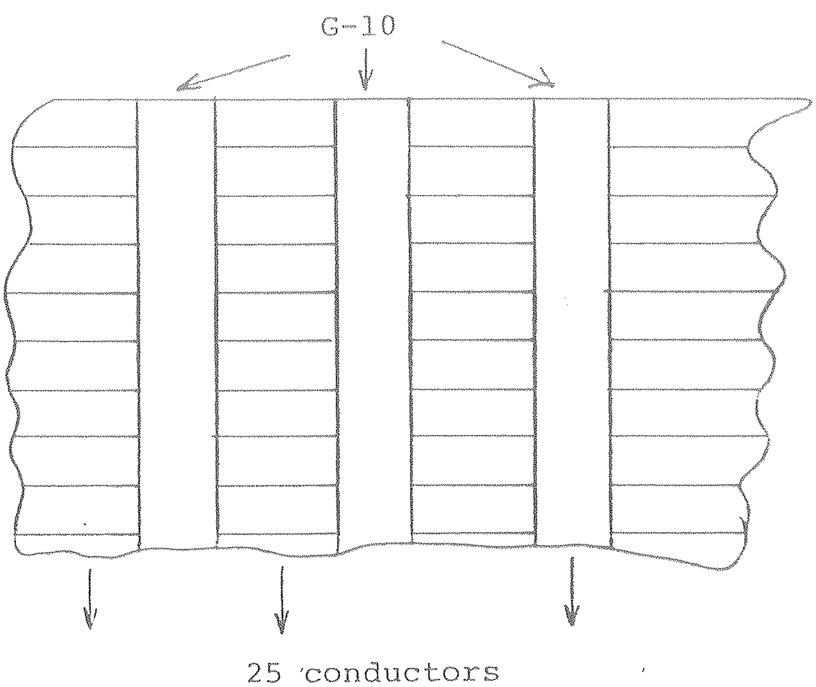


Figure 2 -- TEST SAMPLE

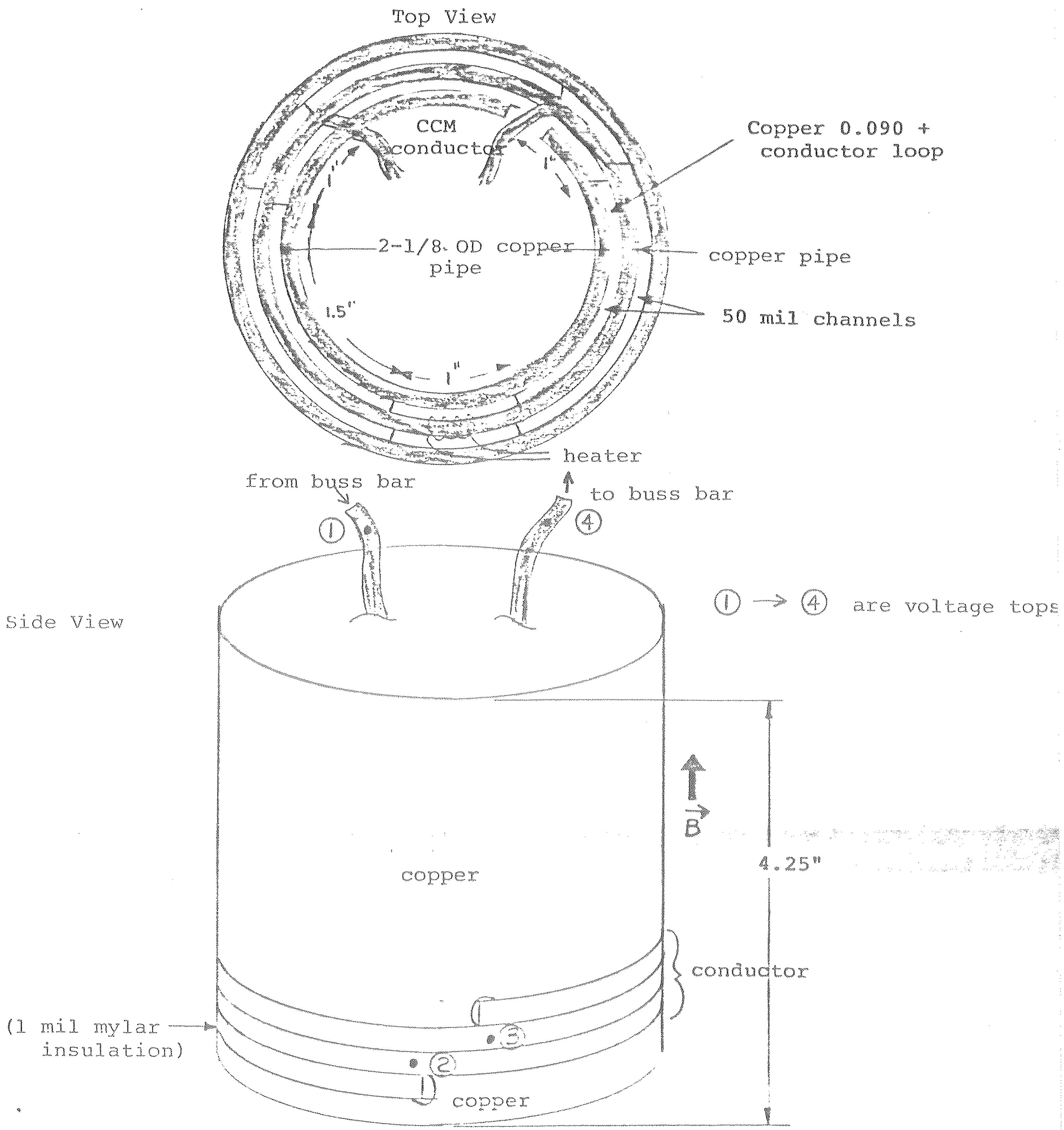
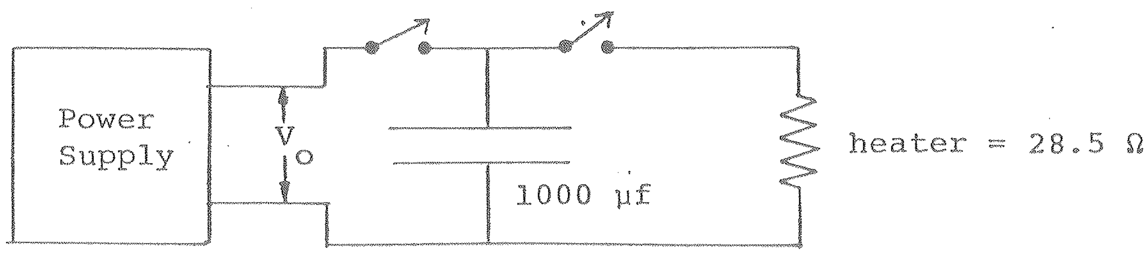


Figure 3



$\tau = 30$ ms

$E = \frac{1}{2} CV^2 = 5 \times 10^{-4} V^2$ Joules

$P_{max} = \frac{V^2}{R} = \frac{V^2}{28.5}$ watts

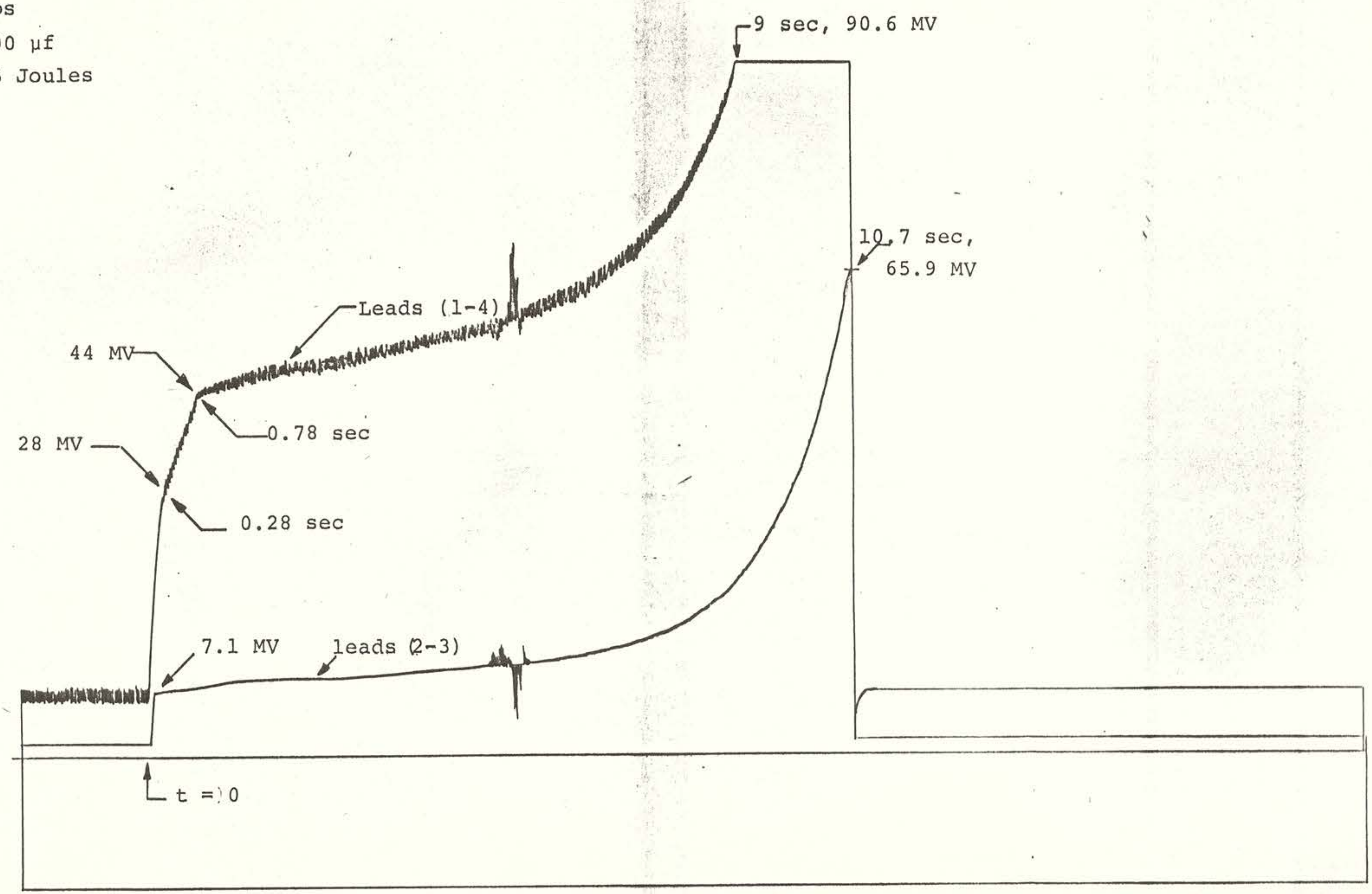
$P_{AVE} \simeq \frac{E}{\tau} = \frac{5 \times 10^{-4} V^2}{0.03} = 0.017 V^2$ watts

Figure 4

1400 amps

30V, 1000 μf

E = 0.45 Joules



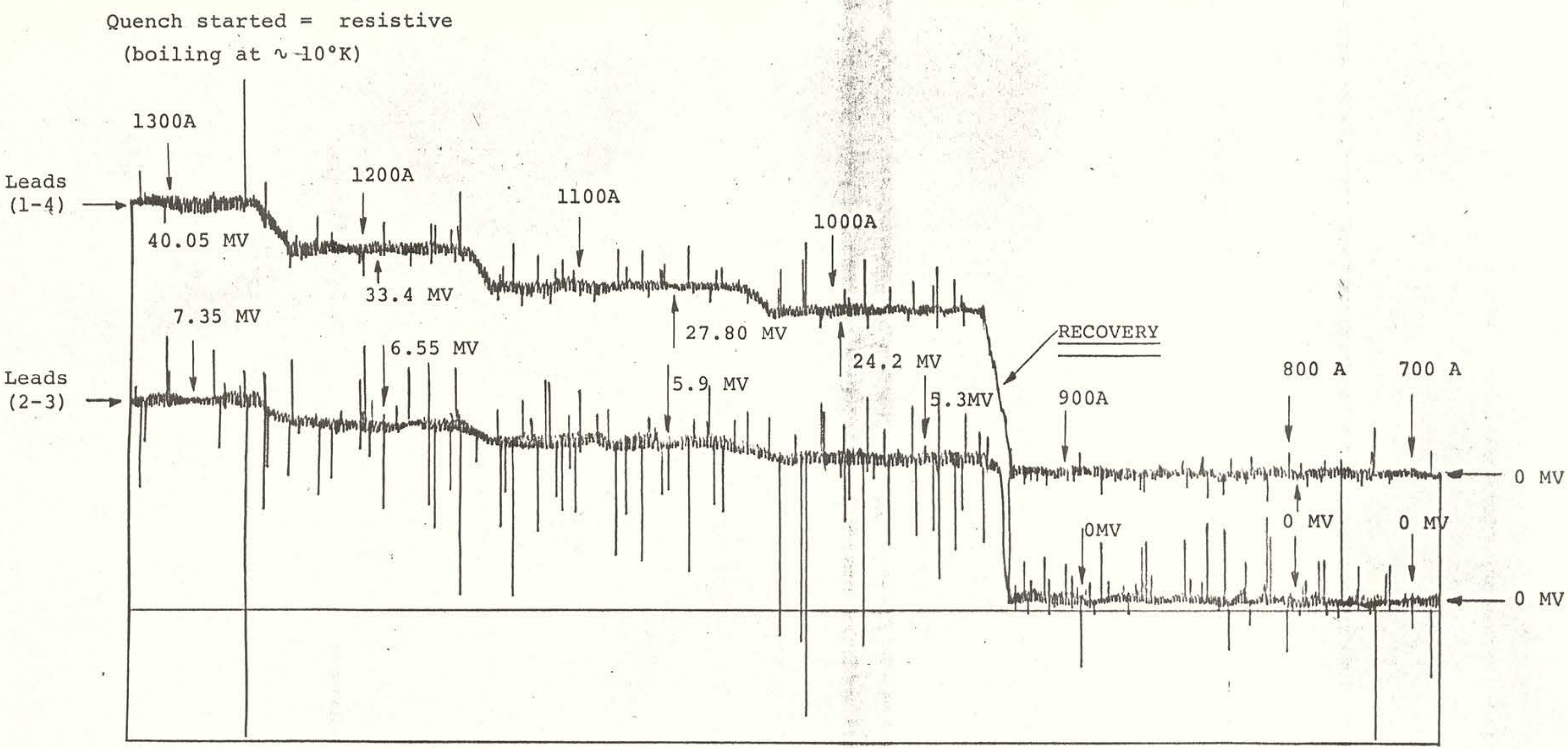


Figure 5

CCM RECOVERY CURRENT

B = 2.85 Tesla

30" Bubble Chamber Documentation Note

TITLE: Dump Resistor Requirements for Safe Discharge During Quench

NAME: Michael T. Mruzek January 14, 1982

1. Object of Report

The 30" Bubble Chamber magnet is a pool boiling design with small helium channels. To limit the maximum conductor temperature during a quench and prevent excessively high discharge voltages, a special dump resistor design procedure has been developed. In particular the coefficient of resistivity of the dump resistor's material and the specific heat of the material are optimized to limit maximum voltages and temperatures. This report details the design work which has been done.

2. Measurement of Conductor Properties

a) Resistance

The experimental determination of the CCM conductor's resistance vs. temperature was made on 1/21/81, 2/18/81 and 3/25/81 in three different experimental set-ups. The temperature range is 33K to 350K. Correlation of the data between experiments was very good. The procedure involved suspending an insulated sample of conductor above a cryogen bath in a tall dewar. Current was passed through the sample until a steady state temperature was achieved. The temperature was measured with a thermocouple soldered to the conductor. The resistive voltage produced by the current was measured with voltage taps a known distance apart. Figure #1 gives the experimentally measured conductor resistance per unit length.

b) Mass per unit length

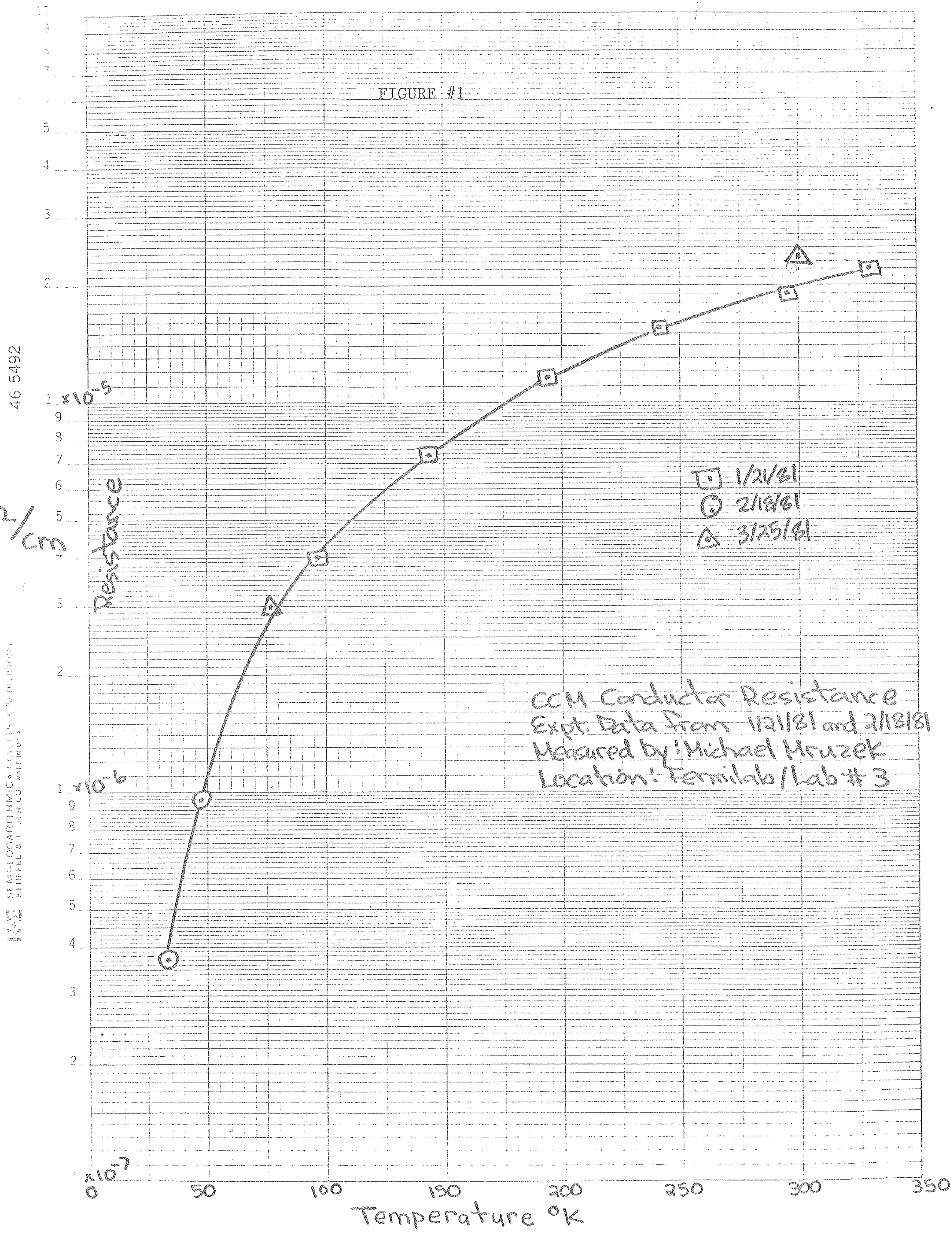
The mass per unit length of conductor was measured with a balance sensitive to 0.1 g. The value determined for the CCM conductor is 0.000754 kg/cm. Several determinations were made and the reported value is their average.

3. Development of Computer Model

a) Introduction

There are several criteria which can be used to analyze the safety of a superconducting magnet system. For example, the Stekkly parameter quantifies the relative heating and cooling of a normal zone by its resistive power generation while submersed in a bath of liquid helium. In practice, this parameter can determine whether a normal zone will tend to grow or collapse, assuming the conductor is in contact with LHe at all times. The possibility of a cooling channel becoming vapor locked is not part of the Stekkly parameter model. To include vapor locking requires a different safety criterion.

FIGURE #1


Ω/cm
Resistance
Temperature °K
0
50
100
150
200
250
300
350
×10⁻⁷
1 ×10⁻⁶
1 ×10⁻⁵
1/21/81
2/18/81
3/25/81
CCM Conductor Resistance
Expt. Data from 1/21/81 and 2/18/81
Measured by: Michael Mruzek
Location: Fermilab/Lab # 3
46 5492
SEMI-LOGARITHMIC • 3 CYCLES × 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Vapor locking seriously affects the wire's cooling. Helium vapor has a low specific heat and convective heat transfer coefficient. The vapor cooling is in general so bad the design engineer can assume it is negligible. In other words, all energy generated by the normal zone remains in the conductor to raise its temperature. If the properties of the wire are known, the wire's temperature is a function of the current and time. If the current remained constant in a normal zone, the wire would eventually reach a temperature high enough to destroy the conductor. It is the objective of quench protection systems to decrease the current in a magnet at a rate such that the wire temperature will not exceed a safe level. The objective of this safety criterion is to determine if the magnet can survive the formation of a large normal zone.

The computer program NZONE is programmed to perform calculations which simulate an ideal experiment. In the ideal experiment a section of conductor is cooled to 4.2K and insulated perfectly from its surroundings. Two electrical leads are attached to the ends of the conductor section. These leads are infinitely thin, infinitely electrically conductive and have zero thermal conductivity. Next a power supply is used to ramp the conductor with current, simulating various discharge time constants. The program calculates the time/temperature behavior of the insulated conductor and therefore provides a maximum temperature limit on any turn in a quenching magnet.

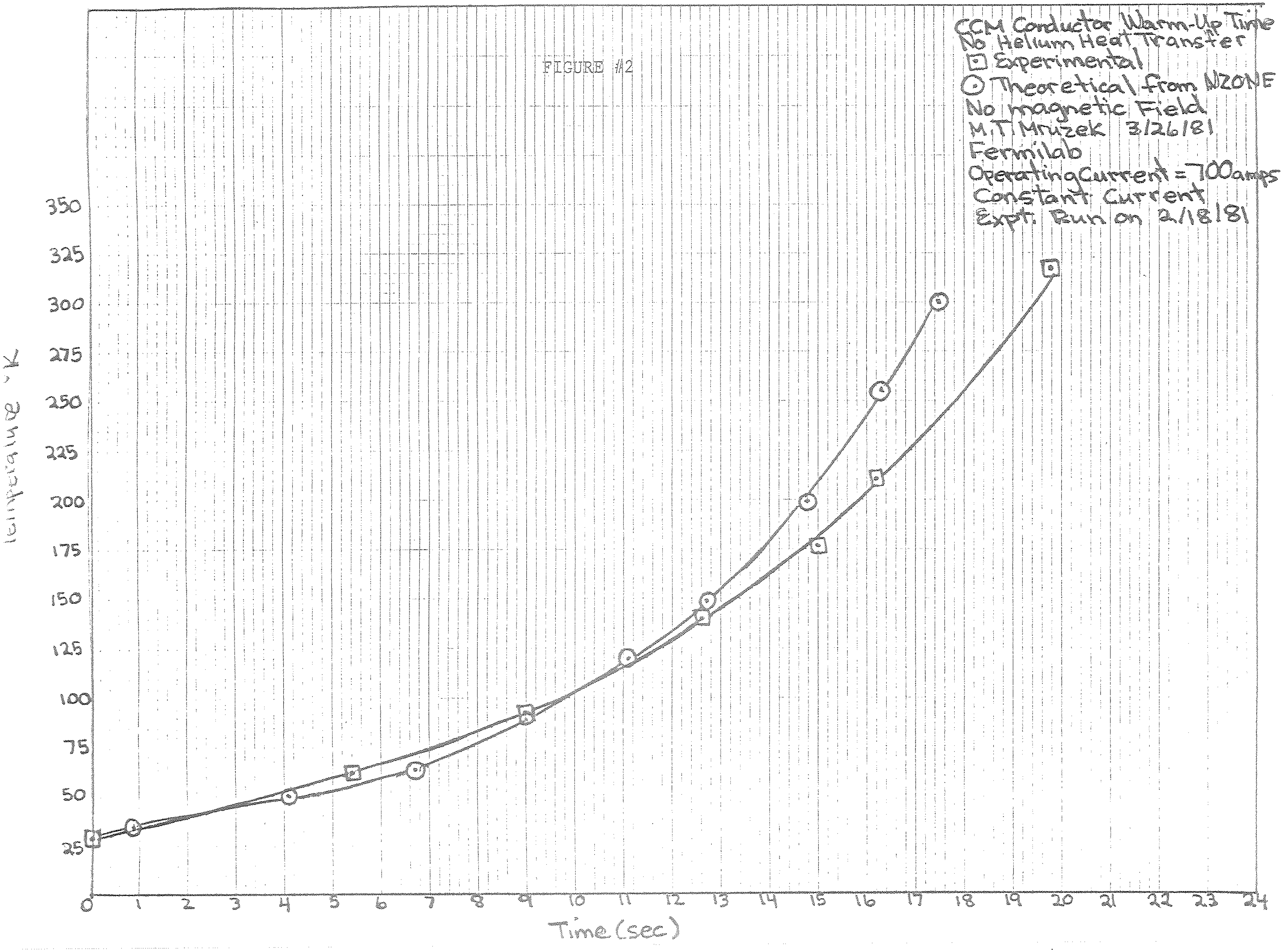
The actual input to the program is actually quite limited. It consists of material properties, mass per unit length of conductor, discharge time constant, operating current, magnetic field and the cross sectional area of the stabilizer. The material properties are for the most part documented in the program's subroutines. The actual measured values of resistance per unit length were used in the program.

b) Program verification

The computational correctness of the program routine was first checked by comparison of the output to results previously calculated by hand. The agreement was found to be very good.

The accuracy of simulation was checked by comparison to an experiment performed on 2/18/81. In the experiment a section of insulated conductor was suspended above a cryogen bath. The current through the conductor was a 700 amp step function. The temperature of the wire was monitored with a copper- constantan thermocouple with long leads. The experiment was repeated several times. A comparison between the computer model and the experiment is shown in Fig. 2.. The agreement is seen to be very good for low temperatures, and remain fairly accurate up to 300K. It is concluded the program may be used to conservatively size the dump resistor.

FIGURE #2


CCM Conductor Warm-Up Time
No Helium Heat Transfer
Experimental
Theoretical from NZONE
No magnetic Field
M.T. Mruzek 3/26/81
Fermilab
Operating Current = 700 amps
Constant Current
Expt. Run on 2/18/81
Temperature °K
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Time (sec)

c) Program Utilization

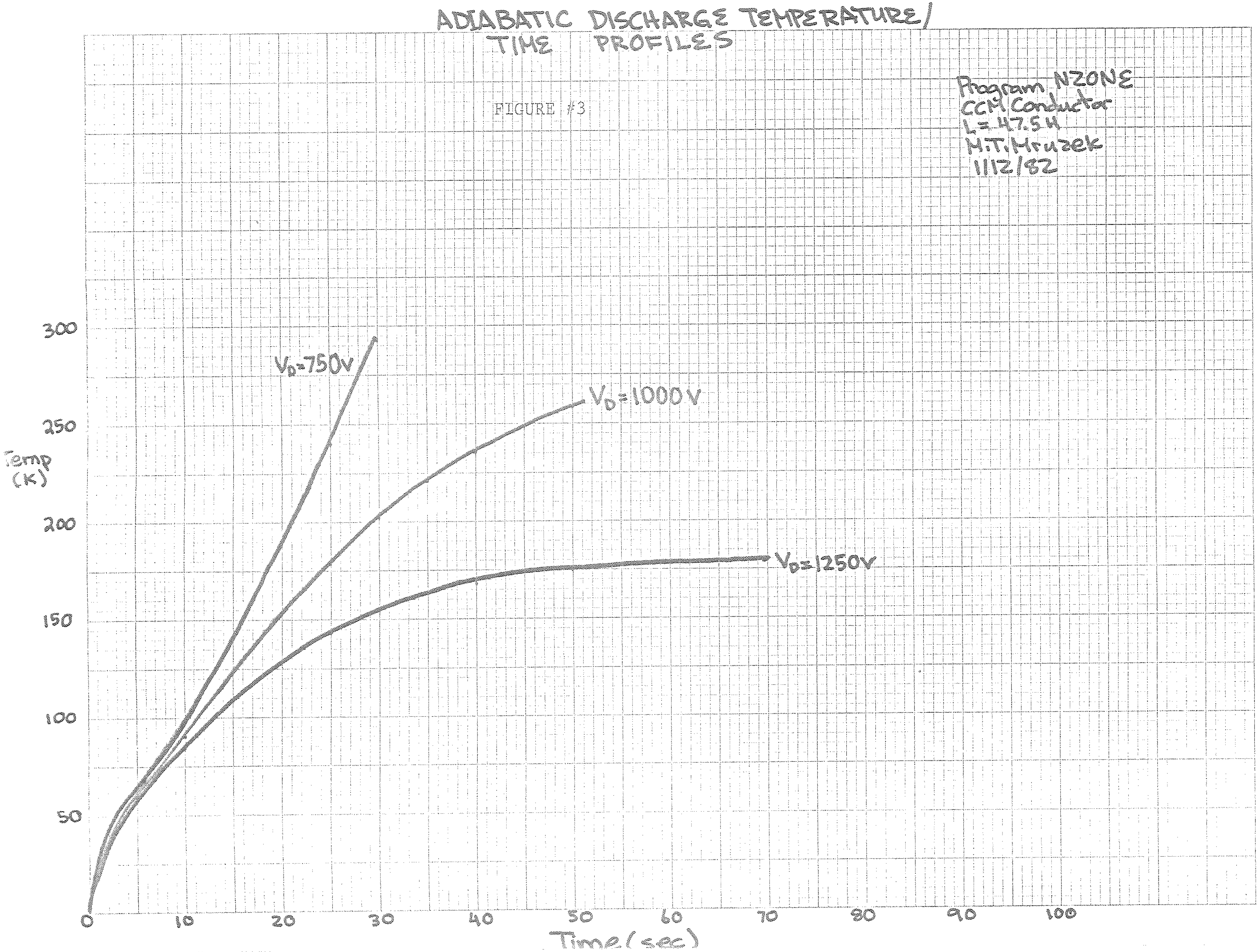
The program NZONE, having been experimentally verified, was then used to determine the size of dump resistor required to prevent excessive wire temperatures. Since the inductance and operating current of the magnet system is fixed, the dump resistor's ohmic value determines the maximum discharge voltage and the time constant. In the program the operating current is taken as 675 amps and the inductance is 47.5 H. The input to the program is a maximum discharge voltage, the value of dump resistance being calculated by the code.

The program was run at three different discharge voltages: 750, 1000 and 1250 volts. The range is large, but smaller steps of voltage might lure the user into a false sense of accuracy. The results of the temperature/time behavioral calculations is shown in Fig. 3. The input program listing for the 750 volt case is attached in Appendix #1. The results show a discharge voltage around 1000 volts or greater is required to limit the quenching conductor's maximum temperature.

4. Development of The Constant Voltage Discharge Theory and Model

a) Introduction

The previous calculations and simulations have shown an initial discharge voltage of 1000 V is required to limit excessive temperature excursions of the conductor. The large


ADIABATIC DISCHARGE TEMPERATURE/
TIME PROFILES
FIGURE #3
Program NZONE
CCM Conductor
L = 47.5 H
M.T. Mruzek
1/12/82
V_D=750V
V_D=1000V
V_D=1250V
Temp (K)
300
250
200
150
100
50
0
10
20
30
40
50
60
70
80
90
100
Time (sec)

initial voltage does decay as the discharge progresses. The most critical voltage is therefore developed at the beginning of the decay. The system equations show a quicker discharge, and hence lower conductor temperature, occurs if the resistance of the dump resistor could be varied to maintain a constant discharge voltage. Figure 4 illustrates the relative current decays of a constant voltage and the normal, constant resistance discharge.

The current decays linearly in a constant voltage discharge. The system equations suggest the magnet discharge voltage can be reduced substantially, therefore the program NZONE was modified to investigate the maximum conceivable benefits from an "ideal" dump resistor (i.e., one whose resistance varies during discharge to maintain constant voltage). The results for various discharge voltages are shown in Fig. 5. The conclusion is an ideal dump resistor cuts the maximum coil voltage in half to 500 volts. Whether such an ideal resistor could be fabricated remains to be seen.

b) Ideal Resistor Realization

It is not probable the ideal resistor could be fabricated precisely, although the generally beneficial effect of increasing resistance vs. temperature is a valuable tool which should be exploited. The constant resistance case is achieved when the mass of the resistor is very large. Then the temperature does not change greatly during discharge and resistance remains constant.

FIGURE #4

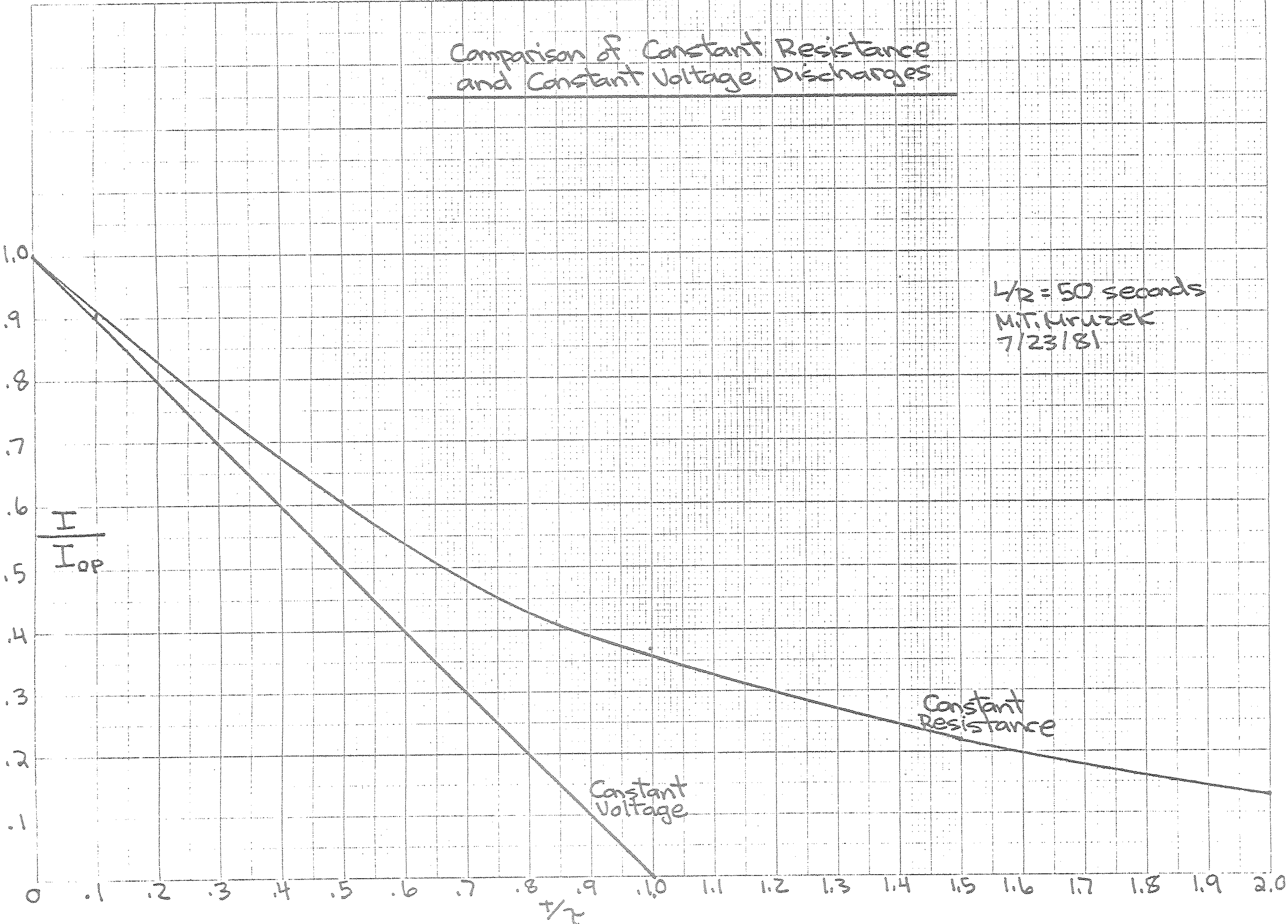
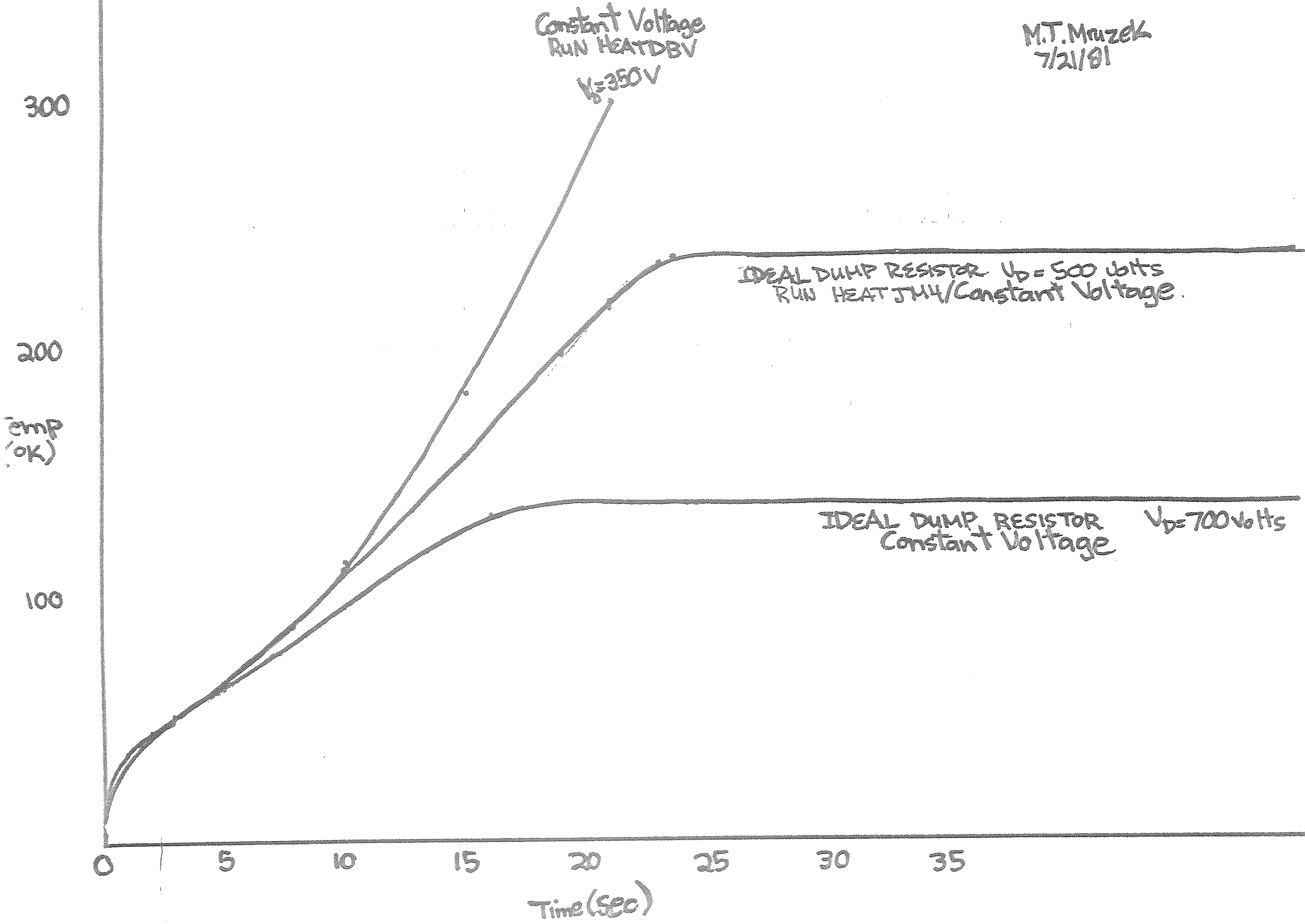

Comparison of Constant Resistance and Constant Voltage Discharges
L/R = 50 seconds
M.T. Hruzek
7/23/81
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
I / I_op
Constant Resistance
Constant Voltage
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
t/τ

FIGURE #5



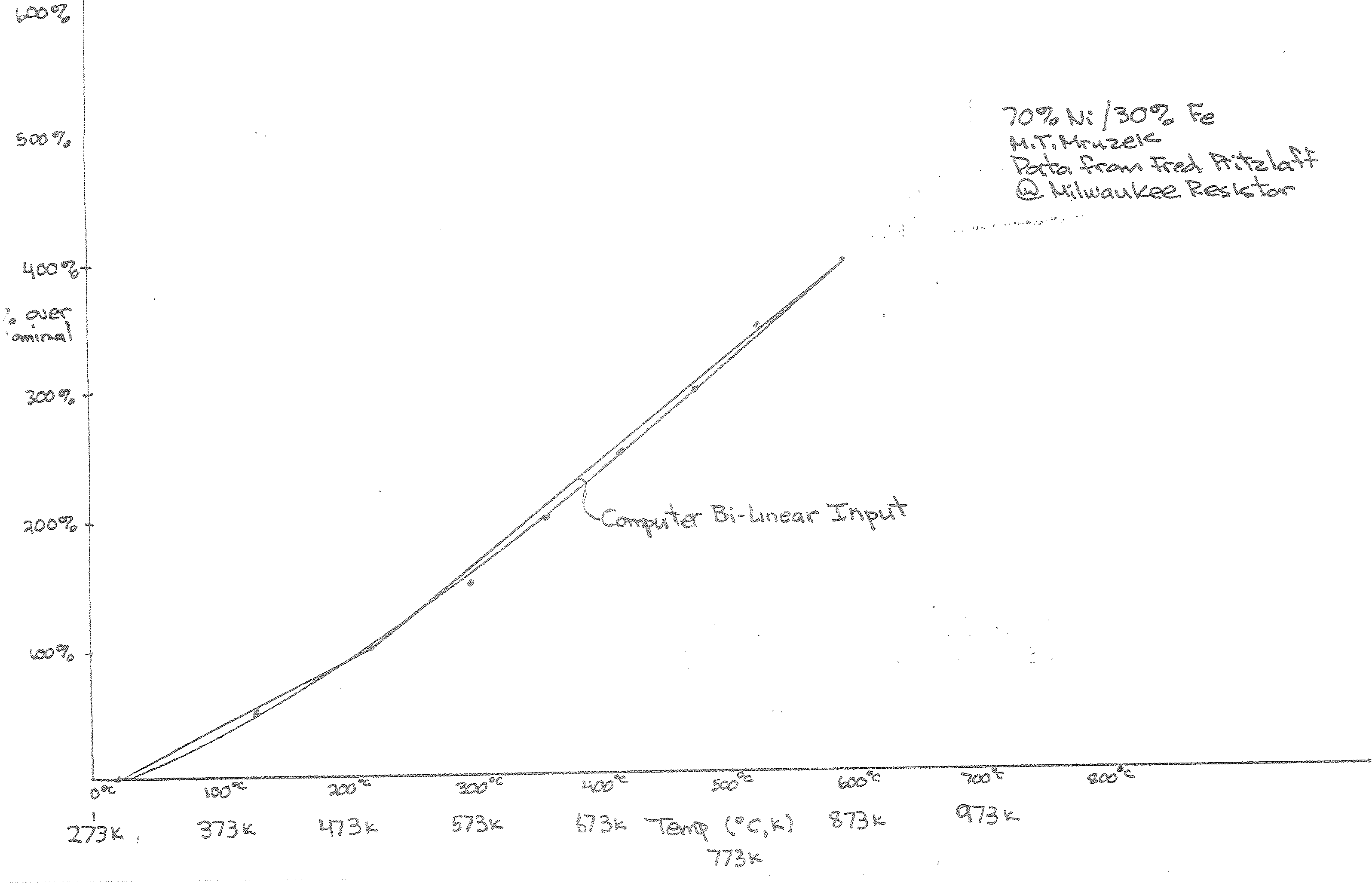
Constant Voltage
RUN HEATDBV
V_S=350V
M.T. Mruzek
7/21/81
IDEAL DUMP RESISTOR V_D=500 volts
RUN HEAT JM4/Constant Voltage.
IDEAL DUMP RESISTOR V_D=700 volts
Constant Voltage
300
200
100
Temp (°K)
0
5
10
15
20
25
30
35
Time (sec)

The incorporation of an ideal dump mode is dependent on the availability of a common engineering material with a high coefficient of resistivity and a low cost per pound. Iron would be suitable, if it were not for its tendency to rust, or the temperature limitations of anti-corrosive coatings. Discussions with several resistor manufacturers has lead to the choice of BALCO*, an alloy consisting primarily of 70% Ni, 30% Fe. The electrical resistivity of BALCO at various temperatures is shown in Fig. 6. Precise data for the specific heat at elevated temperatures was not available, therefore a data search was made for information on pure iron and nickel. Some information on BALCO was also found. The input to the computer was a bi-linear approximation of the data's average, as shown in Fig. 7.

Before the computer program could be run it was necessary to estimate the transient natural convection losses of the resistor grid. This problem was complicated by several unknown factors, primarily uncertainty about the temperature distribution in the grid itself and heat transfer coefficients for heated layers one above the other. The problems were directly related to the gridded element's having a high surface area to weight ratio.

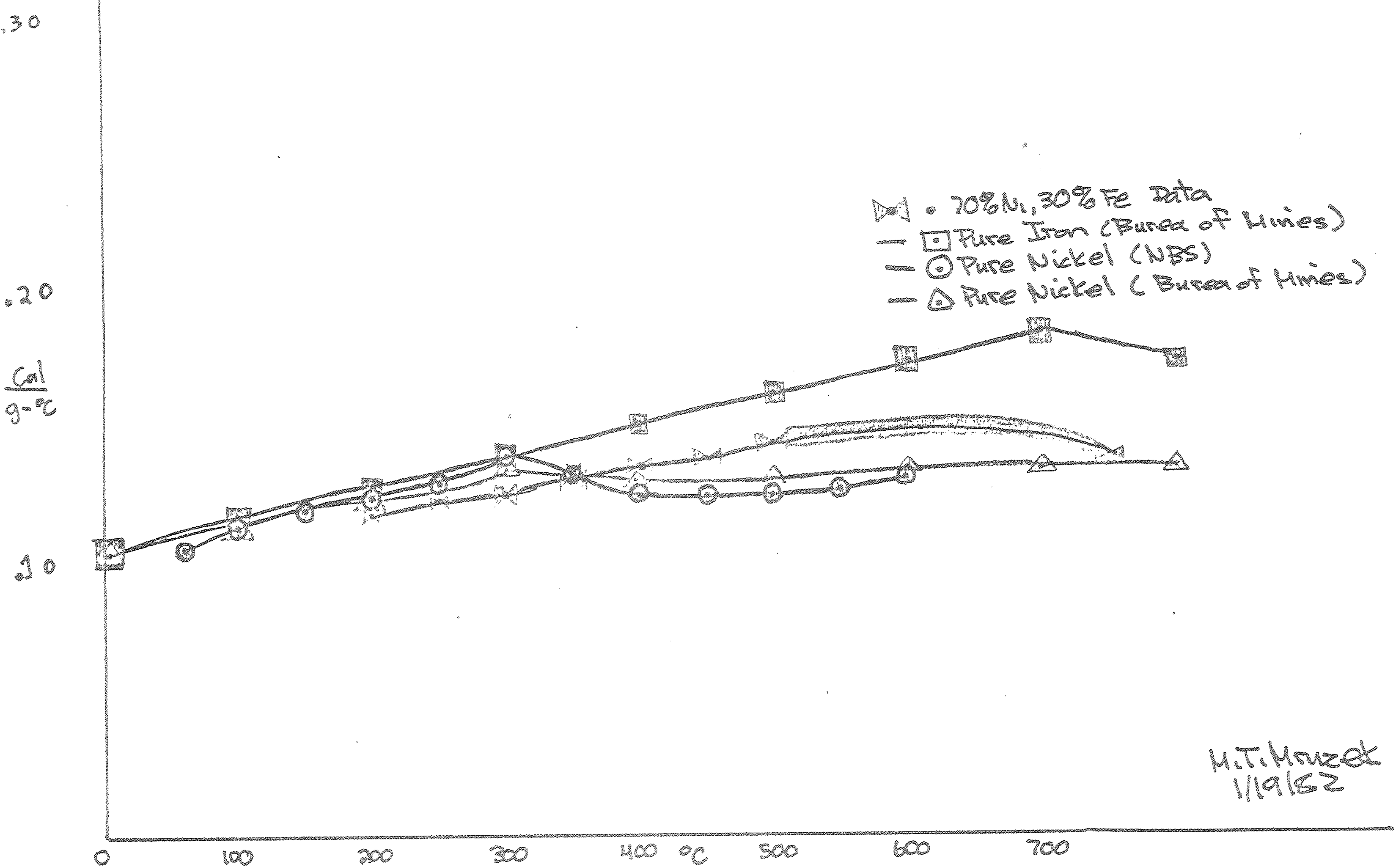
*Manufactured by the Driver Harris Corporation.

FIGURE #6



600%
500%
400%
% over nominal
300%
200%
100%
0°C
100°C
200°C
300°C
400°C
500°C
600°C
700°C
800°C
273K
373K
473K
573K
673K
773K
873K
973K
Temp (°C, K)
Computer Bi-Linear Input
70% Ni / 30% Fe
M.T. Mruzek
Data from Fred Pritzlaff
@ Milwaukee Resistor

FIGURE #7



.30
.20
.10
Cal / g-°C
0
100
200
300
400 °C
500
600
700
• 70% Ni, 30% Fe Data
Pure Iron (Burea of Mines)
Pure Nickel (NBS)
Pure Nickel (Burea of Mines)
M. T. Mrazek
1/19/82

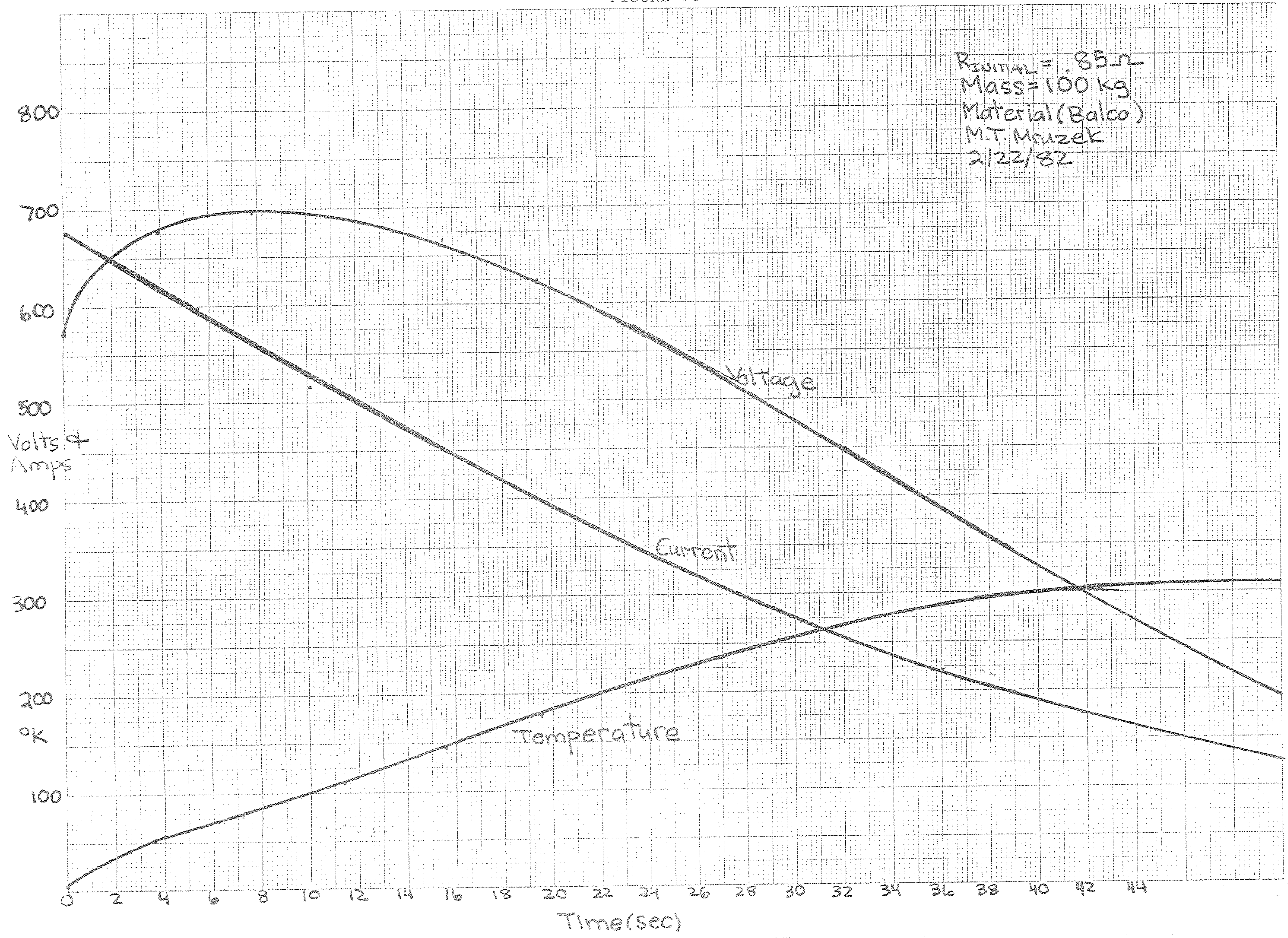
Fortunately, a manufacturer using a different method of construction, consisting of helically wound heavy gauge wire, allowed an order of magnitude reduction in area to weight ratio. The convection losses during operation are now estimated to be on the order of 3%.

The design procedure for the resistor consisted of computer modeling various combinations of resistor mass and initial resistance. The objective was to find the combination which gave the minimum peak discharge voltage and still limited the wire temperature to safe levels. The problem is not easily optimized from theoretical considerations. The combinations of mass and initial resistance are theoretically independent variables, and initial runs treated them as such. However, practical considerations of available wire sizes created a functional dependence of mass on resistance. This limitation was not significant because optimum resistor characteristics were found to be fairly insensitive to the input parameters. The combination selected after several runs was R = 0.85 Ω and Mass = 100 Kg. Peak voltages should be limited to 700 volts. The transient behavior of the resistor/magnet system during a normal discharge is shown in Fig. 8.

5. Summary

1. A computer program modeling the 30 inch conductor during a quench was written.

FIGURE #8


R INITIAL = .85 Ω
Mass = 100 kg
Material (Balco)
M.T. Mruzek
2/22/82
800
700
600
500
Volts & Amps
400
300
200
°K
100
Voltage
Current
Temperature
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
Time (sec)

2. Conductor properties for data input were experimentally measured.
3. The program was experimentally verified to be accurate.
4. It was found peak voltages across the magnet leads could be reduced by allowing the dump resistor to heat up during discharge.
5. An initial resistance of 0.85 Ω and initial mass of 100 Kg has reduced peak voltages from 1000V to 700V while still limiting the conductor temperature to safe levels.

Appendix 4

Experimental Verification of 30" Dump Resistor Thermal/Electrical Behavior

M.T. Mruzek
May 26, 1984

Introduction

The dump resistor for the 30" Bubble Chamber Magnet system is unique because it has been designed to reduce the peak discharge voltage of the coils, while satisfying a conservative safety criterion for the superconducting cable.* It has been shown analytically possible to reduce the peak discharge voltage by 33% and still satisfy the safety criterion.** The purposes of this report are...

1. Verify the temperature versus resistance behavior of the resistor assembly used in previous modeling.
2. Show the convective losses of the resistor assembly are minimal as assumed in previous modeling.
3. Verify the mass-specific heat combination used for previous modeling.
4. Test the resistor to the specified maximum working temperature of 375°C.

Data Collection

The dump resistor was tested in Lab F at Fermilab with a Transrex power supply. Two thermocouples were attached to the Balco coils with a brazed bond. The chromel/constantan thermocouples were read with an Omega digital readout. The current was monitored with a 100 mv/1000 amp shunt on a Linseis chart recorder. The resistor voltage was monitored with a voltage divider of 100 and the same chart recorder on channel 2.

The data collection consisted of first obtaining steady state values of temperature, voltage and current. Next, dynamic constant current runs at 200, 300, 400, 500 and 650 amps were made. Finally, a 400 volt constant voltage run was made. Before ending, both resistor sections were run above 375°C.

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* See "Dump Resistor Requirements for Safe Discharge During Quench" a 30" Bubble Chamber Documentation Note dated January 14, 1982 by M.T. Mruzek.

** Personal notes of M.T. Mruzek and W.W. Craddock.

Results

Objective 1: (R versus T is correct)

The measured resistance of the assembly is plotted in Fig. 1. Also plotted are several points from the bi-linear input previously used for computer and hand calculations. The agreement is excellent.

Objective 2: (Convection losses are minimal)

The convection losses should be small at any given temperature compared to the intended power dissipation at the same temperature during an actual discharge. In practice there is no reason why this is required, although for convenience in analytical calculations it is desirable. Figure 2 is a plot of measured convection losses versus temperature and anticipated power inputs and temperature. The power lost during the discharge due to convection is seen to be negligible compared to the power input.

Objective 3: (Mass/specific heat combination correct)

The transient behavior of the resistor temperature during the 5 constant current and 1 constant voltage runs is plotted in Fig. 3. Some of the higher constant current data was unobtainable because of voltage limitations on the supply. The mass/specific heat combination can be shown correct by predicting the behavior of the resistor during one of the constant current runs. A stepwise iterative technique was used employing the formula

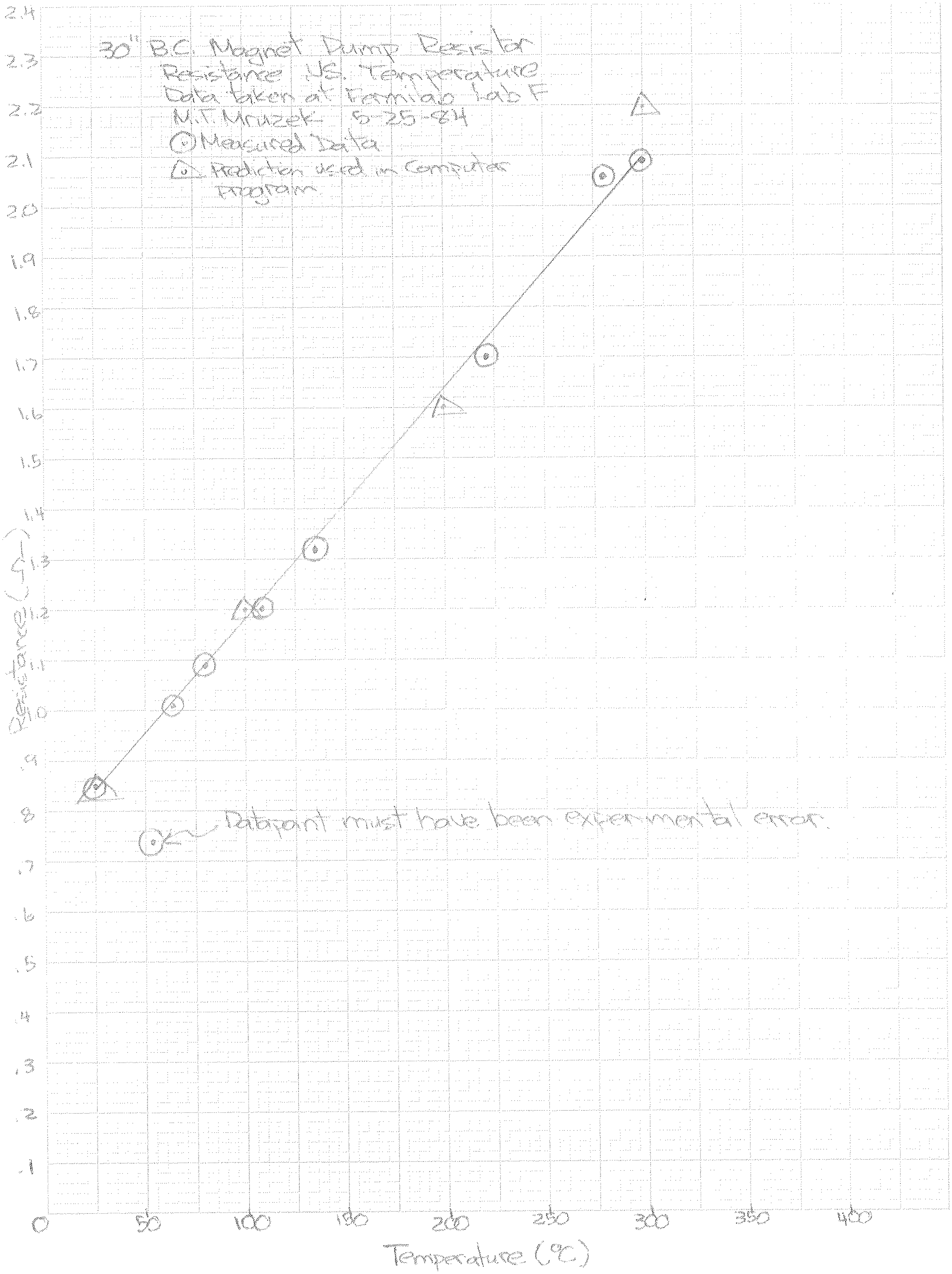
$$\frac{dT}{dt} = \frac{I^2 R}{MC_p} \qquad (1)$$

where T is the resistor temperature, t is the time in seconds, I the current in amps, R the resistance in ohms, M the mass in Kg and C_p the specific heat in J/Kg-^{O}C. The dependence of R on T, the mass of the resistor and dependence of C_p on T were all taken as their theoretical values. The interation was made for the 500 amp case, with the results shown in Fig. 3. The experimental and predicted results are in excellent agreement, verifying the correctness of previous modeling.

Objective 4: (Maximum operating temperatures)

Both resistor units were run to 375^{O}C as specified. Although some initial smoking was observed, it quickly subsided.

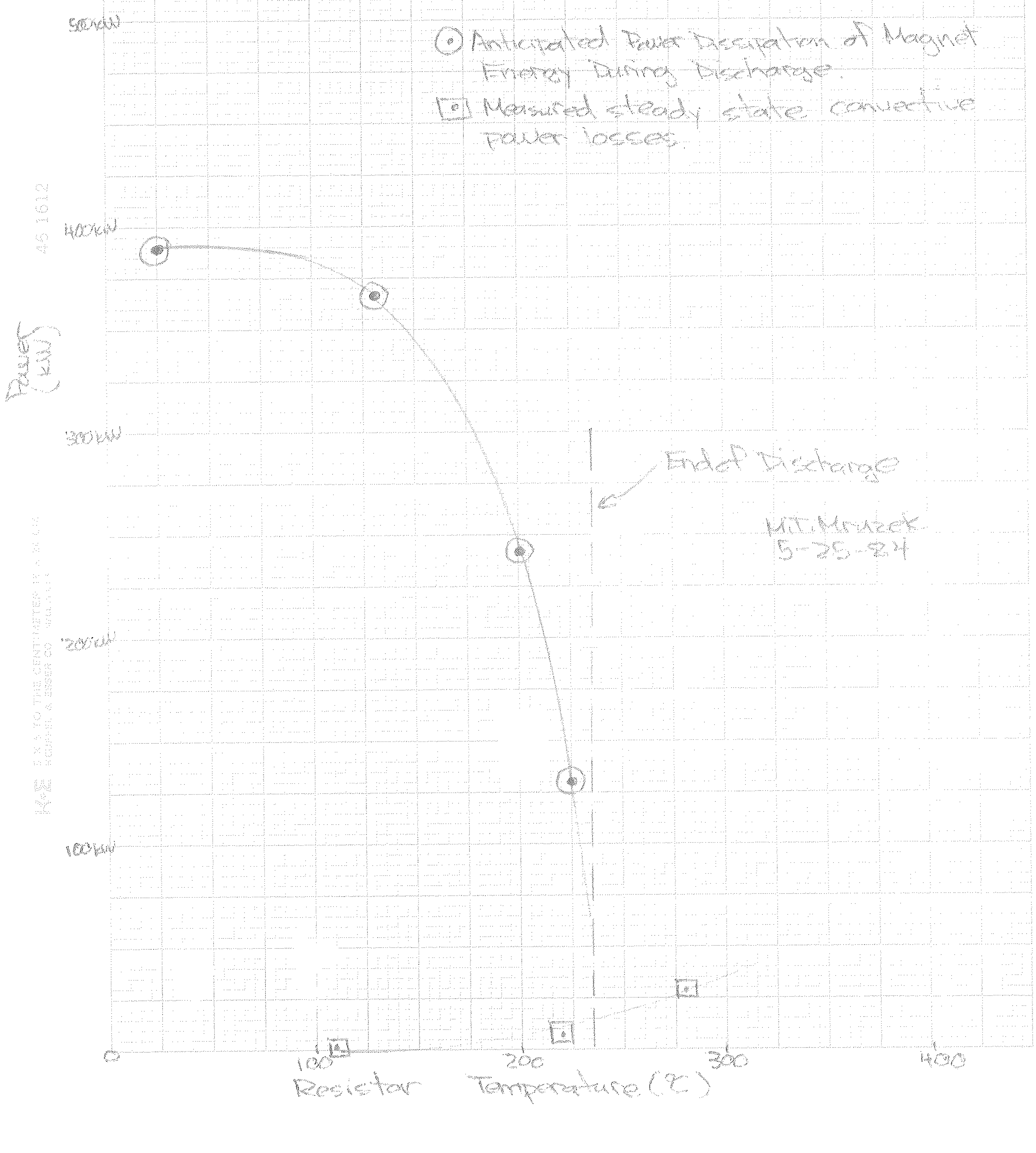
Figure #1

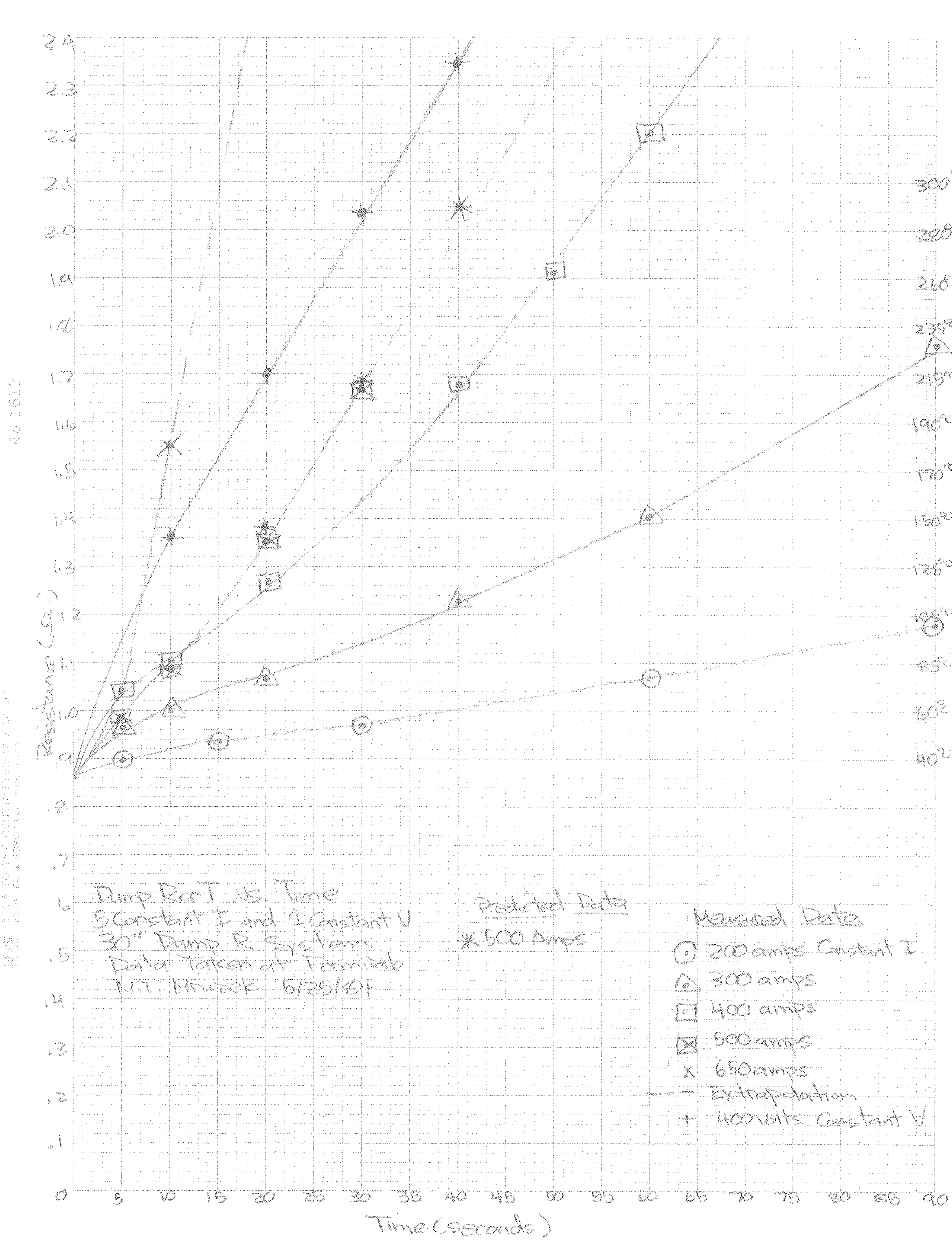


30" B.C. Magnet Dump Resistor
Resistance vs. Temperature
Data taken at Fermilab Lab F
M.T. Mruzek 5-25-84
Measured Data
Prediction used in Computer Program
Datapoint must have been experimental error.
Resistance (Ω)
Temperature (°C)
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
50
100
150
200
250
300
350
400

Figure #2

Comparison of Discharge Power Input VS. Convective Power Output





Dump R or T vs. Time
5 Constant I and 1 Constant V
30" Dump R System
Data Taken at Fermilab
M.T. Mruzek 6/29/84
Predicted Data
* 500 Amps
Measured Data
200 amps Constant I
300 amps
400 amps
500 amps
650 amps
Extrapolation
400 volts Constant V
Resistance (Ω)
Temperature (°C)
Time (seconds)