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EXPERIENCE WITH OPERATION OF A LARGE MAGNET SYSTEM IN THE
INTERNATIONAL FUSION SUPERCONDUCTING MAGNET TEST FACILITY*

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ABSTRACT

Superconducting toroidal field systems, including coils and ancillaries, are being developed through international collaboration in the Large Coil Task. Focal point is a test facility in Oak Ridge where six coils will be tested in a toroidal array. Shakedown of the facility and preliminary tests of the first three coils (from Japan, Switzerland, and the U.S.) were accomplished in 1984. Useful data were obtained on performance of the helium refrigerator and distribution system, power supplies, control and data acquisition systems and voltages, currents, strains, and acoustic emission in the coils. Performance was generally gratifying except for the helium system, where improvements are being made.

INTRODUCTION

Development of reliable superconducting magnet systems meeting the needs of fusion reactors must include not only coils but also all the ancillary systems that are necessary in operation. In the development of toroidal field magnet systems, Japan, the European Atomic Energy Community (EURATOM), Switzerland, and the United States have joined in a development program, known as the Large Coil Task (LCT). The International Fusion Superconducting Magnet Test Facility (IFSMTF) at Oak Ridge National Laboratory (ORNL) is the focal point of the LCT. In the IFSMTF, six different coils from four countries will be operated as a toroidal magnet system, with each coil in turn being tested to determine its capabilities. Concurrently, the operation of the test facility itself is providing much information that will be useful in designing and operating complete magnet systems in fusion reactor plants.

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Comprehensive shakedown operation of the IFSMTF and preliminary tests with the first three coils (from Japan, the U.S., and Switzerland) were accomplished in 1984. The operation of the IFSMTF during the shakedown and preliminary coil tests produced useful data on the performance of the refrigerator, helium distribution system, power supplies, controls, and data acquisition system and on acoustic emission, voltages, currents, and mechanical strains in the coils during charging and discharging.

Fig. 1 Test Stand in Vacuum Vessel.

FACILITY DESCRIPTION

The heart of the facility is the test stand, depicted in Fig. 1. The D-shaped test coils have 2.5 x 3.5 m bore dimensions, weigh about 40,000 kg each, and produce a peak field of 8 T when operating at design current (10 to 19 kA). Each test coil can be subjected to a pulsed vertical field from a pair of coils cooled with liquid nitrogen (LN), which can be remotely moved on a circular track by a helium-actuated drive mechanism. Conductors in three of the coils (from EURATOM, Switzerland, and Westinghouse) are cooled internally by forced flow of helium at 3.8 K and 15 atm. The other three coils (from Japan, General Dynamics, and General Electric) are filled with liquid helium at atmospheric pressure and 4.2 K, providing

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bath cooling of their conductors. The bucking post, torque rings, and base structure are also cooled with liquid helium.

Thermal isolation of the test stand is provided by maintaining a vacuum in the 11-m-diam vessel, which is lined with LN-cooled panels blanketed with super-insulation. This vessel contains penetrations to pass through coil current leads, helium lines, and over 1500 cables from instrumentation. The vacuum pumping system includes roughing pumps, a turbomolecular pump, and a 35-in. diffusion pump.

Liquid nitrogen is supplied from tank trucks through vacuum-jacketed lines to four areas of the facility: the vessel cold wall, the helium purifier and refrigerator cold box, LN-cooled shields on helium lines and vessels, and the pulse coil system. Boiloff is vented.

Fig. 2 Helium system schematic.

The most complex ancillary system in the facility is the helium system, shown schematically in Fig. 2. It must have an unusual degree of flexibility in order to meet requirements of several modes of operation. During cooldown and warmup of the test array, up to 300 g/s of gas can be circulated at a controlled temperature between 300 K and 90 K, with flow distributed to limit thermal stresses. The final stage of cooldown is accomplished by operation of the refrigerator to provide cold helium gas and finally liquid helium. During coil testing operations, helium is provided to the test coils, their superconducting current leads, and test stand structure as required.

Flows and heat loads vary, depending upon the test in progress. During tests of forced-flow coils, the system must provide up to 1500 W of refrigeration at 3.5 K and about 150 W at 4.2 K. When bath-cooled coils are being tested, the 4.2-K load is higher and the 3.5-K load lower. Concurrently, liquefaction continues at a rate dependent on the refrigeration requirements at the time. During intervals between coil tests, when the refrigeration loads are lower, the liquefaction rate is sufficient to build up the inventory of liquid helium depleted during the tests. A 19,000-L storage dewar accommodates the fluctuating inventory of liquid.

The four oil-lubricated screw compressors, with a total power input of 2.0 MW, deliver 300 g/s at 15 atm. Buffer tanks accumulate or provide gas for liquefaction as required. Flow from the compressors, after cooling and oil removal, is cleaned in LN-cooled charcoal and molecular sieve beds of the helium purifier.

In the main cold box, the helium passes first through a LN-cooled heat exchanger and then through regenerative heat exchangers. The gas stream is then directed through additional heat exchangers in the Auxiliary Cold Box (ACB), where a 3.5-K bath cools the gas so it arrives at the forced-flow coils at about 3.8 K. A valving arrangement allows parallel or series connection and recooling of the stream for each of the forced flow coils. In the main cold box the returning gas stream is split between two gas-bearing turbo expanders. One of these provides cooling for the incoming gas; the other feeds into a Joule-Thomson valve that provides liquid at 4.2 K and 1 atm. Some of this liquid helium is further expanded to produce liquid at 3.5 K and 0.5 atm in the ACB bath.

The dewars for the vapor-cooled leads and the bath cooling for the superconducting buses to the coils are supplied with 4.2-K liquid from a 2000-L dewar, which can be replenished from the large storage dewar. Cold vapor from the dewars returns to the main cold box, while gas warmed by passage through the vapor-cooled leads goes back to the compressor suction.

In the event of a quench that produces massive boiling in a bath-cooled coil, fast-acting valves open to vent vapor through the dump tank to atmosphere. At the same time, valves in the lines to the cold box close to minimize pressure transients and consequent risk of damage to the gas-bearing turbo-expanders. If a quench occurs in a forced-flow coil, inlet and outlet valves quickly close and a bypass valve opens. Rising pressure is relieved by vent valves on both supply and return lines.

Fig. 3 Coil current system.

To provide flexibility in testing, each coil has a separate electrical system as shown in Fig. 3. Power supplies provide up to ± 12 V (at forward current only) with adjustable voltage and current regulation. Four of the supplies are rated for 16 kA; two, for 25 kA. When the current in the coil is steady, the voltage is extremely small; voltage is applied to raise or lower the current, typically at a few amperes per second. Each coil can be discharged rapidly by opening the circuit through the power supply. A dump command opens high-current switches S-1 and S-2. After a brief delay, breakers B-1 and B-2 open, forcing the coil current to flow through an air-cooled dump resistor. In this way, up to 100 MJ of magnetically stored energy per coil can be safely dissipated as heat. For bath-cooled coils, with dump voltages around 750 V, currents are reduced with a time constant of about 30 s. Forced-flow coils are brought down faster, with voltages around 2 kV and time constants about 6 to 11 s.

Coil currents flow in room-temperature aluminum buses up to the edge of the large vacuum tank, at which boundary there is a transition to superconductors. Fig. 4 is a cross section of one of the twelve lead dewars. Part of the helium boiled off from the pool in the helium vessel is directed up through the vapor-cooled (V-C) lead, warming to near room temperature as it intercepts heat being conducted down the lead from the warm connection at the top. The remainder of the boiloff is taken out of the top of the helium vessel (through a line not shown) back to the cold box. The lower end of each V-C lead is connected through a superconducting transition section to a superconducting bus that reaches across the vacuum tank to the test coil.

Facility instrumentation includes a wide variety of sensors, many operating at cryogenic temperatures, which provide information necessary for operation of the refrigerator, vacuum system, LN supply, etc. Process control is partly manual and partly through programmable logic controllers. Some variables are indicated directly, whereas nearly all are processed and sorted by a computerized data acquisition

system. The coil protection system rapidly deenergizes ("dumps") a coil if internal voltages indicate a persistent normal zone anywhere in a conductor (threatening damaging temperatures) or if the helium supply to a coil or superconducting bus becomes inadequate.

OPERATIONS ORGANIZATION

Continuous attendance by trained operators, necessary whenever the facility cryogenic systems are in service, is provided by four crews, working rotating shifts. During facility shakedown, each crew consisted of a Supervisor and two Operators. Candidate Supervisors were recruited from scientists and engineers in the magnet development group and candidate Operators were selected mainly from ORNL technicians. Selection was followed by intensive training, consisting of classroom instruction, hands-on operation, and observation and checkout of installation work. After several months of formal training, four-part examinations were given to all candidates. The first was open-book with consultation, requiring each person to locate every valve, control and major system component. The second was a closed-book examination. The third was a comprehensive, open-book examination with no assistance from others. Final examinations were administered orally. All candidates (except one who missed much training because of illness) demonstrated satisfactory proficiency. ORNL management certified seven LCTF Supervisors and nine LCTF Operators before beginning shakedown operations.

Fig. 4

Transition of coil current from room-temperature bus to 4.2 K superconducting bus.

With these limitations, the temperatures in the 200,000-kg test stand were brought down at about 17 K/d. Helium inlet temperature and distribution of flow among the spider frame, bucking post, torque rings, and the windings and structures of three coils were controlled manually without great difficulty. The Swiss requirement that their coil case be kept colder than the windings was met.

After 12 days, cooling of the helium with LN was rapidly becoming inefficient, as the helium temperature was down to 86 K. Coil temperatures were 100 to 110 K, most of the thermal contraction had already occurred, and no new helium leak had appeared. (The leakage rate had increased only to 8×10^{-3} scc/s, consistent with a constant size and changing helium properties.) The decision was therefore made to prepare for the final phase of cooldown. This entailed stopping flow through the test stand for 22 h while the refrigerator was operated in the liquefaction mode to build up the amount of stored liquid to 18,000 L.

Flow through the test stand was resumed, using turbine 1 to supply refrigeration for cooling below LN temperature. Turbine 2 was started when the helium to the test stand reached 20 K. On day 20, portions of the coils began superconducting. (Resistance of each coil to a 10-A current was being measured.) During this 7-day period, the rate of cooldown, limited by refrigeration capacity, increased from 12 to 20 K/d. Three more days were spent in verifying temperatures around the test stand and filling the ACB bath. Liquid helium was then admitted to cool the coils, and all three quickly became fully superconducting.

During the cooldown, with the turbomolecular pump in service, tank pressure decreased and leveled off at about 10^{-4} torr. Mass spectrometer measurements indicated that the major impurity at first was air, which disappeared when the temperature of test stand surfaces fell below about 60 K. No major increase in helium leakage occurred when the JA coil was filled. However, when the GD/C coil and its superconducting buses were filled with LHe the tank pressure rose to about 5×10^{-4} torr, indicating a helium leak rate of about 0.5 scc/s. Since this helium pressure would result in an appreciable increase in heat loads the diffusion pump was turned on. This was able to maintain tank vacuum at about 2×10^{-5} torr with all components full of liquid helium.

After all the coils were fully superconducting, about four days were spent checking the automatic helium refill system, measuring component boiloff rates, and allowing all structures to reach their minimum temperatures before energizing the coils. The helium fill system worked well, although it was necessary to build up pressure in the 19,000-L dewar by

closing its vent valve to achieve an adequate liquid transfer rate. The liquid level in each bath-cooled coil was restored roughly every 3 h by transferring about 180 L of LHe in 30 min. Helium boiloff measured for the coils and facility components were comparable to expected values except for the lead dewars, which appeared higher than expected.

The coil power supplies were used for the first time on July 31, when the current in the GD/C coil was ramped to 330 A at 1 A/s and dumped without incident. Further tests on the following day were interrupted when air leaked into the vacuum jacket on the helium storage dewar. Due to a slight leak in its vapor-cooled shield piping, it has been necessary to pump this vacuum jacket continuously. A mechanical pump in the system stopped and valving failed to prevent air flow back into the jacket. A large amount of air and water condensed inside the jacket, and the resulting heat flow boiled the dewar dry. Five days were spent repairing the pumps, warming the dewar, and evacuating the jacket. During this time the coils and test stand warmed up to 40-50 K and had to be cooled back down.

There were several annoying problems with the helium compressors during recooling of the test stand. As a result, it was two weeks after the dewar vacuum failure before the coils were again cold and ready for further testing. The automatic helium fill system again worked well except for a sticking cryogenic supply valve on the bucking post. Several relief valves began continuously leaking during coil tests, evidently due to freeze damage to the soft seats when the valves operated. The programmable logic controller that handled the refrigerator safety interlocks also began causing frequent compressor shutdowns - this was later traced to a defective memory chip. However, none of these problems significantly interfered with the coil tests, which resumed on August 14 and were concluded on September 3.

During the coil tests, the GD/C and JA coil currents were raised stepwise to their design values (10.2 kA), both singly and with the adjacent coil at 4 kA. Tests included dumping and spontaneous recovery from heater pulses that drove a half-turn of conductor normal while the coil was operating at full current. Results of the coil tests are reported in detail in Ref. 3.

At the outset of the coil tests, some problems were encountered with the current controls in the coil power supplies. These had not been encountered in acceptance tests, in which it had been impractical to include large inductive loads simulating a test coil. There were some delays in coil tests, and on one occasion some capacitors in a power supply were

destroyed by a transient. After slight modification of the internal regulators, performance was adequate for the coil tests.

The facility's unique quench detection and coil protection system worked quite satisfactorily. Because the voltage withstand capability of the GD/C coil was not as high as intended, before the coil tests the taps on the dump resistor were changed to reduce it from 79 to 53 mΩ. The center tap was also grounded to further reduce maximum voltages from conductor or sensors to ground.

The mechanical behavior of the coils and test stand, which was observed by strain gauges and displacement transducers, was in good agreement with predictions. Heat flows into the coils and test stand (including radiation through the cold wall and conduction through gravity supports, current buses, and instrumentation leads) were gratifyingly low, amounting to about 50 W per coil. There were indications of excessive heat flow into helium transfer lines due to poor vacuum in some jacketed sections, probably on the order of a few hundred watts. (After the end of operation, vacuum leaks in these sections were found and repaired.)

Tests designed to demonstrate the forced-flow refrigeration capabilities of the system were attempted before the coils were warmed up. Results were inconclusive because one of the main coldbox heat exchangers plugged up shortly after ½-atm operation of the ACB began, apparently due to air that leaked in through a faulty ACB bath burst disc. Also, helium leakage had reduced inventory to the point that cooling of all components could not be sustained. However, the Swiss coil was briefly cooled below 3.8 K, with a helium mass flow of over 300 g/s and a forced-flow heat load of 250 W. When an additional 500 W was added to the 4.2 K system, compressor inlet pressures began to rise and the tests had to be terminated. The tests sufficed, however, to demonstrate that the ACB heat exchangers were adequate for cooling the forced-flow coils.

Warmup of the system was carried out by circulating helium through the facility at a temperature 50 K warmer than the coils and structure. After two weeks, with temperatures near 250 K, dry air was introduced into the tank. However, warmup over the last 50 K was very slow because there was no provision for heating the circulating helium above ambient temperature. When temperatures reached the 290 to 295 K range, the tank was vented to atmosphere and the lid removed. A visual inspection turned up little damage beyond a loose HeII probe on the GD/C coil and several cracked heat-shrink sleeves on instrument lead cables.

Analysis of the performance of the vapor-cooled leads showed the expected values of helium consumption at zero current. The apparent excessive boiloff occurred when operated at a warm gas flow rate that was too low. This came about because of concern with the warm end temperature, which was below the frost point with vapor flow of less than half the optimum. An ambient nitrogen-purged enclosure plus heat lamps helped to prevent frost at low lead vapor flows. Thus, the lead vapor flow was maintained at a level to minimize frost build up and to provide an acceptable lead resistance rather than at optimum for refrigerator operation. With current in the leads, however, helium losses increased beyond expected values. The reasons are not clear at this time. Several possible mechanisms have been proposed. Further experiments are planned with VC leads in a more realistic configuration than earlier tests.

CONCLUSIONS

Operation showed that in only one important area - the liquid helium system - were substantial improvements required. Indicated needs for other repairs, adjustments, and modifications of the facility systems were relatively minor. The quality of design and construction was demonstrated by operation over an extended period: the test stand under vacuum for 93 d and cold (below 80 K) for 59 d. No damage was suffered as a result of the operation. A helium leak in a superconducting bus duct persisted throughout, but no cold leak developed.

Operation of the helium system was, as expected, a demanding task that often monopolized the time of the three-person facility operating crew. Nevertheless, a satisfactory availability factor was achieved and performance met the needs of the partial-array coil tests.

The IFSMTF will be suitable for its intended purpose, which is to test an array of six different superconducting toroidal field coils.

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