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INTRODUCTION

A yin-yang pair of liquid-helium (LHe) cooled, superconducting magnets were tested last year at the Lawrence Livermore National Laboratory (LLNL) as part of a series of tests with the Mirror Fusion Test Facility (MFTF). These tests were performed to determine the success of engineering design used in major systems of the MFTF and to provide a technical base for rescoping from a single-mirror facility to the large tandem-mirror configuration (MFTF-B) now under construction. The magnets were cooled, operated at their design current and magnetic field, and warmed to atmospheric temperature. In this report, we describe their thermal behavior during these tests.

The assembled magnets, shown in Fig. 1, are covered by their thermal shields and installed in the vacuum vessel. They have a combined diameter of 8.5 m and weigh over 320 tonne. They produced a peak magnetic field of 7.76 T, had 25 km and 1392 turns of superconductor in each coil, and had a total stored magnetic energy of 420 MJ. The coils were made of an externally cooled, copper-stabilized, niobium-titanium conductor that was developed specifically for the MFTF magnets.[1] A section of the magnet's structure is illustrated in Fig. 2. The coil and electrical insulation are contained in the 1.3- to 2.5-cm-thick steel jacket that is enclosed by a 7.6- to 12.7-cm-thick supporting steel case. To provide good transfer of the mechanical load to this case, a high-density plastic is injected into the space between the jacket and a thin, steel bladder. Closely spaced steel buttons keep the bladder from contacting the case. Space left between the bladder and the case is for helium (He) flow

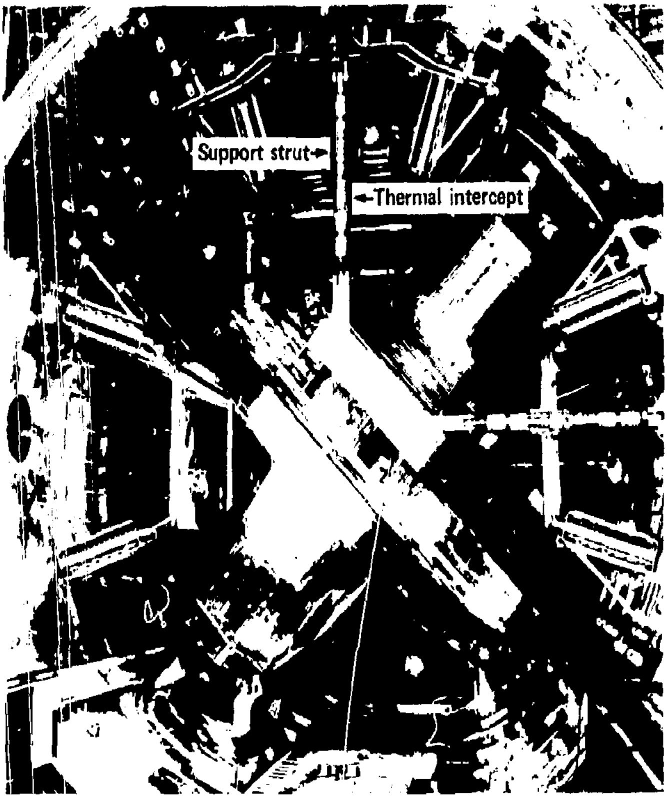

Fig. 1. The MFTF magnets in the vacuum vessel before closure.

during cool-down and warm-up cycles and provides for a guard vacuum to intercept He leaks during operation. (Design details are given in Refs. 2 to 4.)

The magnets were cooled by a cryogenic system[5] that included a He refrigerator having 3100 W of cooling capacity at 4.35 K and a liquid nitrogen (LN) heat exchanger (HX) that can provide over 50 kW of He cooling at a decrease of 100 K. Figure 3 shows the He cryogenic system supporting the magnets. The cryogenic system also included a pressurized, forced-flow LN system that supplied LN to the thermal-protection systems for the magnet and LHe system.

During the first cool-down period of the magnets, gaseous He (GHe) was cooled by only the LN HX before transfer to the

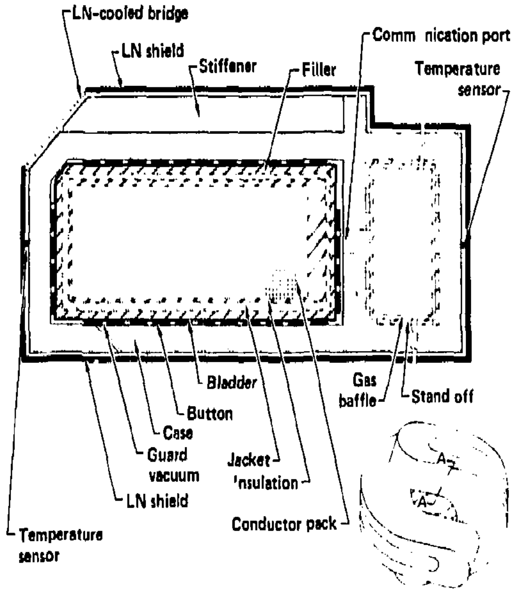

Fig. 2. Sectional ("A-A") view of the magnet showing its construction and thermal shields.

magnet coils and to the guard vacuum channels. When the He temperature returning from the magnets was below 130 K, cooling was provided only by the refrigerator and by a Joule-Thompson expansion valve. During this next phase, flow through the guard vacuum channels was terminated, but GHe left in these channels enhanced heat transfer from the cases to the coils. When the He-return temperature dropped below 20 K, the guard vacuum spaces were evacuated to 100 millitorr.

After completing cool-down and filling the magnet coils with LHe, we developed natural convection through them by thermal siphon flow of LHe between the Dewar and coils. (A 17-m elevation difference existed between the bottom of the magnets and the LHe level in the Dewar.) We estimated the LHe flow and its vapor quality by a finite-element thermal-siphon analysis. Conventional engineering methods were used to estimate the piping-system flow resistances. But, we determined flow resistances of the magnet coils from experimental measurements using GHe flow. These measurements were approximately twice the estimated theoretical losses reported earlier[3] and were correlated by a Fanning friction-factor expression given as $f = 17.3/Re^{0.47}$.

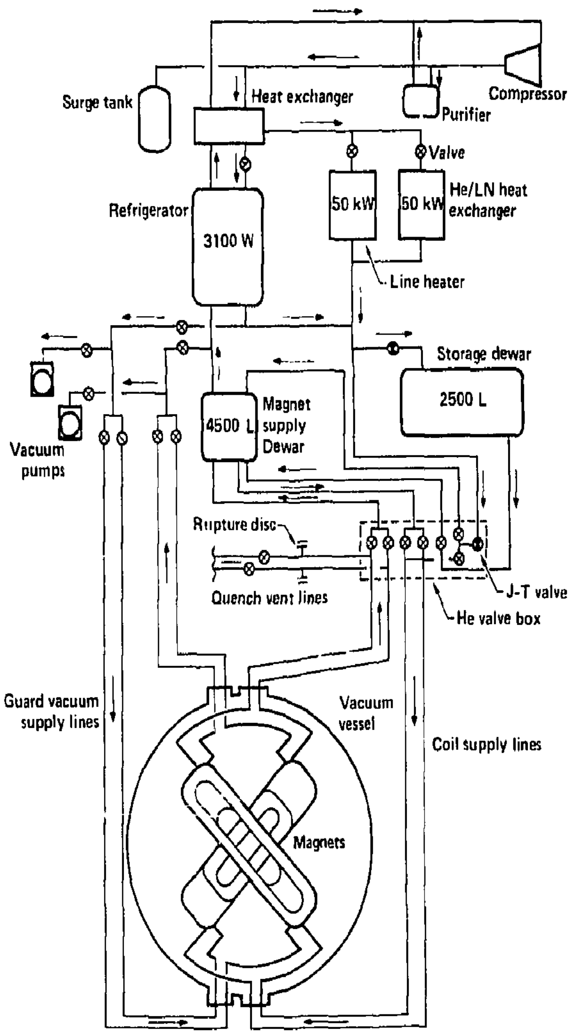

Fig. 3. A schematic of the cryogenic-magnet piping system.

(Re is Reynolds number in terms of bulk velocity and hydraulic diameter in the coils.) Results of our flow analyses, shown in Fig. 4, indicate the steady-state LHe flow through each coil was 230 g/s and maximum bulk quality in the coils was less than 10 vol%.

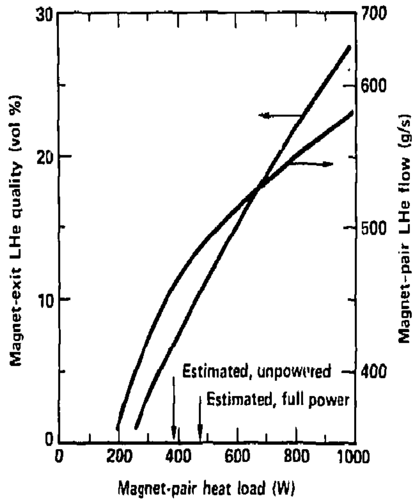

Fig. 4. Calculated flow rate and quality of LHe leaving the magnets.

We achieved thermal protection of the magnets by enveloping them with a system of panel shields (see Fig. 1) filled with subcooled LN. Our panel system was designed to have fluid temperatures less than 85 K and upwards flow throughout to avoid vapor trapping. To intercept heat conduction through the seven support struts to the magnets, we provided additional thermal protection by a LN-cooled annulus (shown in Fig. 1) on each strut. Also, having less than one-microtorr vacuum in the vessel provided some thermal protection. The principal sources of heating were, however, from the LN-cooled shields, support struts, instrumentation wires, conductor joints in the coils, He-vapor-cooled current leads (VCL) and their cryostats.

COOL-DOWN RESULTS

Before initiating cool-down, we evacuated the vacuum vessel to 0.1 millitorr. Next, the LN shields were precooled with cold nitrogen gas for 2 hr, followed by LN filling and temperature stabilization during the next 2 hr. After cool-down of the LN shields, their cryopumping effect caused the vessel pressure to drop to 10 microtorr. Several LN temperature measurements in the shield system indicated shield temperatures were always less than 82 K.

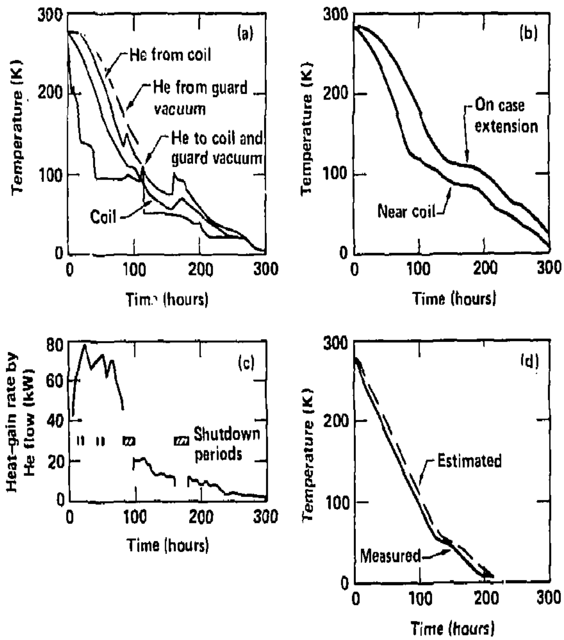

Fig. 5. Selected temperature and heat-transfer histories during cool-down. (a) Temperatures of He supply to coil and to the guard vacuum, exit temperatures from the coil and guard vacuum, and coil mean temperature. (b) Magnet surface temperatures near the coil and on the case extension at the locations indicated in Fig. 2. (c) Heat gain by the He flow through the magnet pair. (d) Estimated magnet mean temperature during cool-down (with delays and recoveries deleted). *Solid curve is from test* data, dashed curve is analytical estimate.[6]

Selected cool-down temperature histories of the magnets are given in Fig. 5. Included are He supply and return temperatures, coil mean temperatures, and He heat-gain rates. Also shown are magnet case temperatures at the two sensor locations indicated in Fig. 2. These two values indicate only the range of case surface temperatures in the section. Only small differences in comparable temperatures between opposite halves of each magnet and between the two magnets indicated their thermal behavior was nearly identical and the flow was well balanced. In fact, we did not need to adjust the flow to either magnet at any time during cool-down.

Cooling-rate irregularities occurred because several maintenance shut-downs were required and manual adjustments were frequently made to regulate supply temperatures. (We limited the difference of magnet return and supply temperatures to less than 150 K so that thermal stresses in the magnet structures would remain below our allowable limit.) Also, this cool-down cycle was the first one for the magnet-cryogenic system and required operator training. Cool-down to 5 K was accomplished in approximately 290 hr. An additional 16 hr were required to fill the magnets and supply Dewar with LHe. When this operation was completed, the LHe-storage Dewar maintained a steady LHe level in the supply Dewar, and the refrigerator supplied LHe only to the storage Dewar.

Our measured total heat gain by He flow through the magnets during cool-down was 25.3 GJ, and estimated cooling by the LN shields was 1.9 GJ, which yields 27.2 GJ of total cooling. Our calculated total heat extraction required to cool the magnets from 280 to 5 K is 27.4 GJ. The Dewar and piping require only 0.2 GJ.

Included in Fig. 5 is a curve of the estimated magnet mean temperature during cool-down, with operation delay and recovery times deleted. The adjacent curve is an estimate of this temperature from an analytical model of the symbiotic cryogenic-magnet system. The analysis is a transient finite-difference calculation of local temperatures in the refrigerator affected by its turbo-expander and HX characteristics and thermal load imposed by the magnets.[6]

OPERATION RESULTS

Several days after the magnets were filled with LHe, we observed temperatures at many locations on the exterior surfaces of the magnets. They ranged from 6.6 to 21.3 K and corresponded to the range of the two temperature-measurement locations in Fig. 2. The higher temperature resulted from thermal-shield heat loads and the relatively greater distance of the sensor from the LHe-filled coils. Also, those areas with support-rod attachments did not have temperatures noticably higher than comparable areas without rod attachments.

A steady-state measurement of heat load to the magnet system, including its supply Dewar and piping, was made when the magnet was not energized. Transfer of LHe from the storage Dewar was stopped and a LHe consumption rate in the supply Dewar was measured. This test yielded a total heat load of 849 W, higher than we expected. Table 1 is an accounting of estimated contributions to this heat load. Note that three of the seven magnet-

Table 1. Accounting of steady-state heat loads.[a]

Source	Description	Head Load (W)
LN shields	Estimated radiation	105
LN-shield supports	Conduction to magnets	32
Intershields	Between LN panels	21
Instrumentation	Conduction to magnets	63
Magnet piping	Conduction to magnets	25
VCL cryostats (2)	Conduction in LHe	30
VCL He flow (4)	Refrigeration of return He	56
Magnet supports	LN cooled supports (4)	34
	Uncooled supports (3)	72
Dewar and piping	Heat leaks	101
Valve-box heating	From uncooled piping	310
Total measured heat load		849

[a]Abbreviations: LN, liquid nitrogen; LHe, liquid helium; VCL, vapor-cooled leads.

support struts did not completely cool, which resulted in additional heat loads. Their LN-cooled thermal intercepts experienced vapor trapping because the LN flow was not enough to overcome a hydraulic head. We intentionally limited the flow to minimize some LN leaks. This condition caused 46 W more heat load than expected. Also, 310 W was presumed to come from uncooled piping, leading in and out of the valve box, for LHe-cooled vacuum pumping panels that were not operating at the time of the heat-load measurement. A post-test inspection of the magnets, thermal shields, and piping systems failed to reveal any indications of other unexpected heat loads.

Estimated additional heat loads that occurred when the magnets were fully energized are 76 W from conductor joints and 12 W from the VCL. If the additional heat loads from the uncooled supports and piping were eliminated, the required refrigeration rate would be 697 W, of which 115 W would be for He gas flow from the four VCL.

Gaseous He flow through each of the four VCL was controlled from 0.2 to 0.35 g/s for magnet currents of 0 to 5775 A. At these flows, the He exit temperature ranged from 273 to 278 K. Copper current buses joining the warm end of the VCL to power cables were maintained from 292 to 298 K by thermostatically controlled heaters attached to the buses. These temperatures were sufficient to prevent moisture from forming on the VCL, buses, or cables. Flow and temperatures in the VCL remained stable, and they performed satisfactorily during the test program.

A magnet quench did not occur at any time during the test program. However, we noted indications of normal zones occurring in the coils. Voltage measurements across coil layers showed voltage jumps during magnet charging that lasted at least one second. This condition usually occurred while the current was increasing near its design limit and was probably the result of conductor temperature increases caused by conductor motion. A recovery to stable superconducting condition was confirmation of the conductor's unconditional cryostability.

WARM-UP RESULTS

Before the magnet warm-up cycle was initiated, surface regeneration tests were performed. This was accomplished by de-energizing the magnets, transferring the LHe out of them, and warming the LN shields by flowing atmospheric-temperature nitrogen through them. Thermal radiation from the LN shields warmed the magnet and He piping surfaces enough to evaporate condensed gases. Less than 4 hr after initiating warm nitrogen flow into the shields, the magnet surfaces were heated enough to raise their temperature above 20 K and complete the regeneration cycle. These results agreed with our analytical estimates.

Approximately 201 hr were required to warm the magnets to a minimum surface temperature of 240 K and to achieve a He return flow temperature of 280 K. During this period, there were no interruptions and the flow was a nearly constant 100 g/s. Heating was supplied by a 50-kW electrical line heater that provided a set-point supply temperature that was 100 K warmer than the magnet return-flow temperature. Return flow to the refrigerator and to the adjoining HX provided precooled flow to the line heater. Overall, magnet warm-up tests behaved as expected and no difficulties were encountered.

SUMMARY

We successfully performed a cool-down and an operation of the MFTF magnets without serious difficulties. All problems encountered can easily be corrected. Most of all, we demonstrated a level of technology (and obtained extensive data and experience) that will be utilized in the MFTF-B magnet system, which will include 42 superconducting magnets and an 11-kW He refrigeration system. We will be able to improve the thermal performance and to simplify instrumentation and control requirements for these magnets.

ACKNOWLEDGMENTS

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REFERENCES

1. D. N. Cornish, D. W. Deis, A. R. Harvey, D. G. Hirzel, J. E. Johnston, R. L. Leber, R. L. Nelson, and J. P. Zbasnik, "Development Work on Superconducting Coils for a Large Mirror Fusion Test Facility, UCRL-78891," *Lawrence Livermore National Laboratory*, Livermore, California (1977).
2. C. D. Henning, A. J. Hodges, J. H. VanSant, E. N. Dalder, R. E. Hinkle, J. A. Horvath, R. M. Scanlan, D. W. Shimer, R. W. Baldi, and R. E. Tatro, "Mirror Fusion Test Facility Magnet System--Final Design Report, UCRL-52955," Lawrence Livermore National Laboratory. Livermore, California (1980).
3. J. H. VanSant, "MFTF Magnet Cryogenics, UCRL-85580," Lawrence Livermore National Laboratory, Livermore, California (1981).
4. J. H. VanSant and R. M. Russ, "Thermal Control for the MFTF Magnet, UCRL-82850," Lawrence Livermore National Laboratory, Livermore, California (1979).
5. J. H. VanSant, D. S. Slack, and R. L. Nelson, "Cryogenic System for the Mirror Fusion Test Facility, UCRL-83590," Lawrence Livermore National Laboratory, Livermore, California (1980).
6. R. T. Potter and K. Z. Tipton, private communication (1983).