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EXPERIENCE IN THE OPERATION OF THE INTERNATIONAL FUSION SUPERCONDUCTING MAGNET TEST FACILITY*

William A. Fietz

U.S. Department of Energy,[†] ER-90 GTN,
Washington, D.C.

ABSTRACT

The International Fusion Superconducting Magnet Test Facility (IFSMTF) was placed under vacuum in October 1985 and cooled in January 1986. It remained at cryogenic temperatures until September 1987, when testing was completed. This paper is an account of the activities of cooling, testing, and maintaining the system during this period. The facility contained six superconducting magnets, arranged in a toroidal array. Each of these D-shaped magnets weighed 40-50 tonnes and was about 5 m by 10 m. The refrigerator system provided atmospheric liquid helium (LHe), about 5000 L in the three pool-boiling coils and the leads, plus a storage capacity of 21,000 L. In addition, the three forced-flow coils were supplied with up to 300 g/s of single-phase helium at 3.8 K and 15 atm. A crew of three or four trained, certified operators handled the cryogenic facility on a 24-h basis for most of the daily activities. Detailed records were maintained, reports of unusual events were prepared, and a continuous record of availability was accumulated. At the end of the 22-month period of operation, the cumulative availability was 57%.

INTRODUCTION

A multinational program of cooperative research, development, demonstrations, and exchanges of information on superconducting magnets for fusion was initiated in 1977 under an International Energy Agency (IEA) agreement. The first major step in the development of toroidal field (TF) magnets was called the Large Coil Task (LCT). Participants in LCT were the U.S. Department of Energy (DOE), the European Atomic Energy Community (EURATOM), the Japan Atomic Energy Research Institute (JAERI), and the Département Fédéral de l'Intérieur of Switzerland.

The goals of LCT were to obtain experimental data, to demonstrate reliable operation of large superconducting coils, and to prove design principles and fabrication techniques being considered for the toroidal magnets of thermonuclear reactors. These goals were to be accomplished through coordinated but largely independent design, development, and construction of six test coils, followed by collaborative testing in a compact toroidal test array at magnetic fields of 8 T and higher.

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[†] On assignment from Oak Ridge National Laboratory.

Fig. 1. Responsibilities in the IEA Large Coil Task.

The United States built and operated the test facility at Oak Ridge and provided three test coils. The other participants provided one coil each. Information on design and manufacturing and all test data were shared by all the participants. Each LCT team included a government laboratory and an industrial partner. The team arrangements and the division of responsibilities are shown in Fig. 1.

The last coil was completed in 1985, and the test assembly was ready in October of that year. Just before the facility was closed in preparation for testing, it appeared as shown in Fig. 2.

Fig. 2. Test stand with six LCT coils—October 1985.

Over the next 22 months, extensive testing was performed. This paper summarizes the operations during the testing period, including cooldown, testing, operations, repairs, and maintenance. The overall performance can be described as very good, both in the coil performance [1] and in the availability of the system.

SYSTEM DESCRIPTION

The facility consisted of seven subsystems: the vacuum system, the test stand structure, the pulsed field assembly, the helium system, the liquid nitrogen (LN) system, the electric power system, and the instrumentation and control system. These are briefly described below. More detail is available in the final report [1].

The vacuum system. Tank vacuum was maintained by a 1-m oil diffusion pump (with a pumping speed $v = 55,000$ L/s), two turbomolecular pumps ($v = 3450$ L/s), and four mechanical roughing pumps ($v = 2000$ L/s).

The cylindrical, 10.7-m-ID tank had a flat bottom and a dished head, as shown in Fig. 3. Its enclosed volume was 960 m^3 , of which 80 m^3 was occupied by equipment. The tank had 39 ports with diameters ranging from 300 to 1220 mm, through which over 1500 instrumentation wires were routed.

The tank vacuum and 84 layers of superinsulation provided the thermal insulation for the LHe-filled coil assemblies and the LN-cooled cold wall that completely lined the inside of the tank. Normally, the turbomolecular pumps were adequate to maintain the vacuum, and the oil diffusion pump was needed only during extensive testing periods when the helium leakage rate was high.

Test stand structure. The test stand structure consisted of a gravity base, the bucking post, and the torque rings, as shown in Fig. 4. The gravity base supported the weight of all the structure plus the six coils and the pulsed coil assembly. It was made up of a six-legged frame supported by rollers on LN-cooled track assemblies. The bucking post, which reacted the centering forces of the energized coils, was a hexagonal column with vertical grooves in each face to align the coils. It was cooled by LHe passages and a reservoir of LHe in its center. Two torque ring subassemblies, top and bottom, supported lateral loads that occurred when the coils were not energized equally.

Fig. 3. Vacuum system assembly elevation.

Fig. 4. Elevation and top views of test stand assembly.

Fig. 5. Pulse coil and torque beam assembly.

Pulsed coil system. To simulate the transient magnetic fields of an operating tokamak reactor, two LN-cooled copper coils were mounted on a rotating torque beam so that they could be moved from coil to coil for individual testing. Figure 5 shows schematically the mounting of the coils. The coils provided a field of 0.15 T at the test coil winding and could be energized in 1 s to full field, maintained there for 15 s or more, and then ramped down.

The assembly was moved by a system of helium gas pistons operating a pinion and ring gear mechanism. The box beam was supported on rollers during the move, and when it arrived in position for the next test, a set of helium gas-actuated wedges lifted the beam and coils, locking the assembly into position. The beam could rotate almost 360°, so that all six coils could be tested.

Helium system. The helium system cooled the coils and their supporting test stand structure to operating temperature and then supplied helium at the proper pressures and temperatures to the coils, structure, and vapor-cooled current leads. The equipment that performed these functions is shown schematically in Fig. 6.

The refrigerator system was composed of four major functional parts: gas storage and supply, compression and purification, refrigeration, and utilization. Primary gas storage was in the buffer tanks and storage tanks. The buffer tanks were normally connected to the system and were essential to the smooth operation of the compressors. They accepted excess gas from the high-pressure compressor output and supplied gas as needed to the low- or intermediate-pressure stages. This operation was carried out automatically by the gas management system to maintain the desired operating pressures at all three points. The other storage tanks could also be used for regulation or valved off to preserve an inventory of gas at pressures between about 3 and 15 bar. In addition, a bank of high-pressure storage tanks could store gas up to about 150 bar. Operation of these tanks was controlled manually by the operators as needed. Gas supply was obtained either from the plant or from high-pressure trailers. Maximum gas storage capacity was 1050 kg at about 17 bar and 450 kg at about 200 bar.

Compression was accomplished in two stages. The input pressure in the first stage was between 0.4 and 1 bar, with an output of about 3 bar. In the second stage the gas was further compressed to the 15-bar operating pressure. Compressors in the first

Fig. 6. Overview of helium system.

stage were driven by two 400-hp motors; those in the second stage, by two 1000-hp motors. The oil used for lubricating and cooling the rotary screw compressors was removed by an elaborate separation system, followed by a purifier containing LN-cooled charcoal and molecular sieve adsorbers, which removed N_2 and O_2 impurities and any remaining oil.

The cold box was made up of heat exchangers, additional purification beds to remove neon and any traces of other gases, and the two gas turbines that extracted heat from the gas, to provide refrigeration. The outputs from the main cold box were cold 15-bar gas, which was further cooled in the auxiliary cold box and supplied to the forced-flow coils, and LHe at 1 bar for the pool-boiling coils, current leads, and storage Dewars. The cold gas from the coils and leads was returned to the cold box.

Delivery of the cold fluids to the coils, leads, and structure completed the operation of the helium system. The multiple paths available were regulated automatically for the most part once a steady-state condition was reached, so that liquid levels and flow rates could be maintained.

Liquid nitrogen system. In addition to providing a cold wall at 99 K that completely surrounded the coil and structure assembly, the LN system served a number of functions, as shown in Fig. 7. It provided cooling for a shield within the helium transfer lines to intercept heat and prove the efficiency of these vacuum-jacketed lines. It cooled the first heat exchanger in the cold box and in the purifier plus a baffle in the oil-diffusion vacuum pump. Liquid nitrogen was also used to cool the lead Dewars and was the coolant for the first part of the cooldown process for the pulsed coils. The liquid was furnished by an outside contractor and stored in two 50,000-L storage tanks. The flow to the various parts of the system was controlled automatically in steady-state operation and required little operator attention.

Instrumentation and control. Over 2000 sensors of various types provided information on the behavior of the coils and facility and allowed the control of the complex

Fig. 7. Schematic of LN system.

system. These sensors included voltage taps, thermometers, strain gages, magnetic field probes, displacement transducers, and helium flow and level sensors. Output from the sensors could be fed directly to the control units to regulate helium levels, for example, and/or into the data acquisition, display, and storage system. Depending on the nature of a signal and its intended use, it could be routed through one or more different front ends. These were called the fast front end, the slow front end, the facility front end, the refrigerator front end, and the transient front end. More detail can be found in Ref. [1].

OPERATION

Organization. Because of the complexity of the system and the need for precise control of the operations, a formal organizational structure was set up [1]. Basically, operations were performed by teams of trained, certified operators on a 24-h/day schedule throughout most of the 22 months. A formal operations manual was prepared and updated as procedural revisions occurred. The Head of Operations, who reported directly to the Program Manager, was responsible for safe and effective operations.

Chronology. Table 1 summarizes the operation of the facility from the first evacuation of the tank to the completion of testing nearly five years later.

Table 1. Periods of continuous operation of IFSMTF

Run	Principal activities	From	To
1	Tank evacuation and cold wall operation	10/04/82	11/06/82
2	Refrigerator acceptance test, startup	01/17/83	05/28/83
3	Refrigerator acceptance test, performance	06/20/83	08/30/83
4	Two-coil cooldown and warmup	11/28/83	01/29/84
5	Three-coil cooldown, two-coil tests, warmup	06/11/84	09/28/84
6	Liquid helium system tests	04/08/85	06/28/85
7	Tank evacuation, leak tests, start cooldown	10/21/85	12/23/85
8	Six-coil cooldown, coil tests	01/16/86	12/23/86
9	Continued six-coil tests	01/05/87	09/04/87

include the normal tasks required either before or after energizing the coils and procuring data, such as preparing the instrumentation configuration, reliquefying the helium boiled off in the test, and night and weekend rest for the experimenters. From this definition an availability factor, the fraction of time that the facility was available, could be obtained. This factor is displayed in Figs. 10-13, covering both the period of two-coil operation in 1983-1984 and the six-coil array tests in 1985-1987. These figures show the major activities and factors affecting the availability of the facility. Reasons for major periods of unavailability are listed in Table 2.

Fig. 10. Principal activities and availability factor for December 1983-October 1984.

Fig. 11. Principal activities and availability factor for November 1985-June 1986.

Fig. 12. Principal activities and availability factor for June 1986–January 1987.

Fig. 13. Principal activities and availability factor for February–September 1987.

CONCLUSIONS

The overall availability of the system, almost 60%, was considered a qualified success. In fact, only one element of the entire facility—the pulsed coil system—was unable to complete its planned program. After the assembly had been successfully moved twice to new locations and used to test three of the coils, excessive leakage in the gas-actuated pistons led to the abandonment of further tests.

The word “leak” is prominent in Table 2. Many other items, such as impurity problems, are directly attributable to leaks into the system. So, one lesson to be learned from the operation of this system is the importance of preventing all types of leakage, into and out of the system. Another common problem, the occasional loss of utilities, had been anticipated and occurred about as frequently as expected. Although providing backup for all utilities would have been impractical, a secondary instrument air source was added during the operating period, and an alternate cooling water source was available from the beginning.

Table 2. Intervals of unavailability and controlling reasons

Month/ year	Days lost	Controlling reason	Month/ year	Days lost	Controlling reason
10/85	1	Audible air leaks at tank penetrations	10/86	1	Suspended solids in demineralised water
11/85	7	Helium leak in CH coil	1/87	14	Abnormal heat leak (pulse coil power leads)
11/85	3	Air leak at instrumentation feedthrough	2/87	1	Pulse coil power controls
11/85	4	Helium oil removal system (installation)	2/87	1	FF coil flow control
12/85	17	Water leak in helium compressor oil cooler	2/87	2	Loss of plant electrical power
12/85	9	Cleanup of helium system (late)	2/87	6	Helium leak from pulse coil movement actuator
1/86	29	Leak in cooldown heat exchanger (replacement)	3/87	1	Suspended solids in demineralised water
2/86	1	Water leak in turboexpander cooler	3/87	3	Insulation on VCL flange bolts
2/86	1	Loss of plant instrument air supply	3/87	3	Helium compressor electrical power breaker
2/86	10	Damage in helium compressor No. 4 (replacement)	3/87	4	Frozen impurities in cold box
3/86	2	Installation of backup instrument air system	4/87	18	Frozen impurities in cold box and purifier
3/86	1	Loss of plant electrical power	5/87	2	Loss of plant electrical power
3/86	1	Data acquisition system front end	5/87	1	Coil power supply switch actuator
3/86	1	Frozen air in helium line from JA coil	5/87	1	Data acquisition system outage
4/86	2	Loss of plant electrical power	6/87	1	Data acquisition system outage
5/86	1	Work on pressure relief valves	6/87	5	Data acquisition system outage
6/86	8	Fault in helium compressor control	7/87	40	Helium compressor shaft seal, air leakage
7/86	12	Loss of plant electrical power and resulting helium compressor problems	7/87	2	Traces of air in helium
8/86	16	Frozen impurities in cold box and purifier	7/87	5	Helium compressor oil leak
8/86	3	Loss of instrument air supply	8/87	2	Loss of plant electrical power
8/86	1	Loss of instrument air supply	10/86-	284	All causes (284 out of 854 days)
9/86	17	Frozen impurities in cold box	9/87		
9/86	19	Frozen impurities in cold box and purifier			
10/86	5	Helium compressor electrical power breaker			

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REFERENCES

- [1] A thorough account of the entire program, with references too numerous to cite here, is contained in "The IEA Large Coil Task: Development of Superconducting Toroidal Field Magnets for Fusion Power," (D S. Beard et al., eds.), *Fusion Eng. Des.*, 7, 1-232 (1988).

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