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MASTER

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THERMAL CONTROL FOR THE MFTF MAGNET*

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INTRODUCTION

The Mirror Fusion Test Facility (MFTF) will have the world's largest magnet. External dimensions of the assembled Yin-Yang magnet will be 7.8 m by 8.5 m by 8.5 m, and it will weigh approximately 300 t (660,000 lb). More than 8000 l of circulating liquid helium (LHe) will be required to maintain the nearly 50 km of superconductor at below 5.0 K while the latter carries almost 6000 A in a magnetic field up to nearly 7.7 T. Such formidable conditions have necessitated extensive planning to achieve the required thermal control.

This paper describes four features of these thermal control plans. First, it outlines the proposed cooldown and warmup schedules for MFTF and the procedure for regenerating external cooling surfaces. Then it discusses the design of an external quench resistor, based on an estimate of the superconductor's maximum temperature. Last, it explains how a computer model of liquid helium (LHe) circulation was used to aid in choosing pipe for the LHe lines.

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To minimize heat loads on the magnet system, all LHe temperature surfaces will be in a $1.3\text{-}\mu\text{Pa}$ (10-nTorr) vacuum and shielded by LN_2 . In fact, the entire magnet, which will be maintained at less than 4.5 K , will be installed in a 12-m -diameter, 18-m -long vacuum vessel that also will be the mirror fusion chamber. The vessel will support the magnet by means of seven LN_2 -cooled hanger and stabilizer rods. External surfaces of the magnet will be shielded by 311 m^2 of LN_2 -cooled panels. In regions where plasma and neutral beam impingements will occur, 100 m^2 of water-cooled panels will shield the LN_2 panels.

A section view of one magnet coil in its major radius region is shown in Fig. 1 and illustrates typical MFTF construction. Tables I and II describe the magnet materials and conditions. A unique feature of the magnet design is the guard vacuum space, which serves two principal purposes. It protects the fusion chamber from developed helium leaks through the support structure, and it provides an additional flow channel to circulate gas for more effective cooldown or warmup of the structural case. Moreover, the vacuum space and the urethane shim help to insulate the magnet coil.

COOLDOWN AND WARMUP

The magnet cooldown schedule will be programmed to prevent unacceptable structural thermal stresses. Cooling gases circulated through the coil and guard vacuum spaces will be supplied at temperatures decreasing from 225 K to 100 K during a minimum 50-h period.

During this period, approximately 20 g/s of helium and 400 g/s of nitrogen will be circulated through the coil and guard vacuum spaces, respectively. Afterwards, the helium flow will be increased to 100 g/s, and the guard vacuum will be pumped down to approximately 13 Pa (0.1 Torr). An additional 50 h are estimated for complete cooldown to 4.5 K. The total energy extraction is approximately 2.9 kJ.

Severe flow asymmetry between the two coils (e.g., 30%) is not expected to cause unacceptable thermal stresses, but flow control will be employed.

During warmup of the magnet, the gas temperature schedules will be nearly reversed from cooldown. That is, the He supply temperature will increase from approximately 75 to 150 K during a 50-h period at a flow of 100 g/s through only the conductor pack. Then N₂ and He will be circulated through the guard vacuum and coil spaces at supply temperatures increasing from 150 to 300 K during the next 70 h.

A numerical analysis of the magnet cooldown and warmup cycles performed by General Dynamics Convair Division [¹] yielded the foregoing thermal schedules. They are intended to prevent thermal stresses from exceeding design limits. However, strain and temperature at many locations will be monitored during thermal cycles.

EXTERNAL SURFACE REGENERATION

Cryopumping panels in the MFTF vessel will periodically be thermally cycled to regenerate the surfaces. The magnet's external surfaces must be warmed to approximately 15 K at the same time to

prevent released gases from recondensing. To accomplish this, the magnet LN₂ shields are to be drained and warm N₂ gas (300 K) circulated through them to radiate heat to the magnet surface. The shield temperature will be controlled so as to minimize cumulative heat transfer to the magnet.

Prior to the regeneration cycle, the magnet must be deenergized to prevent a quench. Subsequently, the LHe must be pumped out so that transfer lines inside the vacuum vessel can also be regenerated. However, by proper thermal control of external surfaces, the time required for recooling the magnet to 4.5 K and reenergizing it should be minimized.

MAGNET DISCHARGE

If any detectable portion of the magnet coil should become normally conducting and not recover to superconducting, the contained energy will be dissipated in an external discharge resistor. This resistor is sized to limit both voltage and maximum conductor temperature.

A conservative method for estimating the maximum conductor temperature is to compute an adiabatic temperature rise using:

$$\int_0^{\infty} I^2 R \, d\tau = \sum_i L m_i \int_{T_0}^{T_{\max}} c_i \, dT \quad . \quad (1)$$

Instantaneous thermal communication between the conductor and adjoining materials is assumed. The participating materials are the

superconductor, copper, interlayer and interturn insulation, and helium gas.

The current history is defined as:

$$I = \begin{cases} I_0, & 0 < \tau < \tau_d \\ I_0 \exp(-\tau/\tau_0), & \tau > \tau_d \end{cases} \quad (2)$$

Since R can be expressed as $\rho L/A$, Eq. (1) can be restated in the following form:

$$\frac{I_0^2 \tau_0}{A} \left(\frac{\tau_d}{\tau_0} + \frac{1}{2} \right) = \sum_i m_i \int_{T_0}^{T_{\max}} (c_i/\rho) dT \quad (3)$$

Solution of Eq. (3) yields the maximum temperature as a function of delay until a discharge is initiated. Figure 2 shows this curve for a current decay time constant of 69 s. This decay constant corresponds to a peak voltage of 1000 V across a 0.17- Ω quench resistor, with 12 H inductance in the magnet (i.e., $\tau_0 = HI_0/V_{\max}$). Copper properties assumed in Eq. (3) are those of OFHC copper having a residual resistivity ratio equal to 150 and a 7.76-T magnetic field [2].

Figure 2 shows that a maximum temperature of 200 K is reached if a 10-s delay in initiating discharge is allowed. Longer decay time constants (i.e., lower quench voltages) result in higher temperatures. This temperature is considered permissible since it is a conservative estimate and is limited to a small region of the coil where both initial transition to normal conduction and peak field could occur. A 200-K temperature rise from 5 K should result in less than 0.1%

thermal expansion of the conductor. Also, 10 s is adequate time to initiate a discharge with an automatic quench detecting system.

Magnet structural materials can also develop resistive heating during a fast discharge by a transformer coupling effect between the magnet coil and surrounding structure. Because of its properties, the copper guard-vacuum bladder will show the greatest temperature increase from this source. Assuming adiabatic conditions, resistive and sensible heating of the copper can be equated:

$$\int_0^{\infty} V^2/R \, d\tau = L_e m \int_{T_0}^{T_{\max}} c \, dT \quad . \quad (4)$$

For a 1392:1 turn ratio, 1000-V peak coil voltage, and a 69-s current decay time constant, this equation becomes

$$\frac{0.26\tau_0}{\gamma L_e^2} = \int_{T_0}^{T_{\max}} \rho c \, dT \quad . \quad (5)$$

Solution of this equation yields a maximum temperature of 70 K for the copper bladder, which is an acceptable temperature increase.

A similar analysis of the stainless steel case yields a temperature of 13 K. Total energy dissipation in the case, bladder, and coil jacket is approximately 7 MJ, or less than 1.5% of the energy contained by the magnet before discharge.

HELIUM CIRCULATION

Important to the thermal control of the magnet is an adequate circulation of LHe. Forced pumping is not practical, so natural circulation was chosen because it has been satisfactory in smaller magnet systems. A computer model of the LHe natural circulation was developed to estimate steady state mass flow rate and vapor quality. Also, a sensitivity study was made to determine which parameters have the greatest influence and to estimate the range of uncertainty for LHe flow rate.

The principal requirement of the LHe system is to maintain quality with less than 10 vol% vapor in the magnet. Heat transfer analyses indicate that significantly higher vapor qualities would probably inhibit cryostability.

A schematic of the LHe system, shown in Fig. 3, illustrates the lengths, bends, and altitudes of the pipes, the dewar and the magnet. Note that the magnet inlet and outlet are approximately 16 and 9 m, respectively, below the LHe dewar.

The conductor pack and magnet shape do not immediately lend themselves to an obvious flow modeling approach. Therefore, in modeling the magnet three approaches were considered: the Blasius friction equation, Darcy's porous media equation, and a three-dimensional orifice model [3]. In selecting an appropriate method, estimates of hydraulic diameter, flow tortuosity, porosity, permeability, friction factor, and effective orifice dimensions were made, and the three approaches were compared by means of their respective pressure drops. The porous media approach resulted in the smallest pressure

drop, the Blasius approach yielded a pressure drop 10 times greater, and the orifice approach gave a pressure drop that was 1000 times greater. We rejected the orifice assumption as unrealistic. We then chose the Blasius friction method over the porous media approach because the former was more conservative. Thus, the magnet pressure loss was estimated with a modified Blasius friction equation in the following form:

$$\Delta P = (f L_m \eta d_h M^2 / 2 \gamma A_p^2 \phi^2) \quad . \quad (6)$$

Flow in the magnet is expected to be laminar by the Reynolds number definition, so that the friction factor is given as

$$f = 64 \mu A_p \phi / \eta M d_h \quad . \quad (7)$$

Pressure losses in the piping system were simply modeled using loss coefficients [⁴] for bends, valves, entrance-exit regions, and other effects. These were calculated as functions of the friction factor f . The effect of two-phase flow was also included by using the Lockhart and Martenelli correlation [⁵]. Flow in the piping system was assumed turbulent.

Helium flow rates were estimated by an iterative computing method. Using an assigned heat load for selected flow model elements and an assumed flow rate, He properties were determined for each element node using NBS data [⁶]. The resulting pressure imbalance in the flow circuit due to cumulative contributions of friction, momentum, and gravity was computed. The flow rate was readjusted and the calculations repeated until the pressure imbalance was acceptably small. This

procedure provided a means for determining the effect of heat load on flow rate (Fig. 4a). Also, vapor quality was determined and appears as a function of heat load in Fig. 4b.

Because the modeling procedure entails some uncertainties, we were interested in how sensitive the results were to changes in certain variables. Table III shows the maximum expected range in these flow parameters, and Table IV shows our estimate for the total LHe-system heat input. The results of the sensitivity study are reflected in Figs. 4a and 4b by the uncertainty range curves.

The effects of two-phase flow are significant for He at mass qualities as low as only 1% and flows near 300 g/s. Surprisingly, the static head inside the LHe dewar is the most significant parameter affecting mass flow rate because of the relatively low fluid flow resistance of LHe. The pipe friction is far more influential on flow than either magnet friction or heat input.

On the basis of this calculation we selected a pipe with a 6-in. (15-cm) inside diameter for the LHe supply and return lines. This pipe size and our estimated system heat load of 460 W yield an equilibrium mass flow rate of approximately 700 g/s. Vapor quality at the top of the magnet is less than 4 vol% (0.7% by mass), and is less than 20 vol% at the top of the return line. These results imply that an adequate safety margin has been provided in the thermal control of the magnet.

NOTATION

A = conductor area
 A_p = area for conductor pack
 c = specific heat
 d_h = hydraulic diameter
 f = friction factor
 H = inductance
 I = current
 I_0 = initial current
 i = material index
 L = conductor length
 L_e = effective length
 L_m = flow path length through the magnet
 m = mass per unit length
 M = mass flow rate
 R = resistance
 T = temperature
 V = voltage

Greek Symbols

γ = density
 η = tortuosity factor
 μ = viscosity
 ρ = resistivity
 τ_d = delay time
 τ_0 = current decay time constant
 ϕ = porosity

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2. Handbook on Materials for Superconducting Machinery (Metals and Ceramics Information Center, Battelle Memorial Institute, Columbus, Ohio, 1974).
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5. Fluid Flow Data Book (General Electric Co., Schenectady, N.Y., 1977).
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Table I. Properties of the MFTF Magnet

Design current, A	5,775
Maximum magnetic flux density, T	7.68
Conductor size, cm	12.4 × 12.4
Copper to superconductor ratio	6.7/1
Effective copper area for current, cm ²	1.25
Conductor surface area for heat transfer, cm ² /cm	8.17
Transition temperature at maximum current and field, K	5.0
Maximum LHe temperature, K	4.52
Number turns per coil	1,392
Conductor length per coil, m	24,785
Coil Porosity	0.32
Stored magnetic energy, MJ	440

Table II. Materials for the MFTF Magnet, and their Weights

Materials	Weight (kg)
Magnet:	
Conductor (copper, superconductor)	52,820
Insulation (G-11)	5,730
Jacket (316 stainless)	16,180
Shim (urethane)	3,370
Bladder (copper)	1,130
Case (304 LKN stainless)	178,370
Intercoil Supports	36,360
Gas baffle	6,180
Total	300,140
Accessories:	
LN ₂ shields (316 stainless)	10,650
Water shields (316 stainless, copper)	3,430
LHe ducts (316 stainless)	2,730
Current leads (copper)	500
Hanger rods (316 stainless)	12,730
Misc. hardware	1,100
Total	31,140

Table III. Uncertainty Range of Flow Parameters

Parameter	Range
Friction factor, f	0.014 to 0.018
Tortuosity factor, η	1.5 to 2.0
Porosity, ϕ	0.30 to 0.35
LHe dewar head, (m)	0.5 to 1.0
Hydraulic diameter, d_h (cm)	0.15 to 0.35
Piping heat leakage, (W)	30 to 80
Length of piping (m)	80 to 100

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Table IV. Liquid Helium System Heat Sources

Source	Heat input (W)
LN ₂ shield radiation	160
LN ₂ shield conduction	45
Magnet hanger rods	60
Conductor joints	45
Instrumentation leads	70
Helium ducts	80
Total	460

Figure Captions

- Fig. 1. A section view of one MFTF magnet coil, showing construction details for both the magnet and for the cooling system that surrounds it. The section is along line AA in the small drawing.
- Fig. 2. Maximum conductor temperature in MFTF as a function of delay time. The decay time constant $\tau_0 = 69$ s.
- Fig. 3. Schematic diagram of the liquid helium circulation. The He transfer lines are 6-in. (15-cm) schedule-10 pipes.
- Fig. 4. Computed He flow rate (a) and vapor quality (b) as a function of the system heat load. The dashed curves above and below the graphs show the extent of uncertainty in each calculation. Assumed LHe head in the supply dewar was 1 m.

VanSant - Fig. 1

VanSant - Fig. 2

VanSant - Fig. 3

VanSant - Fig. 4