TM-295
0420

HOLLOW COPPER CONDUCTORS
FOR THE MAIN ACCELERATOR MAGNET COILS

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The Main Accelerator Bending Magnet coils conductors were designed to give the same pressure drop and temperature rise across one water circuit. For 400 GeV excitation, the coils were designed to allow the water temperature to rise 16°C with a pressure drop of about 190 psi across one water circuit. The trial and error method was used since all the parameters were dependent on each other, and they all had to give a good field region.

The quadrupole coils share the low conductivity cooling water of the bending magnets. At 400 GeV excitation, with the available water pressure and limiting conductor hole size, the calculated temperature rise per water circuit is about 14°C for the 7 foot quadrupole and about 22°C for the 4 foot.

Theoretical hydraulic parameters were calculated. It is the object of this engineering note to give the latest coil parameters and compare them with the measured one.

Copper Conductor

The material used in the fabrication of the magnet coils was Oxygen-free without residual deoxidants "copper 102" per ASTM Specification B188-66a. The material was in the soft annealed condition (Rockwell F 45 max.). The copper was to meet the embrittlement test per ASTM B188-66a.

HOLLOW COPPER CONDUCTORS DESIGN LIMITATIONS

Before one proceeds in designing a hollow conductor for a magnet coil, a few limiting factors should be kept in mind.

The length of the hollow conductor can be limited by the weight per foot. Four hundred pounds is the maximum size billet available. It can also be limited by the hole cross-section. A relatively small hole imposes length limitations due to the tensile strength available with plug rods. Large hollow conductors are drawn on a bench, and the longest bench available can also limit the length. The bending magnet conductors were drawn on a 140 ft. bench. The maximum length of the conductors was 90 feet.

The generally accepted tolerances for internal and external dimensions on a hollow conductor are ±.005". This tolerance is readily obtainable with the modern drawing tools. The tolerance for the bending magnets coil conductors were ±.007" to ±.010" for the outer coils, and ±.003" to ±.005" for the inner coils. The quadrupole coil conductor had ±.003" and ±.005" tolerances. The tolerance on the center hole drift is more critical. A drift of 15% of the wall thickness is commercially accepted. In order to maintain good concentricity, extremely tight control of the extrusion operation is required. The concentricity obtained from the extrusion operation is carried down to the remaining drawing operations. A center hole drift tolerance of ±1/64" was required for the bending magnets inner coils. This was done by control and selection of extruded material.

Other limiting factors in the design of hollow conductors are such things as ratio of major to minor dimensions, normally held to a maximum of 3 to 1. The ratio of copper cross-section to the hole area is important, and a minimum hole diameter of 1/4" is acceptable.

Bending Magnet Coils

The inner coil and two outer coils in the bending magnets are electrically connected in series. The hydraulic circuit is made up of the three coils connected in parallel. This is done using two ceramic insulators feed through. Using the trial and error method, the water hole diameter in the conductors were determined from the cooling water temperature rise and the pressure drop across one water circuit.

The equivalent hydraulic length for each coil had to be calculated. Based on previous tests made on similar coils, a 15% factor was added to the calculable equivalent length. This factor compensated for the restriction of the bends and at the brazed joints. The actual length of the coils was 170 feet for the B-1 and B-2 inner coils (4 turns), 174 feet for the B-1 outer coil (4 turns), and 264 feet for the B-2 outer coil (6 turns).

Quadrupole Coils

The water hole diameter was deterimined from manufacturing capability. One-fourth inch diameter hole was the minimum acceptable for the size of the conductor. The 7 foot quadrupole has four water circuits connected in parallel. Sharing the same cooling water of the bending magnets, the 7 foot quadrupole has a lower water temperature rise than the bending magnets for the same excitations. The length of each quadrant coil is 63 feet.

The length of the 4 foot quadrupole coil is only 42 feet per quadrant. With two water circuits in parallel, the water temperature rise is a few degrees higher than the bending magnets for the same excitation.

Measurement Results

Figures 1 through 4 give the parameters of the Main Accelerator magnet coils. Calculated and measured values are given for the water flows and temperature rise for different excitations. DC excitations were used to power the magnets at an average run time of about 8 minutes. Within this time the temperature gradient was close to steady state. The power to the magnets was calculated using the DC current and resistance of the coils. The calculated resistance checked very closely to the measured one from the coil vendors. Figures 5 through 8 show the water temperature rise per power input to the magnets.

For the bending magnets, the measured water flows and pressure drops agreed fairly well with the calculated one. The water manifold added to the flow resistance, and partially explained the difference. The constant increase of the temperature rise is due to the water friction losses in the coils.

For 400 GeV excitation, the water temperature rise for the B-1 magnets is 17°C and 18.5°C for the B-2 magnets.

The quadrupole magnets measurements show a larger temperature increase due to friction losses. The pressure drop across the magnets averaged about 15% more than the calculated pressure drop across each water circuit. This is due to the increased flow resistance in the manifold. The water flow in each of the quadrant coils, which make up one water circuit, was measured and closely agreed with the calculated values. For the 400 GeV excitation, the water temperature rise for the seven foot quadrupoles is 18.8°C and for the four foot quadrupoles, 26°C.

B-1 BENDING MAGNET COIL PARAMETERS

Number of turns	12	
Outside dimensions of copper conductor	1.113 x .670 Inner Coil 1.096 x .922 Outer Coil	in^2
Diameter of cooling hole	.400 Inner Coil .340 Outer Coil	in
Copper area	.617 Inner, .916 Outer Coil	in^2
Cooling circuits	3	
Resistance (40°C)	5.92	mΩ

	Theoretical Calculations			Measured Average Values DC Excitation			
	200 GeV	400 GeV	500 GeV				
Maximum current density	3728	7698	11,183	4052	5348	6483	A/in^2
Maximum current	∿2300	∿4750	∿6900	2500	3300	4000	A
Average power	∿13.8	∿58.8	∿58.8	37.0	64.5	94.7	kW
Cooling-water temperature rise	3.8	16	16	14.4	18.3	26.0	°C
Total water flow	13.9	13.9	13.9	13.5	13.4	13.9	gpm
Pressure drop	(1) 190	(1) 190	(1) 190	(2) 196	(2) 191	(2) 202	psi

(1) Pressure drop across one water cirucit

(2) Pressure drop across magnet

FIGURE 1

B-2 BENDING MAGNET COIL PARAMETERS

Number of turns	16							
Outside dimensions of copper conductor	1.096 x .922 Inner and Outer Coils							in^2
Diameter of cooling hole	.340 Inner Coil .445 Outer Coil							in
Copper area	.916 Inner, .852 Outer Coil							in^2
Cooling circuits	3							
Resistance (40°C)	7.16							mΩ
	Theoretical Calculations			Measured Average Values DC Excitation				
	200 GeV	400 GeV	500 GeV					
Maximum current density	2700	5575	8098	2347	3873	4695		A/in^2
Maximum current	2300	4750	6900	2000	3300	4000		A
Average power	∿16.7	∿71.1	∿71.1	28.6	77.9	114.5		kW
Cooling-water temperature rise	3.8	16	16	7.7	18.8	28.8		°C
Total water flow	16.8	16.8	16.8	15.1	15	15.4		gpm
(1) Pressure drop across one water circuit	(1) 190	190	190	(2) 195	185	195		psi

(2) Pressure drop across magnet

FIGURE 2

TM-295
0420

7 FOOT QUADRUPOLE COIL PARAMETER

Number of turns	4/pole						
Outside dimensions of copper conductor	1.000 x .565						in^2
Diameter of cooling hole	.250						in
Copper area	.513						in^2
Cooling circuits	4						
Resistance (40°C)	4.5						mΩ
	Theoretical Calculations			Measured Average Values DC Excitation			
	200 GeV	400 GeV	500 GeV				
Maximum current density	4288	8772	12,280	1949	5848	6823	A/in^2
Maximum current	∿2280	∿4800	∿6300	1000	3000	3500	A
Average power	∿10.3	∿45.6	∿45.6	4.5	40.5	55	kW
Cooling-water temperature rise	3.3	14.4	14.4	5	16.6	23.6	°C
Total water flow	12	12	12	10.8	11.4	10.2	gpm
(1) Pressure drop across one water circuit	(1) 190	(1) 190	(1) 190	(2) 209	(2) 213	(2) 218	psi

(2) Pressure drop across magnet

FIGURE 3

TM-295
0420

4 FOOT QUADRUPOLE COIL PARAMETERS

Number of turns	4/Pole	
Outside dimensions of copper conductor	1.000" x .565"	in^2
Diameter of cooling hole	.250	in
Copper area	.513	in^2
Cooling circuits	2	
Resistance (40°C)	2.9	mΩ

	Theoretical Calculations			Measured Average Values			
	200 GeV	400 GeV	500 GeV	DC Excitation			
Maximum current density	4288	8772	12.280	3898	5848	7797	A/in^2
Maximum current	∿2280	∿4800	∿6300	2000	3000	4000	A
Average power	∿6.6	∿29.4	∿29.4	11.6	26.1	46.4	kW
Cooling-water temperature rise	5	22.3	22.3	13.3	22.2	43	°C
Total water flow	5	5	5	4.8	5.2	5.00	gpm
Pressure drop across one water circuit	190	190	190	219	222	217	psi

FIGURE 4

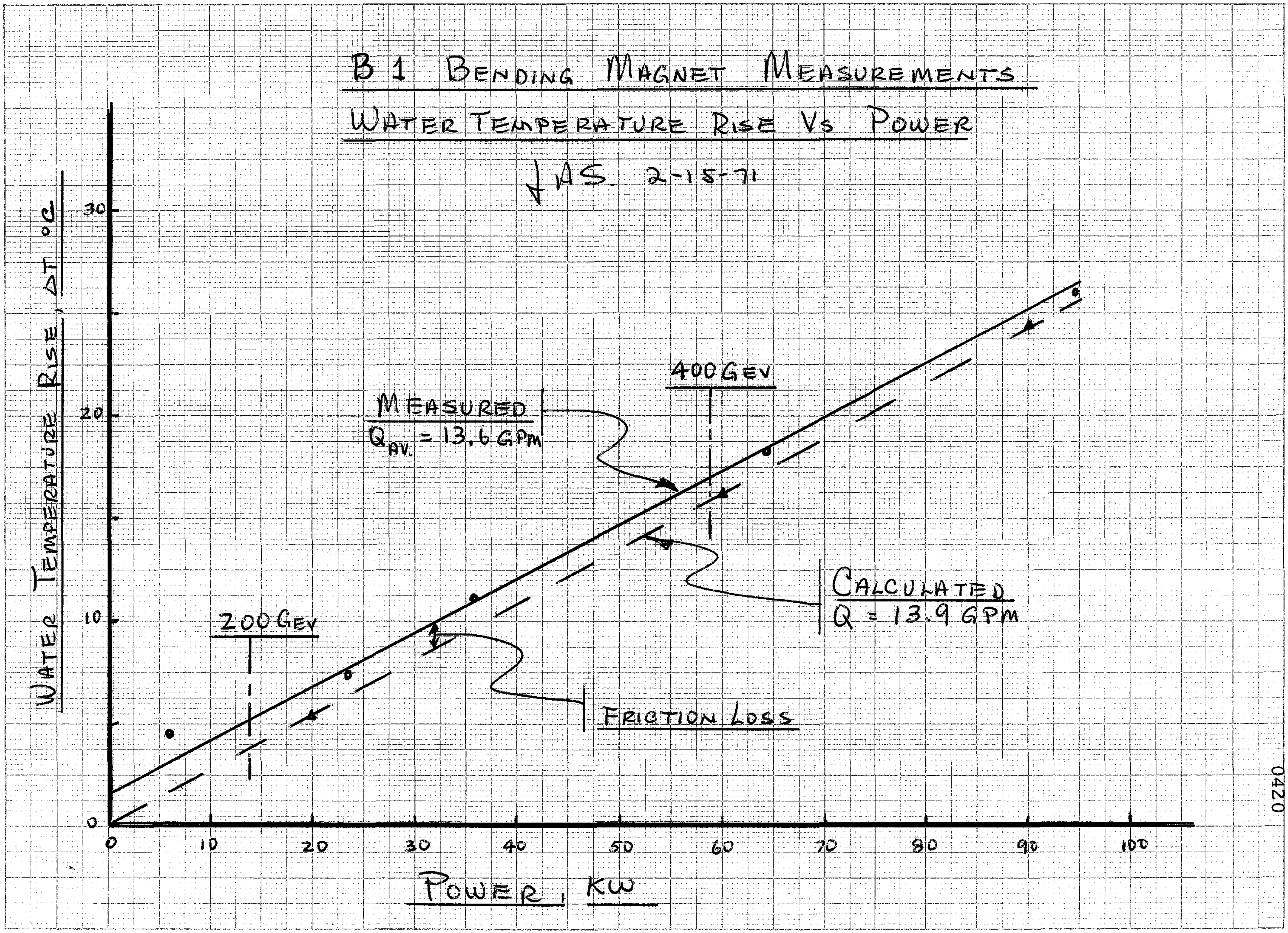
B 1 Bending Magnet Measurements
Water Temperature Rise Vs Power
J.A.S. 2-15-71
Water Temperature Rise, ΔT °C
Power, KW
0
10
20
30
40
50
60
70
80
90
100
400 GeV
200 GeV
Measured
$Q_{AV.}$ = 13.6 GPM
Calculated
Q = 13.9 GPM
Friction Loss

FIGURE 5

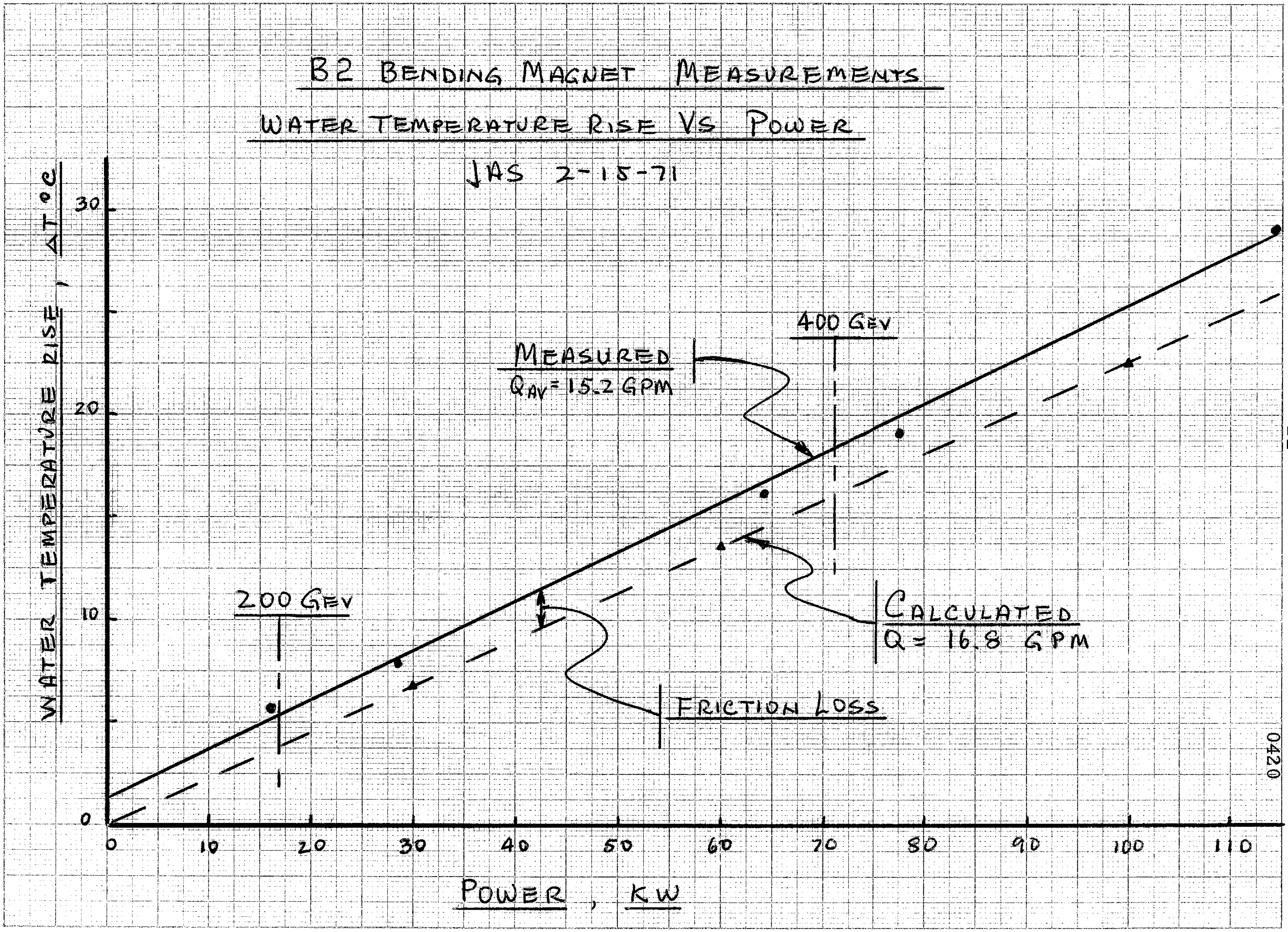
B2 BENDING MAGNET MEASUREMENTS
WATER TEMPERATURE RISE VS POWER
JAS 2-15-71
WATER TEMPERATURE RISE, ΔT °C
POWER, KW
400 GEV
200 GEV
MEASURED
QAV = 15.2 GPM
CALCULATED
Q = 16.8 GPM
FRICTION LOSS
0
10
20
30
40
50
60
70
80
90
100
110

FIGURE 6

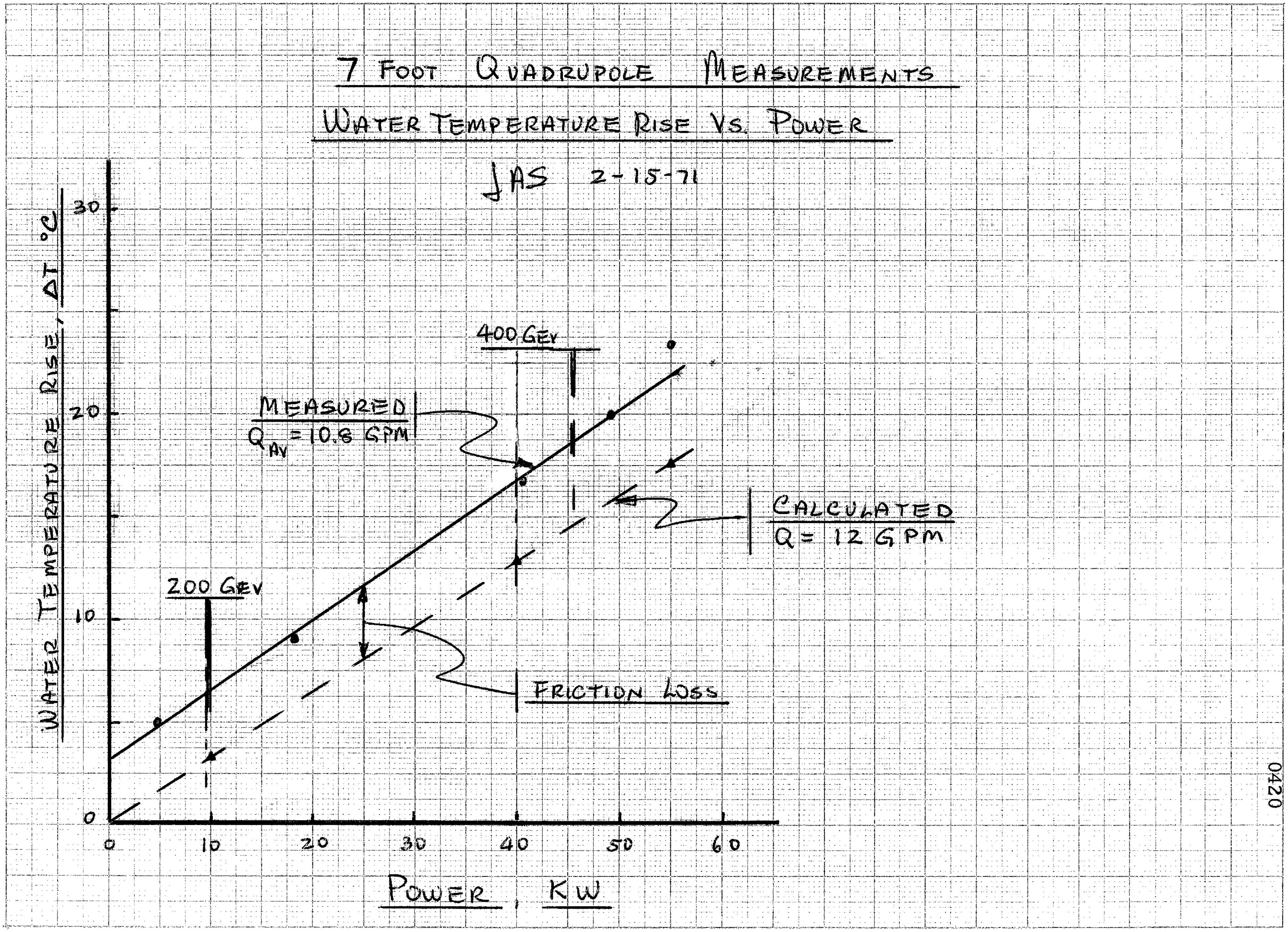
7 FOOT QUADRUPOLE MEASUREMENTS
WATER TEMPERATURE RISE VS. POWER
JAS 2-15-71
WATER TEMPERATURE RISE, ΔT °C
POWER, KW
400 GEV
200 GEV
MEASURED
Q AV = 10.8 GPM
CALCULATED
Q = 12 GPM
FRICTION LOSS
0
10
20
30
40
50
60

FIGURE 7

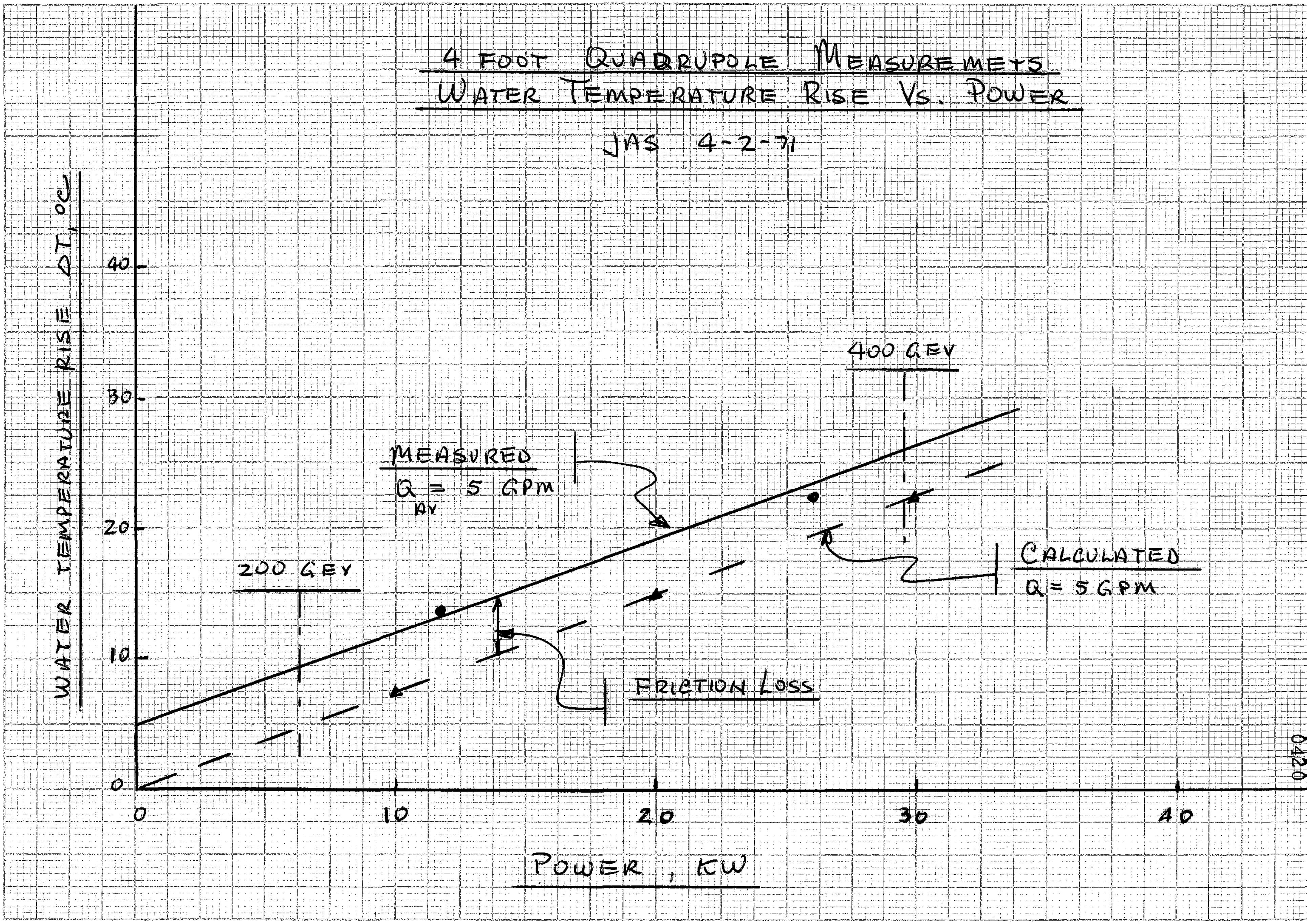

FIGURE 8

TM-295
0420