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STARTUP OF LARGE COIL TEST FACILITY*

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SUMMARY

The Large Coil Test Facility (LCTF) is being used to test superconducting toroidal field coils about one-third the size of those for INTOR. Eventually, six different coils from four countries will be tested. Operations began in 1983 with acceptance testing of the helium refrigerator/liquefier system. Comprehensive shakedown of the facility and tests with the first three coils (from Japan, the United States, and Switzerland) were successfully accomplished in the summer of 1984. Currents up to 10,200 A and fields up to 6.4 T were reached. Data were obtained on performance of refrigerator, helium distribution, power supplies, controls, and data acquisition systems and on the acoustic emission, voltages, currents, and mechanical strains during charging and discharging the coils.

1. BACKGROUND

After construction of the LCTF in Oak Ridge was authorized in 1977, it soon became the focal point for multinational collaboration in large-scale development of superconducting toroidal field coils. An agreement defining the Large Coil Task (LCT) was signed in 1977-78 by the United States, EURATOM, the government of Japan, and the government of Switzerland. Each of the six test coils was designed to Oak Ridge National Laboratory (ORNL) specifications, which defined spatial envelopes and performance but left choices of conductor, winding, and structural design up to each design team.[1] The LCT test programme was planned jointly by project officers representing each participant and was formally adopted by the LCT Executive Committee, which includes one member from each participant. An outline of the LCT test programme is as follows:

Phase	Purpose	Scope
I. Initial	Determine if facility is capable and coils ready	Check at room temperature, cool to 4 K, run low current
II. Partial array (JA, GD/C and CH coils[a])	Test coil interactions, check instrumentation, measure heat loads, shake down facility	Run full current in JA and GD/C singly, run high currents in both. Simulate forced-flow coil tests
III. Full-array, full current	Prove coil performance to nominal design conditions	Impose pulsed fields, observe stability and recovery at full current in test coil, 80% in background
IV. Extended conditions	Test coil capabilities beyond nominal design conditions	Up to 140% singly, higher pulsed fields, out-of-plane forces
V. Sustained operation	Demonstrate durability at maximum capability	Operate with pulsed fields at practical current limit

[a] Current limited to 10 A by partial installation.

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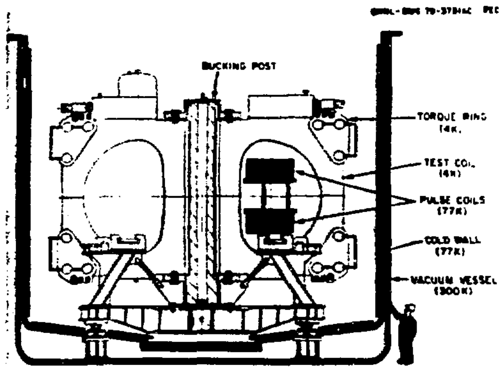

Fig. 1. LCTF Test Stand

The LCTF test stand concept is a compact toroidal array of up to six coils. (The coil structures are designed to withstand out-of-plane loads encountered if not all six positions contain operable coils.) Figure 1 indicates some of the measures provided to minimize heat flow into the 450 tonnes of test stand that must operate at about 4 K. They include 10^{-5}-torr vacuum, liquid-nitrogen-cooled cold wall, reflective blankets, and roller mounting on pedestals.

The Japanese coil was delivered to the LCTF in November 1982 after having been tested in Japan.[2] The coil by General Dynamics/Convair (GD/C) was delivered in June 1983. By December, both coils had been installed.[3] The first cool-down was aborted when helium leaks appeared. While the vacuum tank was open for repairs, in February 1984 the Swiss coil was delivered. Considering schedule the Executive Committee decided that the Swiss coil should be installed with the exception of the high-current leads, Reinstallation of the GD/C coil and (partial) installation of the Swiss coil were finished in June. By early July the tank had been evacuated and an adequate inventory of helium liquefied. Figure 2 is a diagram of the LCT schedule from then on.

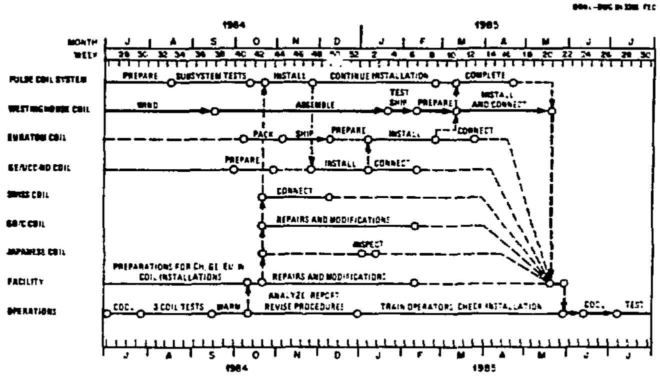

Fig. 2. Large Coil Task Schedule (August 1984 draft)

Delivery of the EURATOM coil is timed for convenience. It was tested in the TOSKA facility at Karlsruhe from March to May 1984.[4] Assembly of the coil by General Electric is being completed in Oak Ridge. Meanwhile, winding of the Westinghouse coil has just been finished.

2. ACCEPTANCE TESTS

In the fall of 1982, tests were conducted to verify the integrity of the cold wall after its assembly and to determine the performance of the tank evacuation system. Pumping speeds agreed with expectations, outgassing rates were reasonable, and air inleakage was extremely low. The cold wall incorporates 114 stainless steel panels, with channels for nitrogen cooling, welded to headers for liquid supply and vapor removal. The experience with assembly welds was outstandingly successful: there was no detectable leak during the integral leak test in vacuum nor in subsequent operations.

Initial operation and acceptance testing of the helium refrigerator system stretched from January to August 1983. During this period, helium gas was circulated to clean up the equipment, leaks were stopped, and numerous minor defects were remedied.[3] As conditions approached flowsheet values, one of the two turboexpanders failed. Inspection of the thrust bearing led the manufacturer to recommend reduction of allowable inlet pressure. Despite this limitation, subsequent operation under loads simulating tests of coils showed that performance still met specifications. Results included: in pure liquefaction mode 450 L/h, and in the forced-flow test mode 1.54 kW refrigeration at 3.5 K plus 0.35 kW at 4.2 K plus 10 g/s (300 L/h) liquefaction. Further experience and data were gained during facility shakedown in 1984, described later.

3. COIL INSTALLATION

Installation of each coil entails positioning and structural connections to collars and torque rings; installing two superconducting buses in helium-tight jackets between the coil and dewars outside the vacuum tank; welding of helium supply, return, and vent lines; and laying out of sensor and heater leads and their attachment to tank wall feedthroughs, followed by pressure, leak, and electrical tests. This work is complicated by the limited space inside the tank, the risk of damage to sensitive items (such as sensor leads), and the necessity of cleanliness appropriate for a vacuum system.

Coil handling procedures, developed in advance using a mockup, ensured safety and efficient, precise positioning. Fitup of each of the first three coils to the bucking post was extraordinarily close. Over the 4.6-m long contact surfaces, clearances after attachment ranged from 0 to only 0.3 mm, well within tolerances set by stress considerations.

Attachment of helium lines, including level probes, typically entails about 16 welds per coil. These have been done with the same orbiting automatic welding device used to assemble the cold wall. No weld made in the tank has ever leaked in subsequent operation.

Safety and quality have been preserved while reducing the times required for coil installation. During installation of the first coil (the Japanese), time was available and was used to verify and improve equipment and procedures over a nine-month period. Two months were required to install the GD/C coil; four weeks were needed to reinstall it after repairs.

4. FIRST COOL-DOWN

When the tank lid was installed and evacuation started, many small air leaks were found at mechanical seals and were soon repaired. When the GD/C coil and piping were filled with helium, leakage was detected. The same was true of the helium system of the Japanese coil.

In both cases leaks were traced to joints between the coil vent line and tubes in which sensors were mounted. After these leaks were eliminated, air inleakage reduced to an acceptable level, and helium liquefied and stored, cool-down was initiated by circulation of helium gas, cooled with liquid nitrogen. A conservative criterion regarding thermal stresses limited the cool-down rate to about 0.8 K/h. When coil temperatures reached 175 K, there was an abrupt increase in tank pressure to over 10^{-3} torr and an increase in the helium concentration in the tank atmosphere. When the pressure in the GD/C coil was reduced, the leakage indications diminished. The leak rate was so large (1 to 5 scc/s) that it was impractical to continue the test. Warm-up was therefore started. Because the leak(s) might close up when the coils became warm, the lid was removed when temperatures on the test stand were about 260 K. Although frost formed on colder surfaces, the leaks were still detectable.

5. REPAIRS OF GD/C COIL

Leaks were found at ports that had been welded shut by GD/C after having been used to inject polyurethane between the winding pack and coil case. Inspection showed that urethane vapors had contaminated closure welds, leading to subsequent cracking and leakage. All port welds were cut out, urethane removed from proximity, and new plugs welded in place. After sensitive helium leak tests, cover plates (or additional weld metal) were applied to reduce further the risk of leakage. Helium leak tests of all sensor lead feedthroughs and thin-section welds on the GD/C coil showed no detectable leak.

Because of experience with damage to sensor lead insulation during work inside the tank, it was decided to improve the electrical insulation and protection of all 120 cables from sensors inside the coil. Close-fitting Teflon tubing was heat shrunk on each cable. Then bundles of cables of similar voltage were protected by slipping Teflon tubing over them. Each bundle was tested by filling the sheath with helium, then imposing 8.5 kV on a bare copper wire in the bundle. After repair of a few defects, no more breakdowns occurred.

6. FACILITY SHAKEDOWN AND COIL TESTS

The rationale for operating the facility with only two or three of the test coils in place developed from the circumstance that the facility and some coils would be finished a year or more before the last coils. Early shakedown of the facility by actual tests of the first coils was therefore a reasonable step to minimize risk of unforeseen problems in the subsequent startup with a full six-coil array. With this in mind, the following critical objectives were established by the LCT Project Officers in 1983:

- Cool down test stand in controlled fashion, in a reasonable time.
- Fill at least one coil with liquid helium, then maintain test stand at 4 K.
- Operate at least one coil at full current, proving operation of power supply, vapor-cooled leads, superconducting bus, dump system, and data system.
- Operate two coils simultaneously, proving quench detection system and stable operation of power supplies with magnetically coupled coils.
- Operate for a substantial period of time with simulated forced-flow coils, simulating all operating modes of the helium system.

All of these objectives were attained or surpassed in one period of continuous operation from June into September 1984. Not only was the operability of the facility and coils demonstrated but, by virtue of the thorough instrumentation, many additional insights or valuable confirmations of design calculations were also gained during the tests.

Operation of the helium system was, as expected, a demanding task that often monopolized the time of the three-person operating crew. Nevertheless, a satisfactory availability factor was achieved, and, by expert adjustment of operating variables, the performance was made to satisfy present needs. The capability for controlled cool-down proved quite satisfactory.[5,6] Ability to support sustained six-coil testing was another matter. Most observed heat flows agreed reasonably well with calculated values, except for those through the vapor-cooled lead dewars, which were anomalously high. The data indicate that improvements must be made to provide adequate margins between projected loads and refrigeration/liquefaction capacity.

A crack at a bellows around one superconducting bus leaked helium throughout the run. The change in mass leak rate with temperature reflected only changes in helium properties, indicating that the size of the crack did not grow. There was no other detectable helium leak. Air inleakage into the tank was quite tolerable. The mechanical and turbomolecular pumps maintained pressure in the 10^{-5}-torr range without any aid from cryopumping on test stand surfaces. After this became effective during cool-down, the vacuum generally held in the 10^{-6}-torr range. The increased helium leakage whenever the bus jacket was filled with liquid was easily accommodated by operation of the large oil-diffusion pump.

The expected residual resistances of the copper in each coil and the critical temperatures for the NbTi superconductors were confirmed. The Japanese and GD/C coils were each taken to design current (10,200 A) both separately and with the other at 4100 A, generating fields up to 6.4 T.

There were some problems with power supply controls that prior tests, with mostly resistive loads, had not revealed. These were resolved without major modification. Magnetic coupling of the coils produced appreciable effects but did not significantly affect control in either constant current or constant voltage modes.

The tests demonstrated the practicality of the unique system that was developed for detecting small resistances in the magnetically coupled set of coils in LCTF. Inductive voltages were effectively cancelled by the use of compensation coils on the faces of the test coils, which permitted small resistive voltages (indicative of a normal zone) to be distinguished. The LCTF quench detection system worked admirably well, remaining operational on one coil when the current in the neighboring coil was ramped or even dumped.

Stress in the test stand member that limits loads in a partial array behaved as expected. Changes in bore dimensions of both coils also agreed with predictions. Acoustic emissions of the Japanese and GD/C coils during load changes were recorded for off-line analysis. Numerous events that were tentatively identified as minor slippages in the winding pack were detected, especially when magnetic forces were first applied. There were significant differences between acoustic emissions from Japanese and GD/C coils. These differences and differences in the measured compression and liftoff of the winding pack appear to be related to differences in designs and assembly procedures of the two coils.

The excellent stability of the Japanese and GD/C coils was demonstrated. Brief pulses of imbedded heaters were used to drive half-turns (5-m lengths) of conductor normal. Figure 3 shows typical behavior in such tests of stability. Spontaneous recovery of full superconducting state occurred in 0.1 to 1.0 s after the heat pulse.

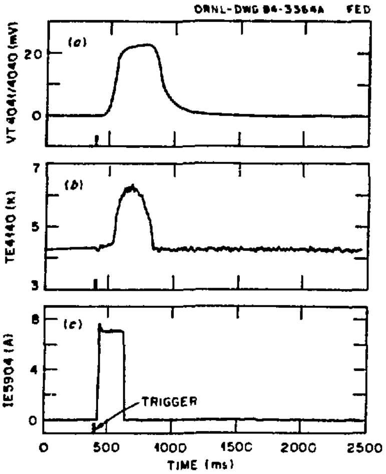

Fig. 3. Results of pulsing half-turn heater with GD/C coil at full current. (a) Voltage across one-sixth turn. (b) Conductor temperature. (c) Heater current.

7. CONCLUSIONS

International collaboration in the development of superconducting toroidal field magnet systems is working well, as evidenced by recent testing of coils from Japan, Switzerland, and the United States in the LCTF.

Operation showed that the LCTF will be suitable for its intended purpose, which is to test an array of six different coils under simulated tokamak conditions. The quality of design and construction was verified by the performance and reliability achieved after the initial shakedown.

In only one important area — helium refrigeration/liquefaction — does it appear that improvements in the facility will be required.

The first three coils were shown to be operable in the LCTF; i.e., they can be cooled to operating temperature with good control of temperatures in structure and winding.

Useful, new information was derived from the tests of two of the large, highly instrumented coils up to full design current. Examples are remarkable stability, inconsequential compression of the windings, and acceptable strain in the complex structure.

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