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THE LARGE COIL TASK AND RESULTS OF TESTING U.S. COILS*

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Abstract

The United States, EURATOM, Japan, and Switzerland have collaborated since 1978 in development of superconducting toroidal field coils for fusion reactor applications. The United States provided a test facility and three coils; the other participants, one coil each. All coils have the same interface dimensions and performance requirements (stable at 8 T), but internal design was decided by each team. Two U.S. coil teams chose bath-cooled NbTi, 10-kA conductors. One developed a Nb_3Sn conductor, cooled by internal flow, rated at 18 kA. All U.S. coils have diagnostic instrumentation and imbedded heaters that enable stability tests and simulated nuclear heating experiments. In single-coil tests, each coil operated at full current in self-field (6.4 T). In six-coil tests that began in July 1986, one U.S. coil and the Japanese coil have been successfully operated at full current at 8 T. The other coils have operated as background coils while awaiting their turn as test coil. Coil tests have been informative and results gratifying. The facility has capably supported coil testing and its operation has provided information that will be useful in designing future fusion systems. Coil capabilities beyond nominal design points will be determined.

Introduction

The United States, EURATOM, Japan, and Switzerland are collaborating in development of superconducting toroidal field (TF) coils for fusion reactors under the terms of the Large Coil Task (LCT) agreement, which was signed in 1978. The objective of LCT is to provide participating fusion programs with the major part of the data base needed for selection of a TF coil concept for future use. Apportionment of responsibilities in LCT is indicated in Fig. 1.

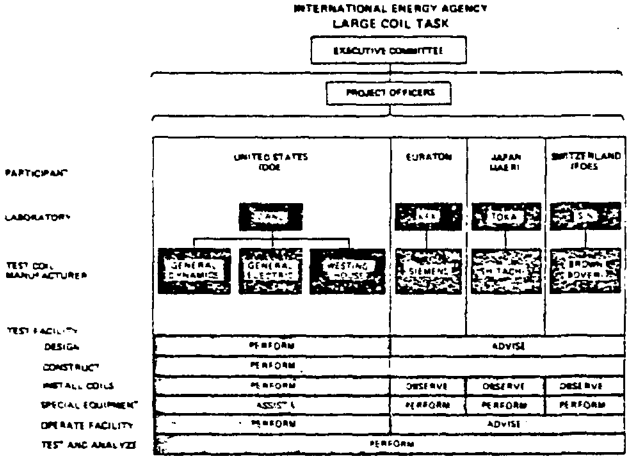

Fig. 1. Responsibilities in the Large Coil Task.

Table 1 is a first-level outline of the test program adopted by the Executive Committee, which includes one representative of each of the four participants. Design-point tests without pulsed fields are under way at this writing.

Table 1. Outline of LCT test program

- Startup
  - Tank evacuation
  - Leak tests at room temperature
  - Test stand cooldown
  - Leak tests at cryogenic temperatures
- Preliminary tests
  - Low-current checkout of I&C
  - Single-coil tests to full current, 6 T
  - Multicoil tests to 0.2 full currents
- Design-point tests
  - Full current, 8 T, without pulsed field
  - Test pulse field system to design current
  - Full current, 8 T, with pulsed field
- Extended-condition tests
  - High-field symmetric torus
  - Full current, higher pulsed fields
  - Highest current and field
  - Higher out-of-plane loads

All coils are designed to specifications that define basic dimensions and performance but leave choices of conductor, winding, structural, and thermal design up to each design team.[1] Test coils are about 0.4 the size envisioned for tokamak reactors, but conductors are full size. The specification requires each coil to be capable of producing 8 T at its windings if the rest of the six-coil torus consists of identical coils at 80% of the test coil current. Design choices are indicated in Table 2. Detailed descriptions of coils have been published.[2-8]

Coils are being tested in the International Fusion Superconducting Magnet Test Facility (IFSMTF) at Oak Ridge. The test stand in its 11-m diam vacuum tank is depicted in Fig. 2. Test coils are attached through upper and lower collars to the hexagonal bucking post and are clamped in torque rings at the outer corners.

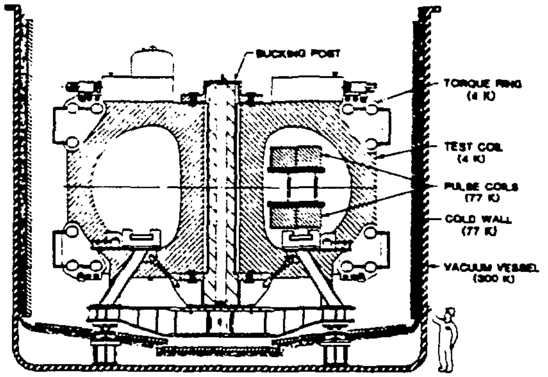

Fig. 2. IFSMTF test stand.

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Table 2. Distinctive features of test coils in the Large Coil Task

Designer/Manufacturer:	General Dynamics	General Electric	Westinghouse	JAERI/Hitachi	KfK/Siemens	SIN/BBC
Superconductor	NbTi	NbTi	Nb_3Sn	NbTi	NbTi	NbTi
Conductor cooling	Immersed in boiling bath 4.2 K, 0.1 MPa	Immersed in boiling bath 4.2 K, 0.1 MPa	Internal forced flow 3.8 K, 1.5 MPa	Immersed in boiling bath 4.2 K, 0.1 MPa	Internal forced flow 3.8 K, 1.5 MPa	Internal forced flow 3.8 K, 1.5 MPa
Conductor configuration	Cable soldered in grooved copper bar	Subelements around copper strip	486-strand cable in stainless steel conduit	Cable soldered in roughened copper bar	Subelements around CuNi core in flat conduit	Solder-filled cable around central tube
Conductor current	10,200 A	10,500 A	17,760 A	10,220 A	11,400 A	13,000 A
Winding configuration	Edge wound, in 14 layers	Flat wound, in 6 double pancakes	Laid in grooves in 24 plates	Edge wound, in 20 double pancakes	Flat wound in 7 double pancakes, potted	Wound in 11 double pancakes, potted
Structure	Type 304L SS welded case	Type 316LN SS welded, bolted case	Aluminum alloy bolted plates	Type 304LN SS bolted, welded case	Type 316LN SS bolted, sealed case	Type 316L/316LN SS bolted case

A pair of copper coils, cooled with liquid nitrogen (LN), are mounted on a carriage on a circular track with provisions for moving remotely to each test coil in turn. It is planned that these coils will be pulsed to produce transient vertical fields at the test coil windings.

The IFSMTF refrigerator, which is rated at 1.5 kW at 4.2 K, supplies liquid helium at 4.2 K to three coils while circulating up to 300 g/s of helium at 1.5 MPa and 3.8 K through the three forced-flow coils. Each coil has its own power supply, with a control system that ramps all coil currents simultaneously. A quench detection system detects very small resistive voltages in the presence of large inductive voltages. If a significant, persistent normal zone is detected, the control system initiates a rapid discharge of all coils through dump resistors outside the vacuum tank.

Experimental data are acquired through a computerized data acquisition system.

Activities Through 1985

The first LCT coil to be completed was the Japanese (JA) coil. It was cooled down and tested in JAERI's superconducting engineering test facility at Naka in November 1981 and the spring of 1982.[8] It was then shipped to Oak Ridge, arriving in November 1982. The General Dynamics (GD) coil was delivered in June 1983. Shakedown tests of the facility with these two coils in January 1984 were interrupted when the GD coil leaked at ports used to inject polyurethane between winding and case. While it was being repaired, the Swiss (CH) coil arrived and was installed except for high-current leads. In the summer of 1984, facility shakedown and preliminary coil tests (up to full current in JA and GD coils) were performed.[10,11] Meanwhile the EURATOM (EU) coil was completed and tested in the TOSKA facility at Kernforschungszentrum Karlsruhe.[9] It was then delivered to the IFSMTF in December 1984. In 1983 the partially assembled General Electric (GE) coil had been brought to Oak Ridge, where it was completed before delivery to IFSMTF in December 1984. Oxford Airco finished the Nb_3Sn conductor in November 1983, and in August 1985 Westinghouse (WH) completed and delivered the last LCT coil. In October 1985 all installation work in the vacuum tank, including the pulse coil system, was completed (Fig. 3).

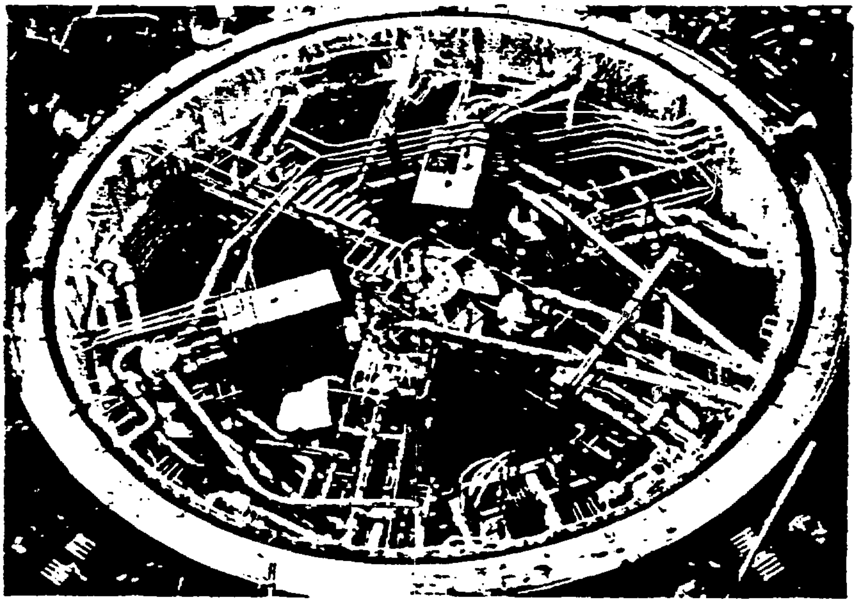

Fig. 3. Six-coil test array in IFSMTF vacuum tank.

Operation of the helium refrigerator met requirements for the partial-array operation in 1984.[12] Afterwards, the helium system was upgraded by additional gas storage tanks and a supplemental 60-L/h liquefier. During the summer of 1985 the system was again operated with a dummy load to determine readiness for six-coil test support. Additional oil-separation components were installed by November.

After the tank was closed on October 24, 1985, air leakage through the hundreds of penetrations was brought down to an acceptable level, and the tank was pumped down to the 8×10^{-4} torr criterion in a total of 16 days. Leakage from cold-wall and pulse coils into the tank was acceptably low from the start. When the tank was evacuated, helium leakage from the CH coil was found to be about 10^{-2} scc/s. The leak proved to be at a defect in a tubing connection in the coil header system and was stopped by welding. A much smaller leak from the GE coil (10^{-3} scc/s) in a bolt cover was also found and repaired. Helium leakage at about 2×10^{-4} scc/s remained, coming from one of the superconducting bus ducts attached to the GD coil. Cleanup of impurities from the helium system was delayed by water leaks in a compressor oil cooler, and it was not until December 16 that cooldown of the six-coil array could begin.

Cooldown of Six-Coil Array

Cooldown was interrupted after 3 days when excessive loss of helium was observed. The leak proved to be in the cooldown heat exchanger, which was removed and found to be damaged by freezing water that had been drawn in with air through a leaking check valve into the nitrogen side of the heat exchanger during previous cryogenic operation of the coldbox. An identical heat exchanger was quickly obtained from Lawrence Berkeley Laboratory and installed.

The progress of the test stand cooldown after resumption on January 18 is shown in Fig. 4, which shows the temperature of helium gas entering the test stand and the mean temperature of each coil. During the first several days, numerous adjustments of helium flow distribution were made to get temperatures in all components (coils and test stand) to come down at the same rate, within prescribed limits on temperature differences (from 40 K to 100 K in different components). The cooldown rate gradually increased to 0.63 K/h, reflecting decreasing specific heat and increasing mass flow rate. When coil temperatures reached 100 K, cooldown was interrupted to let the refrigerator liquefy 10,000 L of helium for later use. After 3 days, cooldown was resumed, now using a turboexpander instead of LN to cool the circulating helium gas. As the specific heat decreased faster than the refrigeration power, the cooldown rate again increased, reaching about 0.7 K/h. On February 13, the WH coil became fully superconducting at a temperature of about 15 K. Problems with startup of the second turbine and an instrument air failure delayed the last stage of cooldown, and it was February 18 before the five coils with NbTi conductor became superconducting as temperatures reached 9 K.

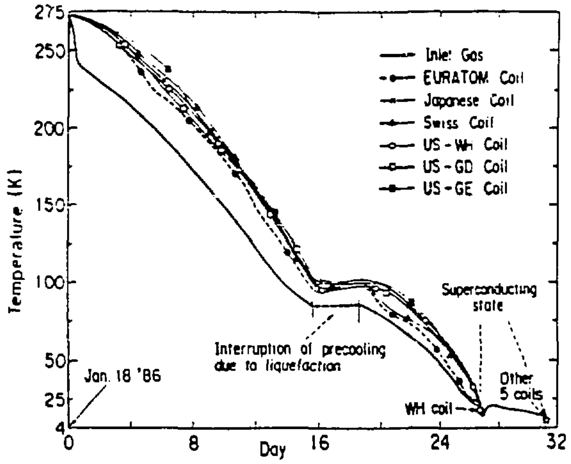

Fig. 4. Temperatures of helium supply and coils during cooldown.

During the six-coil cooldown, no new leak appeared in either helium or nitrogen cryogenic systems within the vacuum tank. This was especially significant since this was the first time that the GE and WH coils had been cooled. During the course of the cooldown, the total rate of helium leakage in the tank gradually increased, finally reaching about 0.3 scc/s at 4.5 K. This variation of leakage rate with test stand temperature was consistent with the expected behavior due to helium property changes if the leak path remained unchanged. The source later proved to be the duct that houses a the superconducting bus attached to the GD coil. The leakage went up to 3 scc/s with liquid in the duct, always decreasing to the 10^{-3} range as the duct was allowed to boil dry. By operating the diffusion pump on the vacuum tank whenever the leaking duct was filled, the tank pressure could be held to about 1.2×10^{-4} torr. With the duct dry, the two turbomolecular pumps were able to keep the tank at about the same pressure.

All coils behaved predictably during cooldown. The pool-boiling coils had low coolant velocities in the windings at the flow rates that could be provided by the facility, resulting in relatively low heat transfer coefficients. The force-flow coils, on the other hand, had higher velocities in the coolant channels, with good heat transfer but higher pressure drop.

The rate of cooldown was as low as it was because the capabilities of the facility's cryogenic system are small in relation to the amount of heat to be removed.[13] To bring the 420-tonne test stand from room temperature to operating temperatures, 25,000 MJ of heat must be removed. Of this about 90% is removed during the first phase, down to 100 K, when LN is the heat sink. During this phase, coils could have been cooled much more rapidly if a greater mass flow had been available or if allowable ΔT restrictions had been relaxed. (In domestic tests, with more cooling power per coil, the JA coil was cooled to superconducting temperature in 120 h; the EU coil, with allowable ΔT half as great, in 203 h.) During the second phase the cooldown rate was limited by turboexpander capacity, which decreased from 10 kW at 100 K to 0.6 kW at 20 K.

Tests of U.S. Coils

Cooldown was itself a very significant test of the coils, which was quite successful in that the rate was reasonable and no new leak or excessive stress resulted. Subsequent tests of all LCT coils are described in some detail in other papers at this Applied Superconductivity Conference. See Ref. 14 for a summary. Selected highlights are given below.

Strain measurements indicated that all U.S. coils can achieve design-point operation without excessive stress in either conductor or structure. In the pool-boiling coils, significant displacements of winding packs relative to the coil cases were measured, accompanied by conductor strains larger than would be predicted if this behavior were ignored.

The large internal forces produced in the coil windings during high-current operation had no detectable effect on electrical insulation. Specifically there were no additional shorts in sensor leads, such as had been produced during assembly of the GE coil.

Numerous acoustic emissions and small spikes in compensated voltage were observed during charging and discharging of every coil. There were significant differences, however, especially between pool-boiling and forced-flow coils, in the patterns and correlations.

All 3 coils showed a high degree of stability. The GD coil quickly and spontaneously recovered from a full-turn (11-m) normal zone induced by heaters while the coil was at design current with the field at the conductor up to 8 T. The GE coil, in a single-coil test at full current and self-field (6.4 T), recovered from a normal zone two-thirds of a turn in length. In this test there was evidence of accumulation of vapor in the winding pack at the top of the coil, an effect which had been anticipated with the broad, flat-wound conductor. Recovery progressed from the ends of the normal zone in this case. Tests of the WH coil showed, as expected, substantial tolerance for temperature excursions and clearly revealed the effects of a "warm slug" of helium circulating around the winding.

Tests indicated that the current-carrying capability of the WH conductor will be sufficient for design-point operation and probably for the foreseen extended-condition tests. It is much less than that of single-strand samples, however, presumably because of effects of strain during conductor handling and coil manufacturing. The total electrical resistance of the 44 conductor joints in the header region is 0.3 μΩ, considerably higher than expected from development tests. This produces almost 100 W of heat during operation at full current (17.8 kA).

Tests showed, as expected, significant heating by eddy currents in the WH structure during field transients. Connection of the plates is through the numerous, uninsulated bolts, resulting in a widely distributed heat source. Dumps from high current cause no damage or unacceptable effect on the cryogenic system but must be followed by some hours of cooling to regain operating temperature.

The sensor lead feedthroughs on the GD coil continued to operate at liquid helium temperature without detectable leakage of helium. However these feedthroughs are suspected as the location of the electrical breakdown between conductor and ground which occurs now at a lower voltage than before the beginning of the six-coil operation. This has necessitated a slower dump of the GD coil, which is, however, tolerable.

Facility Operation

Extended operation of the test facility (continuous from mid-January for more than 8 months at this writing) has produced significant information on performance, reliability, and sources of problems. In general, performance of facility systems ranges from adequate to highly satisfactory. On the other hand, reliability/availability of some systems still leaves much to be desired.

Thermal isolation of the test stand has proved to be effective, as the total rate of heat flow into each coil averages only about 70 W when there is liquid helium in the current bus ducts; 120 W when the ducts contain only gas. The required rate of liquid helium supply to the vapor-cooled lead (VCL) dewars and attached bus ducts averages 36 L/h (434 L/h for all 12).

The liquefaction capability of the helium system depends sensitively upon conditions. With no additional refrigeration load, liquefaction rates up to 400 L/h have been achieved with the facility refrigerator. When the test stand is being kept cold but coils are deenergized and VCL dewars are empty liquefaction in the facility refrigerator exceeds boil-off by about 100 L/h. During tests with all six coils at high current, boil-off exceeds liquefaction by about 150-200 L/h. Supplemental liquefiers (CTI 1430 and CTI 2800) produce about 40 and 60 L/h that can be conveniently added to the facility helium system. This situation is satisfactory, as coil testing can be supported up to about 40% of the time during any week, with transitions and recuperation during midnight shift and weekends.

Instrumentation, control, and data acquisition systems have encountered problems but have generally worked quite satisfactorily. The controls on each coil power supply required some adjustments, which was complicated because of the great difference between the high-inductance, very low-resistance characteristics of the coil and buswork and any dummy load that could be devised for pretesting the supplies. The system for coordinating the simultaneous energizing and deenergizing of the six separate coils and power supplies has worked quite well.

An index that has been used to characterize facility availability is the fraction of the time that is spent in previously planned activities (coil testing and alternating periods of recuperation of liquid and other preparations for coil tests). For the 11-month period from October 24, 1985, through September 23, 1986, this fraction was 0.56. The remaining fraction of the time was spent on unplanned but necessary activities. Table 3 lists the principal causes of downtime or necessary, unplanned activities. The availability index was only 0.24 for the first 3 months, rose to 0.87 for 5 months, and then dropped down to 0.36 for the last 3 months.

Table 3. Facility problems that have interfered with coil testing November 1985 - September 1986

Problem area	Delays (days)
Air leaks into helium system (Mar-Sep 86)	54
Leak in cooldown heat exchanger (Dec 85)	29
Water leak in coil cooler (Nov 85)	17
Faults with helium compressors (Feb-Jul 86)	18
Interruptions of plant services (Feb-Aug 86)	13
Power supply controls (Mar-Sep 86)	8
Current leads (Apr-Aug 86)	6
Data acquisition system (Mar,Jun 86)	2
	147

Some sections of the helium system must be operated at subatmospheric pressure in order to provide 3.8 K helium to the forced-flow, NbTi coils. Although this was the condition from March onward, no problem from air inleakage appeared for more than 3 months.

For the next ~3 months, impurity blockages in the cold heat exchangers occurred repeatedly. Evidence suggests that air leaked into the VCL dewars during some occasions when they were at subatmospheric pressure. (They normally operate slightly above atmospheric pressure.) Measures are being taken to prevent this from happening again and to clean out impurities.

Other comments on experience with IFSMTF operation follow.

- The structure that supports and restrains the coils is quite satisfactory.
- Assembly of the movable pulse coil system was quite difficult, and its operation at cryogenic temperature is still untried.
- Reliability and performance of thermal isolation, including vacuum components, have been satisfactory.
- Capabilities of the helium refrigerator, when operating at best efficiency, are adequate to support coil testing on a satisfactory duty cycle.
- Leaktightness of the helium system was originally unsatisfactory but has been significantly improved.
- Oil removal and purification equipment in the helium system is quite effective.
- Reliability of helium screw compressors has not been as good as expected.
- Gas-bearing turboexpanders have operated reliably (one or two failures) despite continually varying operating conditions.
- Manual control of the refrigerator to meet diverse and varying loads has been an extremely demanding task for operators.
- Condensation of atmospheric moisture on cold current leads was not handled adequately at first but is gradually being brought under control.
- Accuracy and durability of sensors in cryogenic service have been satisfactory.
- Problems with some components of instrumentation and data acquisition systems have been a nuisance, affecting rate of progress during coil tests.
- Data acquisition system software is very satisfactory.
- Highly sensitive quench detection systems have been shown to be practical.
- Control systems have always operated safely.

Interim Conclusions

Many of the objectives of the LCT have already been met. Design and manufacturing capabilities of six powerful teams were organized and exercised to produce large superconducting TF coils that embody diverse approaches to meeting the requirements of tokamak reactors. Coil tests to date have shown that:

- a high degree of quality assurance was achieved,
- all six concepts are likely to meet LCT specifications,
- instrumentation and test procedures are producing a wealth of data not otherwise available, and
- there are significant differences, advantages and disadvantages among the six designs and manufacturing techniques.

Test results and analyses have bolstered the confidence of LCT participants that practical superconducting magnet systems with rational, cost-effective designs that satisfy tokamak reactor requirements can be available when needed. LCT is providing the base and direction for the further, relatively modest, development efforts that will be required.

Facility operation, as expected, has been a valuable experiment in its own right. Prolonged operation of a fusion-relevant superconducting magnet system has been demonstrated. Lessons have been learned that will be useful in achieving quite satisfactory availabilities in fusion reactor systems.

The LCT is providing an excellent example of productive international collaboration, in which resources are combined to enable a major undertaking and in which cross-fertilization of ideas and practices has been beneficial to all participants.

Plans

Experiments to explore the capabilities of the test coils beyond the nominal design point have been identified, and plans are being firmed up as results of design-point tests become available. It is expected that the LCT test program will be completed in 1987. Participants will analyze and compare results, provide detailed input to their fusion reactor design teams, and widely disseminate information of general interest. Plans are being developed for uses of the LCT coils and facilities in further large-scale development of fusion magnets.

Acknowledgments

The successes in the implementation to date of the Large Coil Task are testimony to the abilities, diligence, and cooperation of many people and organizations in four countries. Especially noteworthy is the effective collaboration of the LCT participants through their site representatives at the IFSMTF.

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