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**Summary Report on the MIR 20.0 ft. Dipole Magnet
Performance/Thermal Test**

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Introduction

A formal request for the development of a test plan for the MIR dipole was made on November 23, 1993 (see attachment #1). The test would evaluate the effects of the thermal stresses exerted on the coil assembly as a result of expected thermal expansion.

Some preliminary calculations for the coil assembly time constant and the thermal reaction forces within the coil assembly, resulting from thermal expansion, followed the initial test plan request.

Initially, the proposed test plan called for a performance test to be conducted at power levels equal and below the specified design level (2000, 3500 and 5000 Amps DC) followed by an insulation thermal cycle life test. The thermal cycle test would be repeated for a reversed flow direction and finally, the coil will be subjected to twice the normal magnitude of thermal expansion and contraction by reversing the flow direction after every cycle (a cycle being powering the coil until temperatures stabilize and then turning the power off until temperatures are back to the originating temperature).

The final draft for the thermal test came from the Accelerator Division/Main Injector department (see attachment #2). This plan called for a performance/thermal test to be conducted at power levels equal and above the specified design level (5000, 7000 and 9500 Amps DC). Two sets of measurements were taken; the first being with cold water entering at the coil center and exiting at the outer turn (see Figure 1) while the second set will represent the reverse setup (see Figure 2). It was also requested that test calculations be performed prior to conducting the test for investigative and comparative reasons.

The decision whether or not to perform the insulation thermal cycle life test was reserved for a later time, after analyzing the performance/thermal test results and studying the thermal cycle life test requirements.

This report will deal mostly with the performance/thermal test, its objectives, calculations, procedure, results, conclusions and observations.

Test Objectives

There are four main objectives to the performance/thermal test:

- a. Learn about the magnet performance and behavior when subjected to almost twice its rated current namely, 9500 Amps DC (when at normal operating conditions the current is not expected to exceed 5000 Amps RMS)

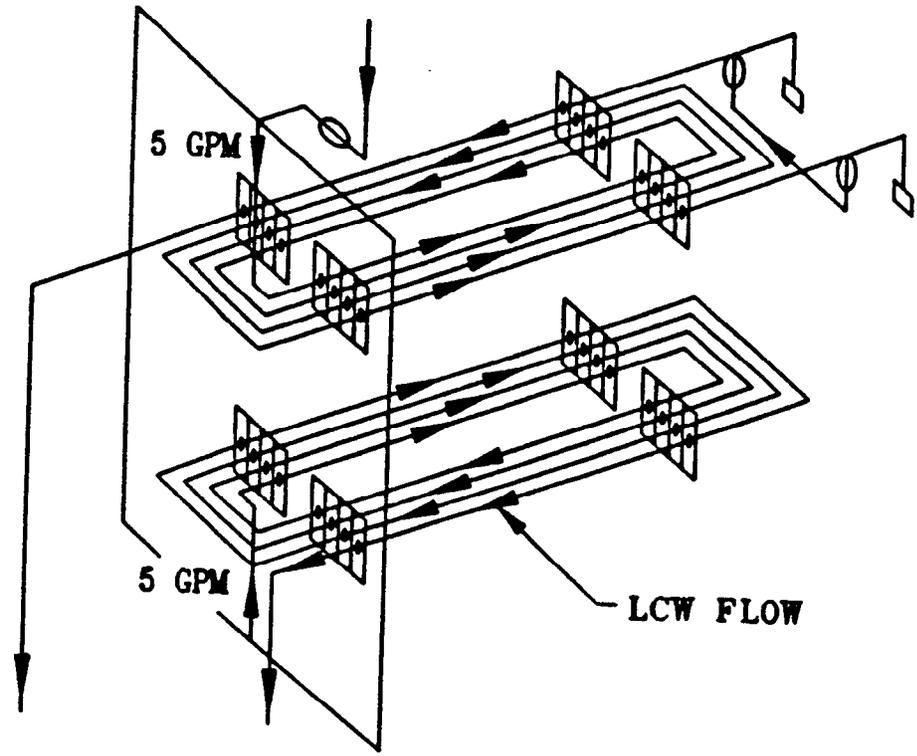


Figure 1: Present Design Scheme-LCW Enters at Coil Center

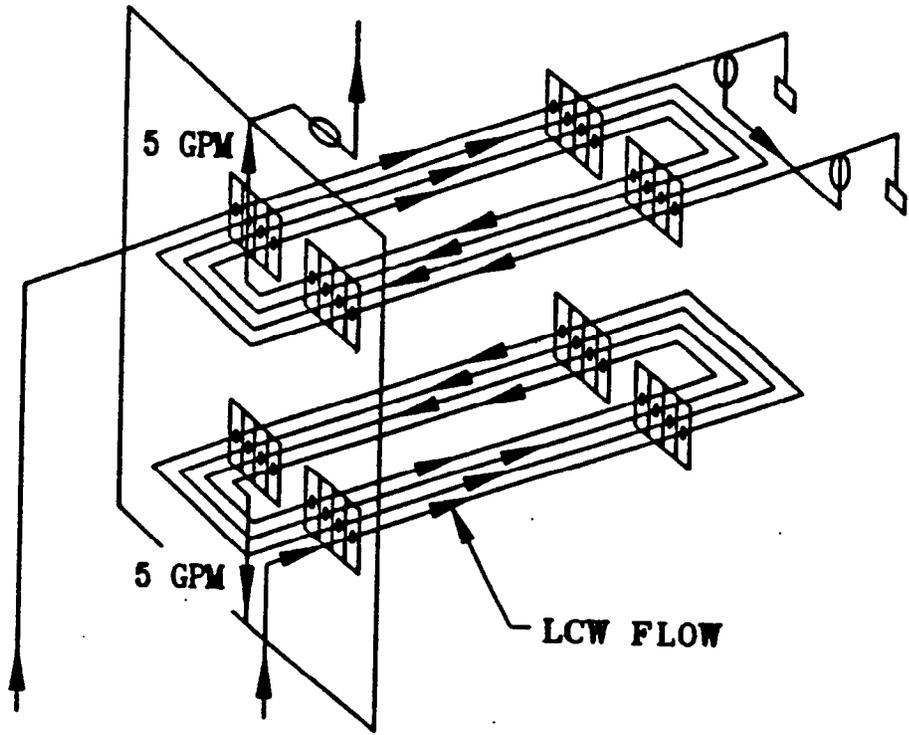


Figure 2: Proposed Design Scheme-LCW Enters at Outer Turn

- b. Compare calculated performance values such as water/coil temperatures and coil thermal expansion when water flow rate and pressure differential are constant and their relationship to the change in current levels (5000 and 9500 Amps DC).
- c. Compare magnet performance when cold water enters the coil at the center and exits at the outer turn (see Figure 1) to that when cold water enters the coil at the outer turn and exits at the coil center (see Figure 2).
- d. Gather information and data which will be used to evaluate the need and feasibility for a second phase testing, namely, a thermal cycle life test. This test would simulate operating conditions in the tunnel and help in understanding the behavior of the insulation system when exposed to cyclic mode of power off and on situations. Fatigue is the suspected mode of failure and such a test would verify the integrity of the insulation.

Test Calculations

A mechanical model of the coil assembly should take into consideration the interaction and interdependency between the various turns and the epoxy between them as well as the effects that the coil assembly ends have on the interaction between turns. The proposed model (for half of a coil assembly) consists of four springs in parallel, where each spring represents the various turns. It is assumed that all the turns have the same length. Since they have the same cross sectional area and are made from the same material it can be assumed that they all have the same spring constant. For each spring (turn) the spring constant will be:

$$K = \frac{AE}{L} = K_1 = K_2 = K_3 = K_4$$

where:

A – cross sectional area of the coil - 4.0x1.0 inch²

E – modulus of elasticity - for copper - 17×10^6 psi

L – length of coil section [inch]

the spring deflection will be:

$$X = \delta = \alpha L \Delta T$$

where:

α – coefficient of thermal expansion - for copper - $9.8 \times 10^{-6} \frac{\text{in}}{\text{in} \times F^\circ}$

ΔT – temperature change

and thus the force will be:

$$F = KX = \frac{AE}{L} \times \alpha L \Delta T = AE\alpha\Delta T$$

As shown in Figure 3 b the two parallel springs ① and ② can be replaced with an equivalent new spring having a spring constant of :

$$K_{\psi} = K_1 + K_2 = 2K$$

the force associated with these springs is that of the inner spring, namely, in this case spring ①, and its value will be:

$$F_1 = AE\alpha\Delta T_1$$

and thus the deflection of the new equivalent spring will be:

$$\delta_{\psi} = \frac{F_1}{K_{\psi}} = \frac{\alpha AE\Delta T_1}{2K} = \frac{\alpha AE\Delta T_1 L}{2AE} = \frac{\alpha\Delta T_1 L}{2} = \frac{\delta_1}{2}$$

Namely, that due to the end effect, the total deflection of two turns when the inner one is trying to expand will amount to half the expansion of an independent inner turn.

Similarly the same method can be applied for springs ③ and ④ (see Figure 3 c) which will be replaced by an equivalent spring having a spring constant of:

$$K_{\psi} = K_3 + K_4 = 2K$$

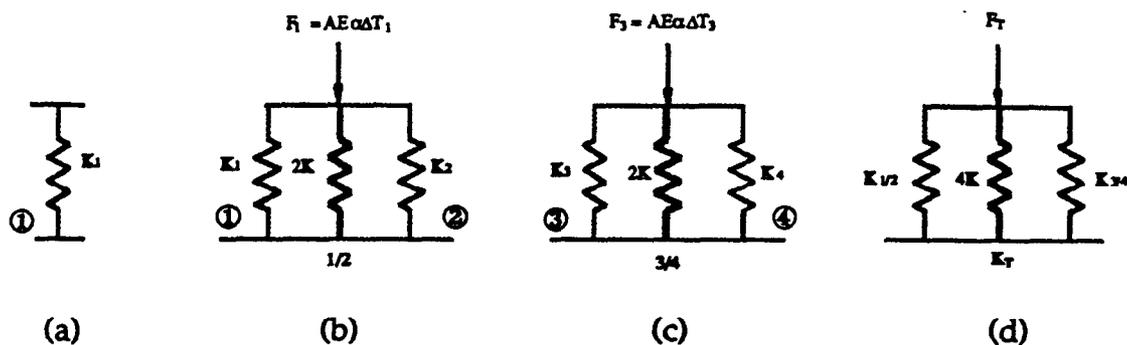


Figure 3: Spring Model Simulating End Coil Assembly.

and the associated force:

$$F_1 = AE\alpha\Delta T_1$$

The final model will consist of the two equivalent springs in parallel (see Figure 3 d) which again will be replaced by one equivalent spring having a spring constant of:

$$K_r = K \sqrt{r} + K \sqrt{r} = 4K$$

The associated forces acting on this spring will consist of forces F_1 and F_2 in addition to forces F_3 and F_4 which have not been accounted for earlier. Thus, the overall displacement of the whole system will be:

$$\delta_r = \frac{F_r}{4K}$$

where:

$$F_r = F_1 + F_2 + F_3 + F_4$$

thus:

$$\delta_r = \frac{\alpha A E L (\Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4)}{4 A E} = \frac{\alpha L}{4} (\Delta T_1 + \Delta T_2 + \Delta T_3 + \Delta T_4)$$

where:

$\Delta T_1; \Delta T_2; \Delta T_3; \Delta T_4$ - average temperature values calculated at mid-point locations of each turn (points # 2 ; 6 ; 10 ; 14) for half the coil assembly A, B, C, D, as shown in Figure 4.

thus:

$$\delta_r = \frac{\alpha L}{4} (\Delta T_2 + \Delta T_6 + \Delta T_{10} + \Delta T_{14})$$

Assuming the change in temperature is directly proportional to the length:

$$\Delta T_2 = \frac{\Delta T}{8}; \Delta T_6 = \frac{\Delta T}{8} \times 3; \Delta T_{10} = \frac{\Delta T}{8} \times 5; \Delta T_{14} = \frac{\Delta T}{8} \times 7$$

where:

ΔT - overall temperature differential of the coil assembly [C°]

Calculate the overall temperature differential - ΔT :

$$\Delta T = \frac{P_m}{\dot{m} \times c_p}$$

where:

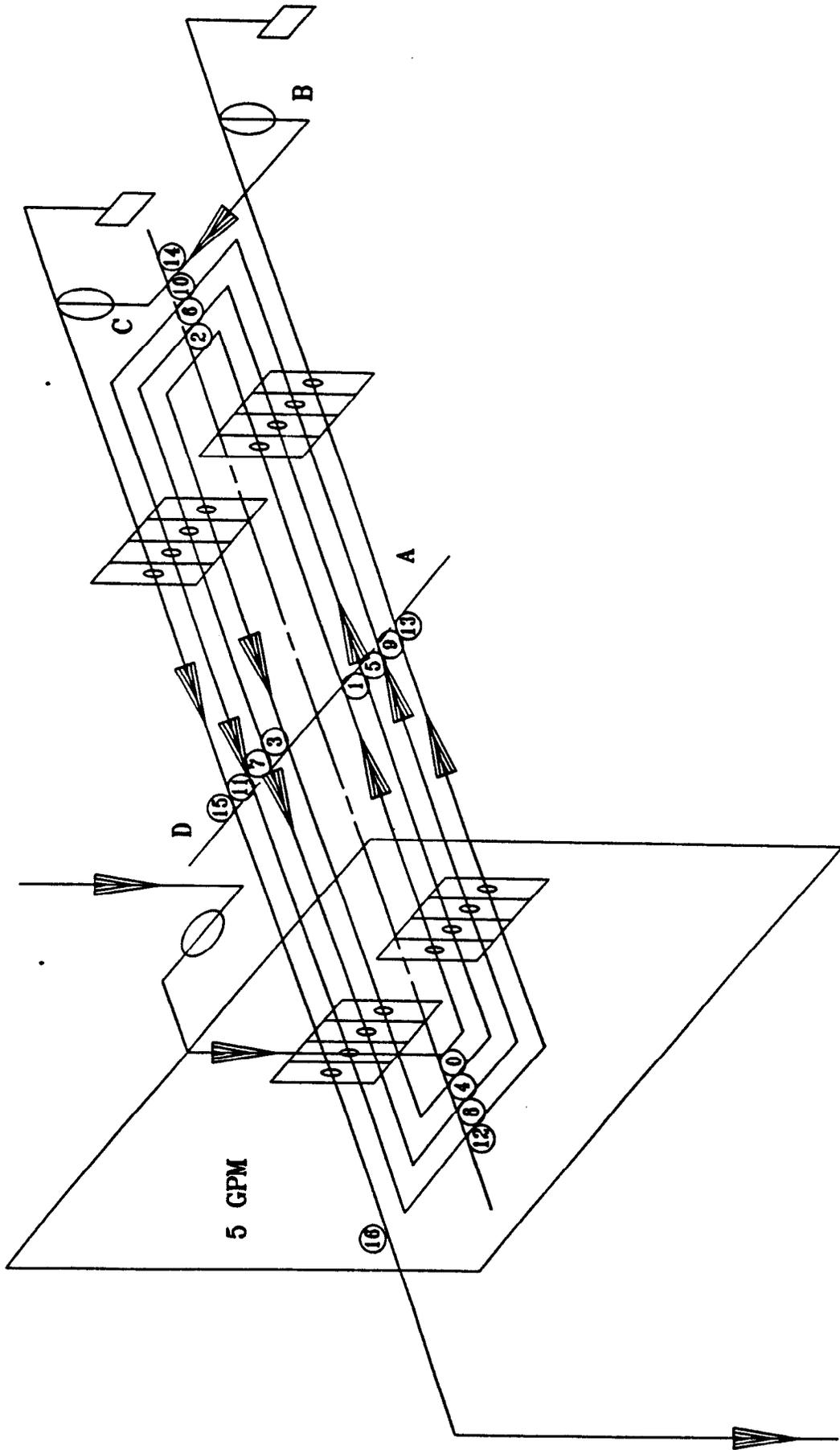


Figure 4: Average Temperature Location at the Half Coil Assembly

P_m – average power, produced by the coil, to be dissipated into the water. [kW]

\dot{m} – mass flow rate through the coil [kg/sec]

c_p – specific heat of water [4.2 kJ/kg C° at 300°K]

when calculating ΔT for water :

$$\Delta T = \frac{P_m}{\dot{q} \times 0.0631 \times 4.2}$$

where:

\dot{q} – volumetric flow rate [GPM]

thus:

$$\Delta T = \frac{P_m \times 3.8}{\dot{q}}$$

$$P_m = I^2 R$$

where:

R – the total magnet resistance [$7.4 \times 10^{-4} \Omega$]

$1/2R$ – resistance of a single coil [$3.7 \times 10^{-4} \Omega$]

for $I = 5,000 \text{ Amps}$:

$$P_m = 5,000^2 \times 3.7 \times 10^{-4} = 9.25 \text{ kW}$$

and:

$$\Delta T = \frac{9.25 \times 3.8}{4.0} = 8.8^\circ \text{C} = 15.8^\circ \text{F}$$

for $I = 9,500 \text{ Amps}$:

$$P_m = 9,500^2 \times 3.7 \times 10^{-4} = 33.4 \text{ kW}$$

and:

$$\Delta T = \frac{33.4 \times 3.8}{4.0} = 31.7^\circ \text{C} = 57.1^\circ \text{F}$$

The values for the average temperatures $\Delta T_1; \Delta T_2; \Delta T_{12}; \Delta T_{12}$ will then be:
for $I = 5,000 \text{ Amps}$:

$$\Delta T_1 = 2.0; \Delta T_2 = 5.9; \Delta T_{12} = 9.9; \Delta T_{12} = 13.9$$

for $I = 9,500 \text{ Amps}$:

$$\Delta T_1 = 7.2; \Delta T_2 = 21.5; \Delta T_3 = 35.8; \Delta T_4 = 50.0$$

These values of ΔT can now be used in the expression for the coil assembly total expansion developed earlier using the spring model (see page 4):

for $I = 5,000 \text{ Amps}$:

$$\begin{aligned} \delta_r &= \frac{9.8 \times 10^{-6} \times 125}{4} (2.0 + 5.9 + 9.9 + 13.9) \\ &= 3.063 \times 10^{-4} \times 31.7 = 9.71 \times 10^{-3} \text{ in.} \end{aligned}$$

for $I = 9,500 \text{ Amps}$:

$$\begin{aligned} \delta_r &= \frac{9.8 \times 10^{-6} \times 125}{4} (7.16 + 21.5 + 35.8 + 50.0) \\ &= 3.063 \times 10^{-4} \times 114.5 = .035 \text{ in.} \end{aligned}$$

Now, that we have the overall deflection of the coil assembly (at the end), it is possible to estimate the load (in tension or compression) acting on the insulation between the turns at the end of the coil assembly.

The load exerted on each bar (turn) will be equal to the difference between the force which results from the thermal expansion of an individual turn and the force resulting from the total deflection of the whole assembly, namely:

$$\begin{aligned} F_{(n)} &= K(\delta_r - \delta_n) = \frac{AE}{L} \times \frac{\alpha L}{4} (\sum \Delta T - 4\Delta T_{(n)}) \\ &= \frac{AE\alpha}{4} (\sum \Delta T - 4\Delta T_{(n)}) \end{aligned}$$

The load on the insulation is a product of the force balance of two adjacent bars acting on the insulation between them, namely:

$$F_{ins.(n)} = F_{(n+1)} - F_{(n)}$$

The magnitude of the various forces acting on the bars as well as those acting on the insulation between the bars is summarized in Table 1. The force on the insulation is actually an average of the differential forces between two adjacent bars. Those differential forces are not equal in each case due to round

off errors. Note that regardless of the water direction, the two turns closer to the water inlet into the coil are in tension while the two turns closer to the water exit are in compression. However, the insulation between those turns is in tension when the water exits the coil assembly at the outer turn and in compression when the water exit is at the inner turn.

Table 1: Forces on Bar & insulation @ coil end

Amps DC	Bar # (hot to cold)	Force on Bar (Lbs.)	Ave. Force on Insu. (Lbs.)
5,000	1	-3,982	2,647
5,000	2	-1,316	
5,000	3	1,349	
5,000	4	3,958	
9,500	1	-14,251	9,516
9,500	2	-4,788	
9,500	3	4,741	
9,500	4	14,298	

Given the above loads, it is possible to calculate the deformation in the insulation.

The deformation can be calculated, using Hooke's law as:

$$\delta = \frac{F_{max} \times l}{E \times A}$$

where:

l – insulation thickness (gap between two conductors) - .125 in.

E – modulus of elasticity for epoxy in tension and compression.

using Material Development Lab test data for irradiated epoxy

$E = 150,000 \text{ psi}$ (see attachment 4)

A – cross-sectional area of the epoxy along a 1.0 inch span. ($1.0 \times 4.0 \text{ in.}^2$)

Note that this is the projected area of the coil cross-section.

Calculate the deformation of the insulation over a 1.0 inch span (since that has been all along the area used for spring constant $\frac{AE}{L}$):

for $I = 5,000$ Amps:

$$\delta_{max} = \frac{2,647 \times .125}{1.5 \times 10^5 \times 1.0 \times 4.0} = 5.5 \times 10^{-4} \text{ in.}$$

for I = 9,500 Amps:

$$\delta_m = \frac{9,516 \times 125}{1.5 \times 10^5 \times 1.0 \times 4.0} = 1.98 \times 10^{-3} \text{ in.}$$

Calculate the stresses (tension/compression) in the insulation over a 1.0 inch span:

for I = 5,000 Amps:

$$\sigma_{\text{tension}} = \frac{F_{\text{max}}}{A} = \frac{2,647}{1.0 \times 4.0} = 662.0 \text{ psi}$$

for I = 9,500 Amps:

$$\sigma_{\text{tension}} = \frac{F_{\text{max}}}{A} = \frac{9,516}{1.0 \times 4.0} = 2,379.0 \text{ psi}$$

This value is lower than the lowest tensile strength value measured at Material Development Lab for irradiated epoxy test samples of approximately 6,000 psi. (see attachment 4)

The shear stress can be obtained based on the tension/compression deformation calculated earlier for the 1.0 inch long insulation area (1.0x4.0 *inch*²). The shearing strain for small angular deformation γ is proportional to the shearing stress for values within the elastic range and Hooke's law for shear becomes:

$$\sigma_s = \gamma G$$

where:

γ – angular deformation [radians]

G – modulus of elasticity in shear [psi]

The mathematical relationship between the elastic constants E and G is given by :

$$G = \frac{E}{2(1 + \mu)}$$

where:

μ – Poisson's ratio

for Epoxy an average value is .34²

$$G = \frac{150,000}{2(1 + .34)} = 55,970 \approx 56,000 \text{ psi}$$

The angular deformation γ (see Figure 5) will be:

$$\tan \gamma = \frac{\delta_{\max}}{l}$$

where:

l – insulation thickness (gap between two conductors) - .125 in.
for $I = 5,000$ Amps:

$$\tan \gamma = \frac{5.5 \times 10^{-4}}{.125} = 4.4 \times 10^{-3}$$

$$\gamma = .252^\circ = 4.4 \times 10^{-3} \text{ rad.}$$

for $I = 9,500$ Amps:

$$\tan \gamma = \frac{1.98 \times 10^{-3}}{.125} = 1.58 \times 10^{-2}$$

$$\gamma = .91^\circ = 1.58 \times 10^{-2} \text{ rad.}$$

The maximum shear stress in the insulation near the coil ends (see Figure 5) will be:

for $I = 5,000$ Amps:

$$\sigma_s = 4.4 \times 10^{-3} \times 56,000 = 246.4 \text{ psi}$$

for $I = 9,500$ Amps:

$$\sigma_s = 1.58 \times 10^{-2} \times 56,000 = 884.8 \text{ psi}$$

In the case where the hot water exits the coil assembly at the center, we have the phenomenon in which the inner coil is trying to expand while the adjacent turn is holding it back thus putting it in compression. Unlike the other turns, the inner turn does not have supports on both sides, a fact which could cause it to be in a buckling mode.

The critical buckling force for the inner turn can be calculated using Euler formula for columns. The Euler formula for a column with one end fixed and one end free is:

$$P_{\alpha} = \frac{\pi^2 \times E \times I}{4l^2}$$

where:

I – moment of inertia of the coil cross section (1.0x4.0 inch)

$$I = \frac{4 \times 1^3}{12} = .33in^4$$

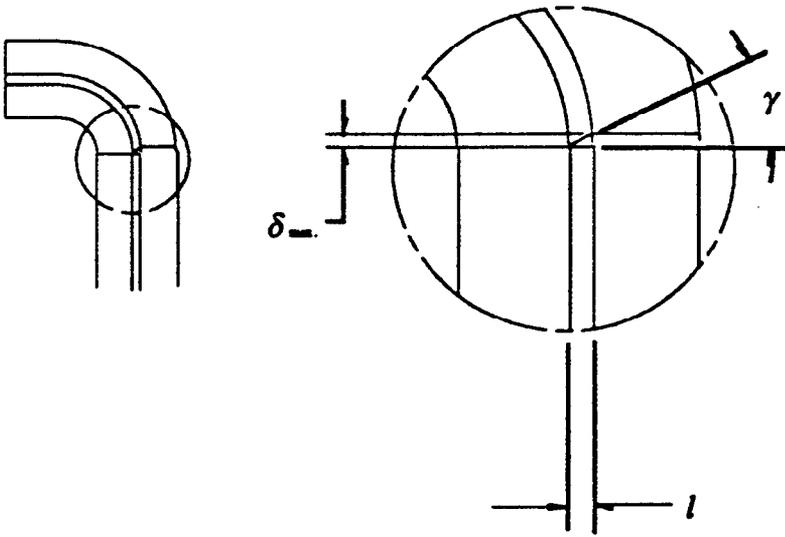


Figure 5: Shear Area at the Coil Assembly End

thus:

$$P_{ca} = \frac{\pi^2 \times 17 \times 10^6 \times .33}{4 \times 125^2} = 885.9lbs$$

This critical load is substantially smaller than the expected compressive loads (see table above) and can be a concern if the insulation next to it becomes delaminated. Apparently, the epoxy as well as the insulating fiberglass tapes are causing the whole coil assembly to act as one rather than individual coil

turns. This scenario explains the coil assembly's apparent stability in spite of the calculated instability shown above.

Calculate the critical load for four turns working in unison:

$$I = \frac{4 \times 4^3}{12} = 21.33in^4$$

and:

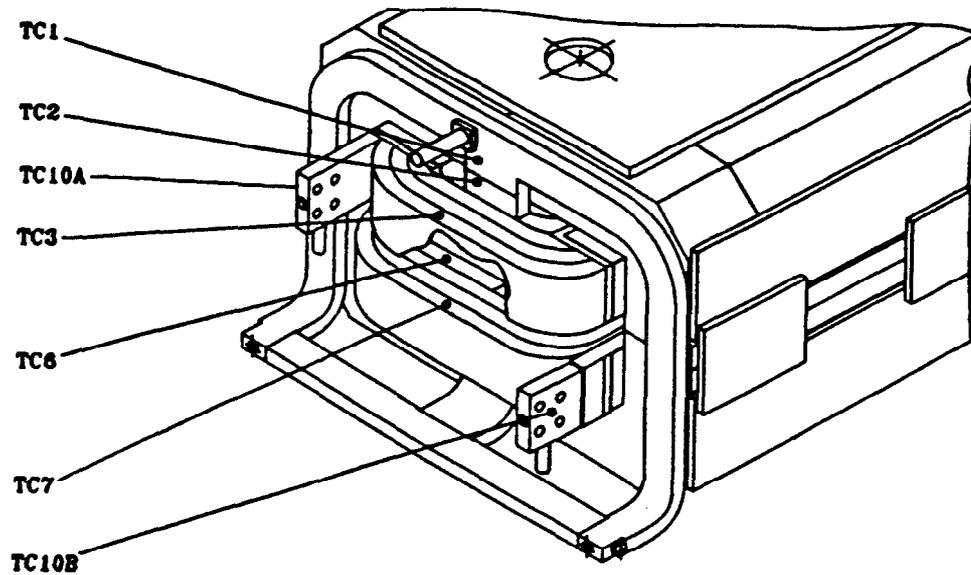
$$P_{\alpha} = \frac{\pi^2 \times 17 \times 10^6 \times 21.33}{4 \times 125^2} = 57,261lbs$$

This critical load is much larger than the maximum expected compressive load and thus, if the assumption could be made that the assembly is working as one unit, buckling would not be of concern.

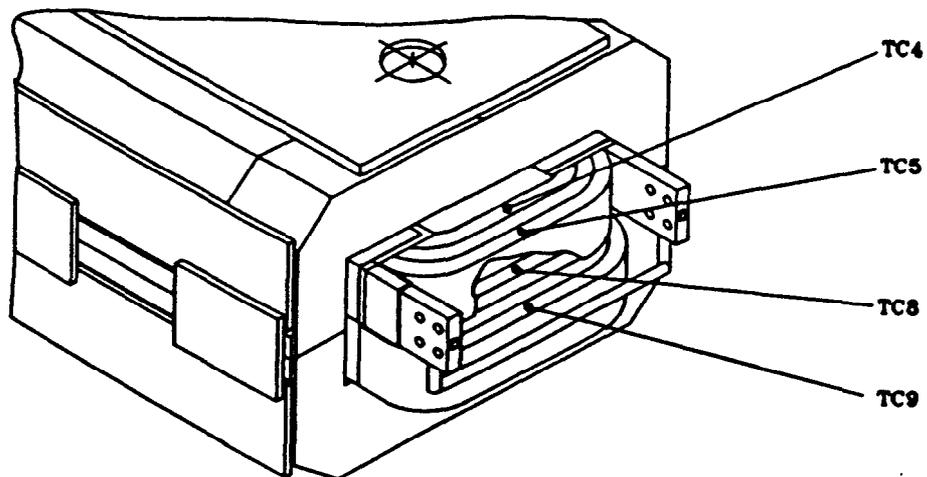
Test Procedure and Setup

Magnet IDB003 was tested on stand C at MTF. The following data was recorded throughout the test:

- Water supply/return temperature going into or out of the manifold which is common to both the upper and lower coil assemblies. (TC1 in Figure 6)
- Water return/supply temperatures for both upper and lower coil assemblies. (TC10A&B in Figure 6)
- Coil temperatures at the inner and outer turns at each coil assembly (upper and lower), total of eight locations per magnet. (TC2 through TC9 in Figure 6)
- Thermal expansion of the coil assemblies measured at the inner and outer turns of each coil assembly (upper and lower), total of eight locations per magnet. (see Figure 7)
- The time it took for coil temperatures to stabilize when the magnet was powered-up and similarly when power was turned off.
- Flow rate to each coil assembly taken just before temperatures were recorded.
- Pressure differential over the entire magnet was measured and recorded as well just before temperatures were recorded.

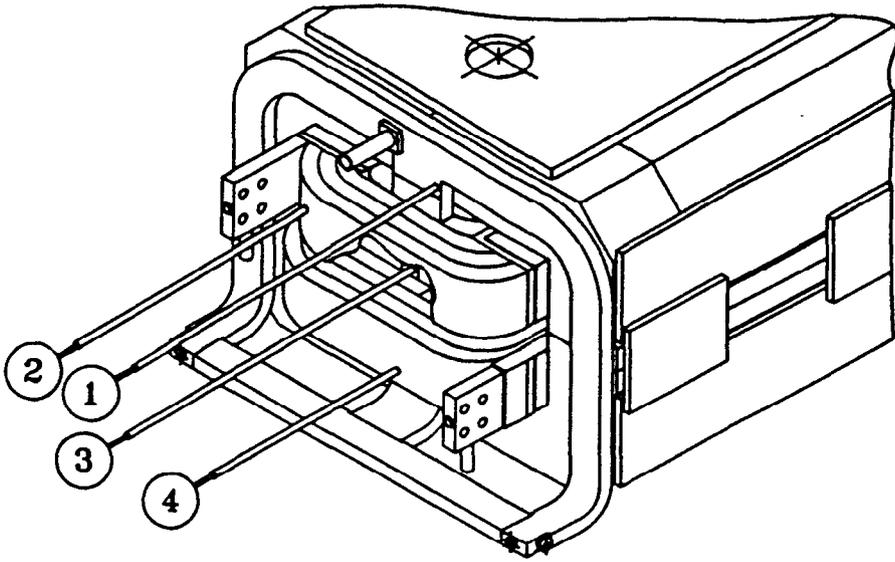


LEAD END

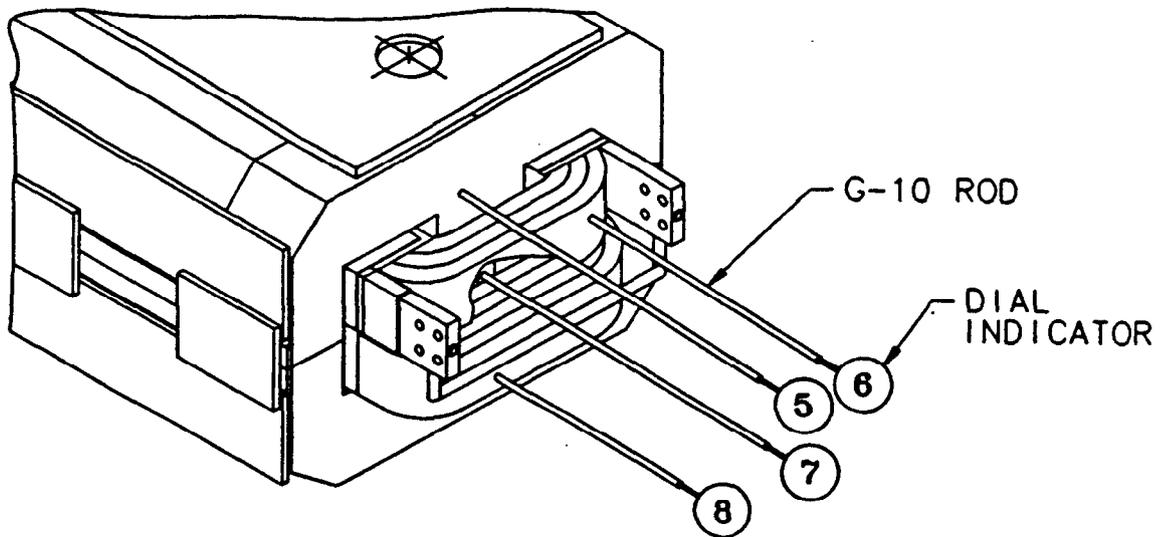


RETURN END

Figure 6: Thermocouple Setup



LEAD END



RETURN END

Figure 7: Dial Indicators Setup

The test consists of two parts. In the first part of the test, the cold water enters the coil assembly through the manifold at the lead end and into the inner turn, while the exit port is at the outer turn. (see Figure 1) In the second part of the test the water hookups are reversed, the cold water enters the coil assembly at the outer turn and exits at the coil center. (see Figure 2) Each part of the test is comprised of three different cycles, one for each power level ($\approx 5,000, 7,000$ and $9,500$ Amps DC). Each cycle is made of a power on segment and a power off segment. A segment duration extends between the time the magnet was powered on or turned off, to the time temperatures stabilized. Thus;

1 Test = 2 Parts;

1 Part = 3 cycles = 6 segments

The magnet was instrumented with thermocouples which in most cases were bonded directly to the coil insulation on top of the coil assembly on the narrow side of the copper conductor (see Figure 6). The thermocouples dedicated to measuring the water supply and return temperatures were bonded directly on the coil's bare copper. All thermocouples (total of eleven channels), were connected to an Omega channel recorder unit. Temperatures of all eleven channels were recorded at various time intervals (ranging from 3 to 8 minutes) during a test segment.

Measurements of the coil assembly thermal expansion were taken by utilizing dial indicators, which picked-up the movements of both the inner and the outer turns of the coil assembly. To eliminate magnetic interference, the dial indicators were placed away from the coil assembly, while the motion of the coil assembly was transferred to the dial indicators via G-10 rods which were in contact with the coil assembly surfaces (see Figure 7). The reading of the dial indicators took place at the end of each test segment. At the end of each power off segment, all dial indicators were set back to zero.

Discussion of Results

The performance/thermal test results for the low and high power levels ($\approx 5,000$ and $9,500$ Amps DC) were compiled in Table 2. An analysis of the test results indicated the following:

Temperature: The calculated temperature rise for power input of 10.6 kW in a dipole magnet and flow rate of 5.0 GPM was 8.0 C° (per John Satti - see Attachment #3). The calculated temperature rise for 5,000 Amps DC and a flow rate of 4.0 GPM was 8.8 C° (see page 5). These calculated values are not too far off from the average measured temperature rise of 8.2 C° (see Table 3). The difference can be attributed to the fact that while some of the heat generated in the coil apparently was removed by conduction via the steel core

Table 2: Performance/Thermal Test Results-MIR Dipole (20.0ft)

Power [Amps DC]	Power Status	Measurm. location	Max. ΔT [C°]	Max. δ [mils]	Time to ΔT [min]	Flow [GPM]	ΔP [psi]	LCW Inlet
5,009	ON	out/upp/L	9.0	11.0	18.0	4.0	33.9	center
	OFF	out/upp/L	8.9	9.0	7.0	4.0	33.9	center
9,507	ON	out/upp/L	28.4	48.0	20.0	4.0	33.9	center
	OFF	out/upp/L	28.1	48.0	17.0	4.0	33.9	center
5,025	ON	in/upp/L	7.7		15.0	4.0	33.9	out coil
		out/upp/L		12.0				
	OFF	in/upp/L	7.0	10.0	8.0	4.0	33.9	out coil
9,514	ON	in/upp/L	27.8	41.0	19.0	4.0	33.9	out coil
	OFF	in/upp/L	27.7	41.0	15.0	4.0	33.9	out coil

Table 3: Comparison of calculated and measured values

(based on $\dot{m} = 4.0$ GPM)

Property	Calculated Value		Measured Value [Ave.]	
	5000 [Amps DC]	9500 [Amps DC]	5000 [Amps DC]	9500 [Amps DC]
ΔT [C°]	8.8	31.7	8.2	28.0
δ [inch]	9.7×10^{-3}	.035	9.4×10^{-3}	.040

and some by convection into the air surrounding the coil assembly ends, the calculated value of 8.8 C° assumed that all of the heat was transferred into the water. Another contributing factor may have been the fact that the thermocouples were mounted on the insulation. The highest temperature rise of 28.4 C° was recorded when the magnet was powered to approximately 9,500 Amps DC. This value would have been somewhat lower (≈25.0 C°) in the case of 5.0 GPM which is the expected flow rate in the tunnel. Overall the measured results values were lower than the calculated values by less than 15%.

Thermal expansion: The thermal expansion was calculated using the parallel spring model (see page 2). The assumptions were that all the turns have the same length and that all the materials involved were acting within their elastic limits. Some other assumptions were that the coil turns were acting as individual units (as oppose to one continuous coil) activated by a single load which resulted from the thermal expansion. It was also assumed that each of the turns (or actually half a turn) had a constant temperature differential associated with it ($\Delta T_1, \Delta T_2$, etc.). The calculated and measured results compared quite well (less than 15% difference) as shown in Table 3. This difference can be attributed to the assumptions made while using the model as well as to the accuracy of the measurements taken.

Stresses: The performance/thermal test did not measure stresses. In calculating the stresses of the insulation it was assumed that the epoxy material was following Hooke's law and that the epoxy was within its elastic limits. The highest calculated value of the tension/compression stress, calculated for 9,500 Amps DC, (see page 8) was less than half the lowest tensile strength value measured for irradiated epoxy samples at MDL. (see attachment 4) In calculating the shear stresses it was assumed that its maximum level will develop at an area farthest from the magnet mid-point (at coil end), on the straight portion of the coil turn (see Figure 5). While the epoxy between the cross turns (the portion of the coil which is perpendicular to the magnet center line) is in tension or compression, the epoxy along the coil length is in shear. Here as well, the angular deformation was derived from the compression (or tension) of 1.0 X 4.0 *inch*² projected area of epoxy at the coil end portion. Though being somewhat conservative, the assumptions used seem to follow a logical approach. The maximum calculated shear stress is as low as the lowest value of shear strength measured at MDL during an overlap shear test, using Fermi's curing schedule on a 1/4 inch test sample. This calculated value however, is about 30% lower than the lowest average value obtained during the overlap shear test. (see attachment 5)

Buckling load: Although the calculated critical buckling load for a single turn is lower than the highest calculated compressive load, it is assumed that all four turns act as an assembly thus, preventing the inner coil from buckling. Calculation of the critical buckling load for a bar having a cross-sectional area equivalent to four turns yielded a critical buckling load which was far greater

than any expected compressive load. Hence, assuming the epoxy is holding the turns together, buckling should not be a concern.

Pressure differential: The pressure differential per coil assembly at 5.0 GPM, was calculated both by hand and by using computer programs. The hand calculated pressure differential of 42.0 psi (see Appendix A) is within $\pm 10\%$ of the 38.0 psi obtained by John Satti when he used his computer program (see attachment 3) or the 45.0 psi obtained by me through another computer program³. The calculated value for ΔP_{mm} at 4.0 GPM (using the same relationship shown on page 19 Appendix A) is 15% lower than the value measured at MTF. This difference can be attributed to the fact that MTF is not geared to measure the pressure differential across a magnet as well as to the fact that the calculations did not take into account pressure losses due to turns, elbows, restrictors etc.

Observation and Concluding remarks

Most of the test objectives were accomplished:

- a. No problems were evidenced during the magnet powering to 9,500 Amps DC (which is about twice the expected operating current level, or 3.6 times the operating power level)
- b. Calculations and test results for water/coil temperatures and coil thermal expansion were compared for power levels of 5,000 and 9,500 Amps DC (see Table 3 and discussion page 12 - 14).
- c. There was no apparent difference in the magnet performance when cold water entered the coil assembly at the center and exited at the outer turn to that when cold water entered at the outer turn and exited at the coil center.
- d. The information to be used for a possible second phase thermal cycle life test was obtained. Specifically, the so called time constant or the cycle time it took for the coil temperatures to stabilize at the end of power on/power off test segments. However, this subject needs more analysis.

Overall, results from the performance/thermal test were somewhat encouraging. No apparent problem was observed during the test. Comparatively speaking, the temperature rise results as well as the thermal expansion test results came close to the calculated values. However, in order to support and understand the test results, a finite element analysis model of the coil assembly should be produced. The objective being to reach an agreement between the test results, the mathematical and analytical results. A first step can be a simplified finite element analysis model representing two adjacent coils and the insulation between them. The pattern of stresses in the insulation when subjected to relative motion between the bars as a result of ΔT , (thermal expansion) can be compared to that established in the

mathematical model. Ultimately, however a full finite element model of the coil (or 1/4 of it) should be established which could then be expanded to include fatigue analysis.

The long term reliability of the insulation should be further studied. The need, feasibility and extent of the thermal cycle life test should be looked into. As the calculated stress values proved to be quite significant I feel that the insulation fatigue issues should be recognized. The higher the stress, the fewer will be the cycles before failure can be expected. I strongly recommend that at least one full size model be subjected to a life test, although such a test would most likely be a lengthy one. The main concern in a long term operation of the magnet in the tunnel is that of the possible cycle fatigue resulting from power on and off situations. The long term cycle life test is intended to simulate that scenario. The high and low cycle fatigue in organic composites with glass fibers should be studied, or more specifically, the failure modes of insulation in magnets or similar electrical systems.

Another open issue would be the determination of the method for testing the integrity of the insulation after the completion of the test. Testing methods like the AC Corona testing or the Ultrasound test should be studied and possibly be employed either on-site or at an outside facility.

Neither the calculations nor the performance/thermal test have demonstrated a significant difference in the magnet performance between the two LCW hookup schemes. The insulation is under tension or compression depending on the scheme used. As to shear in the insulation, according to my model, there should not be a difference. However, in the scheme in which the water exits in the coil center, there is the possibility of buckling of the inner turn. This area should be further investigated, since depending on the strength of the bond between the copper and the epoxy that coil could possibly buckle in the direction of the magnet center line. (see buckling calculations on page 9)

Recently, I have been working with MDL on developing tests and analyzing data already generated of epoxy and copper coated epoxy samples which were tested in shear, tension, compression and flexure. Some test specimens were also irradiated prior to being tested. Other tests involve column buckling of single copper bars as well as two bonded bar assembly using epoxy and fiberglass tape, to determine the strength of the assembly. This data can be used to support the analysis.

In conclusion, this test and the analysis done thus far have given us a better understanding of the state of stresses in the coil insulation. However, more work is required in order to have the means to qualify the magnet design and long term performance.

References

1. C. F. Lewis and M. W. Hunt "Materials Engineering - Materials Selector 1991, Penton Publishing, 1990
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Fermilab

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November 23, 1993

To: Arie Lipski 
From: Nelson Chester
Subject: Thermal Test for Fermi Main Injector Dipole Magnet

Confirming our conversation today, I would like to have you develop a Test Plan for the Main Injector Dipole Coil Assemblies that will evaluate the effects of the mechanical stresses placed on the coil assembly as a result of expected thermal variations.

I would like you to begin this project after Thanksgiving and have a first draft of a Test Plan proposal ready by the end of December. The following people should be able to give you input: Dave Harding, Phil Martin, Bruce Brown, Jim Kerby, and John Satti, as well as myself.

It would be good if you can join in on the Main Injector Magnet Project Group meetings that are held every Monday at 1:30 PM in the Headquarters Conference Room to give a status update and have an audience to hear questions you may have.

The Main Injector magnets are produced in two lengths: 160" and 240". Since the thermal effects would appear to be more severe in the longer magnet I would propose you focus your thoughts on that length magnet. Jack McBride can help provide you with drawing numbers for various parts of the subject magnets as you need them.

One of the possibilities for a test that may be tried is to electrically heat the coil(s) and then pass coolant through the coil passages in an alternating fashion in such a fashion as to thermal cycle the assembly. This possibility has yet to be worked through in its entirety and developed. It may or may not be appropriate but it can be considered. Once you come back from vacation after Thanksgiving, lets plan to get together so that I can help bring you up to speed on the magnet design.

PC: T. Nicol
G. Pewitt
P. Martin
D. Harding
B. Brown
Jim Kerby



Fermilab

Main Injector Department
Mail Station 323, X4547

February 7, 1994

To: Gale Pewitt

From: Phil Martin

Subject: Thermal Test of Main Injector Dipole

Following up on our telephone conversation of Friday, February 4, this memo is intended to document what it is we agreed we would like done.

1. Measurements should be made of the some of the temperature-related properties of an MI dipole. These include thermal expansion as measured with dial indicators, and inlet and outlet water temperatures (or conductor temperatures) as measured with thermocouples. The measurements should be done at several currents, e.g. 5000 A, 7000 A and 9500 A, and with water connections in two configurations, in which the outer turn of the magnet is either the coolest or the hottest. The measurements may be done by recording data manually, but the measurements need to document the response vs. time. Each measurement should be repeated at least once in order to assist in assessing the measurement errors. The measurements should be done on a 6-m dipole when one is mounted on the test stand at MTF; however, the relative priority of this is not so high as to require that a 6-m dipole be mounted immediately. Meanwhile, measurements on a 4-m dipole would be definitely worthwhile.

2. These measurements should be accompanied by (ideally, preceded by) calculations of the same quantities being measured. In addition, calculations of the expected stresses in the epoxy should also be done.

3. Once this first series of measurements and calculations are done, we will discuss what, if any, further tests, especially extensive thermal cycling, should be done, and if so, where these should be done, with which magnet(s), and what the full scope of the tests include, such as magnet dissection, etc.

4. The preliminary measurements should be completed no later than March 1, so that, prior to the DOE ER Semiannual Review, we have time to analyze the results and formulate our plans for further testing.

cc:	S. Holmes	D. Bogert	N. Chester
	A. Lipski	D. Harding	B. Brown
	P. Mazur	T. Nicol	J. Kerby

John Sztu
02-22-1994

MIR DIPOLE 1/2 COIL

DIAMETER = .5 in LENGTH = 180 ft POWER = 10.6 kW
DESIRED TEMPERATURE CHANGE = 8 °C
AVAILABLE PRESSURE DROP = 38 psi

THE INITIAL FLOW RATE = 5.0 GPM

THE INITIAL REYNOLDS NUMBER = 52534

THE INITIAL FRICTION FACTOR = 0.0199

THE INITIAL PRESSURE DROP = 38.9 psi

THE INITIAL TEMPERATURE CHANGE = 8 °C OR 14.4 °F

THE REQUIRED FLOW RATE
FOR THE AVAILABLE PRESSURE DROP = 5.0 GPM

THE REQUIRED REYNOLDS NUMBER = 51739

THE REQUIRED FRICTION FACTOR = 0.0206

THE ACTUAL PRESSURE DROP = 37.9 psi

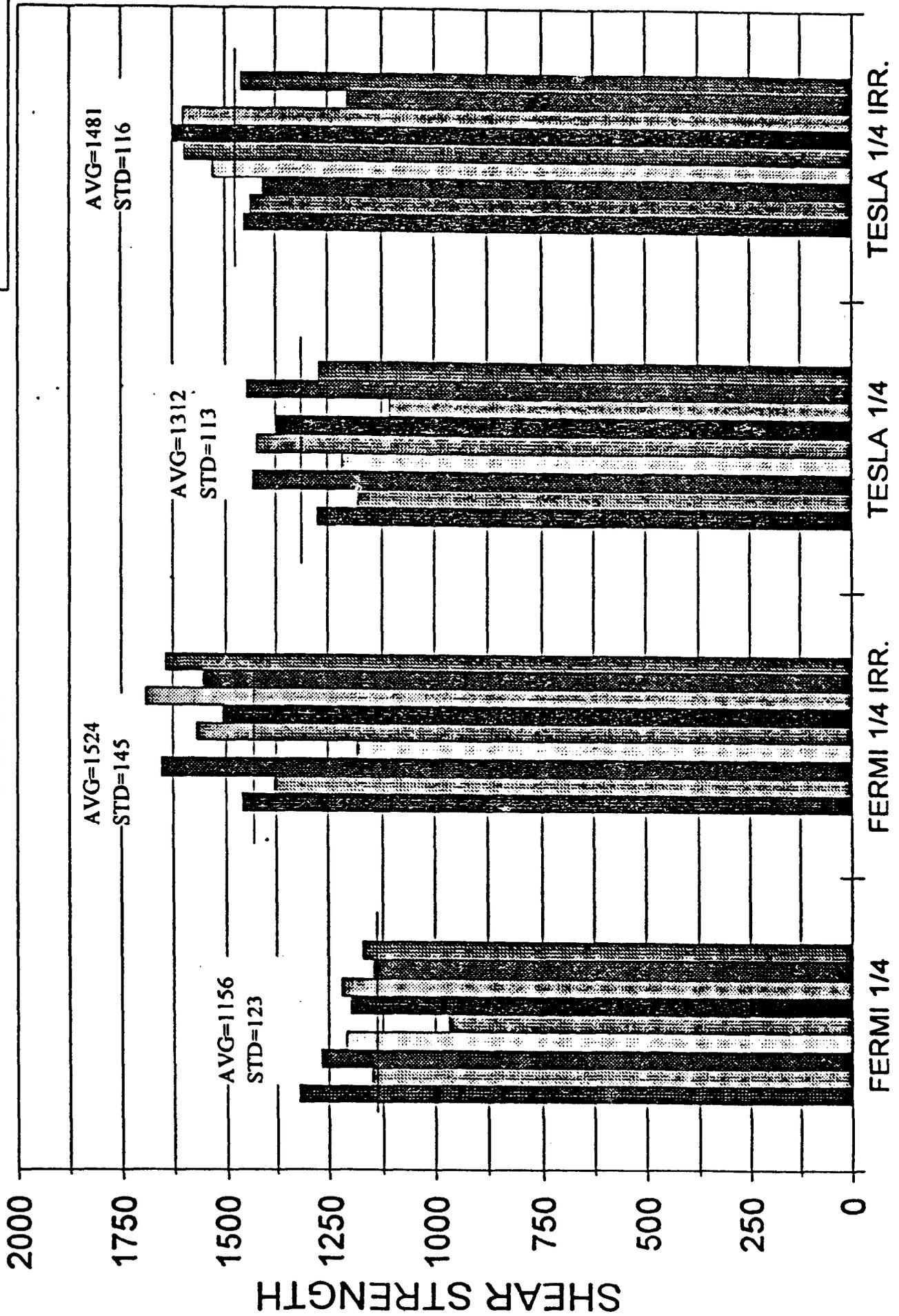
THE TEMPERATURE CHANGE
FOR THE REQUIRED FLOW RATE = 8.1 °C OR 14.6 °F

SOLUTION OF THIS CALCULATION REQUIRED 13 ITERATIONS

OVERLAP. SHEAR

6-30-94

Drawn and Compiled by:
B. Sizemore



APPENDIX A

Checking some of the values used by John Satti in his calculations:

Given:

$$\Delta P_{\text{tunnel}} = 100 \text{ psi}$$

$$L = 180 \text{ ft}$$

$$V = \sqrt{\frac{144 \times D \times 2g \times \Delta P}{\rho \times f \times L}}$$

where:

L – length of coil [ft]

D – diameter of the water passage in the coil - [ft] – .50in = .042ft

ρ – density lb/ft³ - for water @ 70F° $\rho = 62.3 \text{ lb/ft}^3$

f – friction factor derived from the Moody diagram

$f = .019$ (per John Satti)

thus:

$$V = \sqrt{\frac{144 \times .042 \times 2 \times 32.2 \times 100}{62.3 \times .019 \times 180}} = 13.52 \frac{\text{ft}}{\text{sec}}$$

$$q = V \times A$$

where:

q – volumetric flow rate [ft³/sec]

A – flow area [ft²]

$$A = \frac{\pi D^2}{4} = \frac{\pi \times .042^2}{4} = .0014 \text{ ft}^2$$

$$q = 13.52 \times .0014 = .019 \frac{\text{ft}^3}{\text{sec}} = 8.5 \text{ GPM}$$

Next, the pressure drop for the magnet at $q = 5.0 \text{ GPM} = .011 \text{ ft}^3/\text{sec}$ can be checked, since that is the expected flow for the MIR dipole in the tunnel.

$$V = \frac{.011}{.0014} = 7.96 \frac{\text{ft}}{\text{sec}}$$

$$R_{e,s} = \frac{\rho V D}{\mu}$$

where:

μ – absolute viscosity [lb/(ft)(sec)]

for water @ 70 F° $\mu = 6.72 \times 10^{-4}$ lb/(ft)(sec)

$$R_{e,s} = \frac{62.3 \times 7.96 \times .042}{6.72 \times 10^{-4}} = 31,000 \geq 4,000$$

The pressure drop is:

$$\Delta P = \frac{\rho \times f \times L \times V^2}{144 \times D \times 2g}$$

where:

f – derived from the Moody diagram - .023 for smooth pipe.

thus:

$$\Delta P = \frac{62.3 \times .023 \times 180 \times 7.96^2}{144 \times .042 \times 2 \times 32.2} = 42 \text{ psi}$$

It was assumed that after adding to the above pressure drop additional losses due to manifolding and elbows that the total pressure drop will be ≈ 50 psi.

The expected flow during the test at MTF which will simulate the working conditions at the tunnel was calculated as follow:

$$\frac{\Delta P_r}{\Delta P_{MTF}} = \left(\frac{q_r}{q_{MTF}} \right)^2$$

where:

ΔP_r and q_r – pressure drop and flow at the tunnel respectively.

ΔP_{MTF} and q_{MTF} – pressure drop and flow at MTF respectively .

$$q_{MTF} = \left(\frac{\Delta P_{MTF}}{\Delta P_r} \right)^{\frac{1}{2}} \times q_r$$

thus:

$$q_{MTF} = \left(\frac{60}{50} \right)^{\frac{1}{2}} \times 5.0 = 5.5 \text{ GPM}$$

As it turned out, due to system limitation at MTF, the maximum flow rate which could be produced during the test was only 4.0 GPM.

APPENDIX B

MIR 20.2 ft. dipole #IDB003 performance/thermal test data

Part A: LCW H₂O into center of coil assembly (using two return lines.)

Room temp → 5000 Amps:

Flow rate ΔQ was balanced @ 4.0 GPM/coil
 ΔP = 110/24 (stand supply vs. return)

Time	ΔP	ΔQ _u	ΔQ _l	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
15:00	110/24	4.0	4.0	7.8	8.1	9.6	9.6	9.5	9.5	9.2	8.0	8.3	9.9	10.5
15:03 Power was turned on to 5009 Amps														
15:10	110/24	4.0	4.0	8.3	10.9	13.2	11.1	13.4	11.1	12.6	9.6	12.8	14.7	15.0
15:16	110/24	4.0	4.0	8.9	12.4	15.3	12.0	15.1	12.2	13.7	10.2	13.7	16.8	16.1
15:21	112/26	4.0	4.0	9.2	12.5	15.8	12.1	15.1	12.3	14.1	10.6	14.0	17.2	16.3
15:26	112/26	4.0	4.0	9.4	12.4	15.8	12.2	15.3	12.3	14.2	10.8	14.7	17.3	16.3
15:30	112/26	4.0	4.0	9.5	12.4	15.9	12.3	15.1	12.3	14.3	10.9	14.7	17.7	16.3

Dial Indicator Readings:

#1 0.008	#5 .009
#2 0.011	#6 .009
#3 .008	#7 .009
#4 .00925	#8 .007

Time	ΔP	ΔQ _u	ΔQ _l	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
15:38 power was turned off														
15:41	110/24	4.0	4.0	9.8	11.6	14.9	11.5	14.0	11.6	12.6	9.8	13.0	15.2	14.2
15:45	110/24	4.0	4.0	9.6	10.0	13.0	10.7	12.1	10.4	10.5	9.1	10.4	12.5	12.4
15:59	110/24	4.0	4.0	8.6	8.8	11.2	10.8	10.5	9.7	9.7	8.7	9.8	11.1	11.6

Dial Indicator Readings:

#1 .002	#5 .001
#2 .003	#6 .001
#3 .000	#7 .000
#4 .001	#8 .000

Dial indicators were set back to zero.

Time	ΔP	ΔQ _u	ΔQ _l	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
16:16 Power was turned on to 7048 Amps														
	110/25	4.0	4.0	8.1	4.2	10.6	10.4	10.6	10.5	11.0	9.2	11.0	12.4	13.4
16:20	110/25	4.0	4.0	9.3	13.2	16.6	12.7	16.3	12.9	16.0	11.3	16.6	18.8	18.2
16:26	110/25	4.0	4.0	10.0	14.9	20.4	13.9	19.2	14.1	18.0	12.4	19.0	23.1	20.4

Test started again since the magnet was tripped

Time	ΔP	ΔQ_u	ΔQ_l	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
Power was turned back on to 7048 Amps														
16:42	110/25	7048		8.7	9.9	11.8	10.8	11.2	10.9	11.5	10.0	11.3	13.6	13.7
16:47	110/25	4.0	4.0	9.6	13.7	17.6	13.6	17.1	13.5	16.7	11.8	17.4	20.0	19.6
16:55	110/24	4.0	4.0	10.4	15.8	21.4	14.7	20.4	15.0	19.1	13.3	20.1	24.5	21.5
17:04	110/24	4.0	4.0	10.8	16.3	22.2	15.0	21.1	15.3	19.5	13.8	20.9	25.2	21.9
17:13	110/24	4.0	4.0	11.2	16.4	22.3	15.2	21.4	15.4	19.8	14.1	21.0	25.6	22.2

Dial Indicator Readings:

#1 .024	#5 .020
#2 .022	#6 .021
#3 .018	#7 .018
#4 .020	#8 .018

Time	ΔP	ΔQ_u	ΔQ_l	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
Power was turned off at 17:16														
17:19	110/24	4.0	4.0	10.9	13.0	17.4	12.5	16.1	12.7	14.2	11.2	13.8	18.8	16.4
17:20	110/24	4.0	4.0	9.4	10.9	12.9	10.8	12.4	11.3	11.3	9.8	10.7	14.0	13.2

Dial Indicator Readings:

#1 .00	#5 .000
#2 .000	#6 .000
#3 .000	#7 .00
#4 .002	#8 .000

Dial indicators were set back to zero.

NOTE: It takes about 1.5 minutes to read all 11 channels.

Room temperature → 9500 Amps.

Flow rate ΔQ was Balanced @ 4.0 GPM / coil
 @ ΔP = 112/26 (Stand supply vs. return)

Time	ΔP	ΔQ _u	ΔQ _l	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
9:24	112/26	4.0	4.0	7.8	9.2	10.7	9.3	10.3	9.4	9.3	8.0	8.0	10.9	11.1
9:26 Power was turned on to 9507 Amps														
9:30	112/26	4.0	4.0	8.3	14.7	17.6	14.0	18.1	14.7	18.3	12.4	19.2	20.9	17.9
9:35	112/26	4.0	4.0	10.4	18.8	26.6	16.6	25.5	17.0	23.6	15.2	26.1	29.8	26.3
9:41	112/26	4.0	4.0	11.9	21.1	31.3	18.4	29.5	18.8	25.9	16.9	28.9	34.3	28.9
9:46	112/26	4.0	4.0	12.8	22.2	32.9	19.4	30.9	19.6	27.3	17.7	29.9	36.5	30.2
9:53	112/26	4.0	4.0	13.5	23.0	34.2	20.2	32.7	20.3	28.1	18.3	30.9	37.7	31.0
9:58	112/26	4.0	4.0	13.6	23.3	34.5	20.3	32.1	20.7	28.3	18.9	31.4	37.6	31.1

Dial Indicator Readings:

- | | |
|---------|----------|
| #1 .046 | #5 0.425 |
| #2 .048 | #6 .046 |
| #3 0.36 | #7 .038 |
| #4 .038 | #8 .042 |

Time	ΔP	ΔQ _u	ΔQ _l	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]	[C°]	[C°]	[C°]	[C°]	[C°]	[C°]	[C°]	[C°]	[C°]
10:00 power was turned off														
10:03	112/26	4.0	4.0	13.6	19.7	30.11	17.2	28.1	16.9	22.7	15.9	25.1	32.2	29.0
10:08	112/26	4.0	4.0	11.4	14.0	18.0	13.3	16.5	14.6	14.7	12.4	14.4	19.4	16.2
10:12	112/26	4.0	4.0	10.3	11.4	14.1	12.0	14.1	12.4	12.4	11.1	12.3	15.7	14.4
10:17	112/26	4.0	4.0	9.5	10.8	10.2	12.9	12.2	11.3	11.2	10.1	10.2	13.4	13.2

Dial Indicator Readings:

All dial indicators are at 0.00

Part B: LCW H₂O into outer turn of coil assembly

Room temperature → 5000 Amps.

Flow rate ΔQ was balanced @ 4.0 GPM/coil ΔP=114/24 (stand supply vs. return)

Time	ΔP	ΔQ _U	ΔQ _I	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
11:13	112/26	4.0	4.0	8.6	9.3	9.4	9.9	10.0	10.2	9.3	8.9	8.1	9.2	10.7
11:16 Power was turned on to 5025														
11:21	112/26	4.0	4.0	12.8	13.1	12.2	19.2	12.9	13.0	11.7	12.5	10.9	10.8	11.7
11:26	112/26	4.0	4.0	14.9	15.0	13.1	16.0	13.7	14.8	12.4	14.1	11.1	10.9	12.2
11:31	112/26	4.0	4.0	15.8	15.9	13.4	16.5	14.3	15.0	12.7	14.4	11.6	10.8	12.3
11:37	112/26	4.0	4.0	16.1	16.3	13.8	16.9	14.7	14.8	13.1	14.6	11.7	11.0	12.1

Dial Indicator Readings:

#1 .010	#5 .010
#2 .012	#6 .010
#3 .009	#7 .009
#4 .010	#8 .008

Time	ΔP	ΔQ _U	ΔQ _I	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10A	TC10B
[MIN]	[PSI]	[GPM]	[GPM]	[C°]	[C°]									
11:39 power was turned off														
11:42	112/26	4.0	4.0	14.5	15.1	12.6	15.6	13.7	13.7	11.4	12.9	10.4	10.5	12.1
11:47	112/26	4.0	4.0	10.6	11.4	10.8	12.0	10.8	10.8	10.0	10.1	9.3	9.9	11.4

Dial Indicator Readings:

#1 .002	#5 .001
#2 .002	#6 .001
#3 .002	#7 .001
#4 .002	#8 .001