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CONF-820948--17

EMPLOYMENT OF THE LARGE COIL TEST FACILITY IN TOROIDAL FIELD COIL DEVELOPMENT*

DE84 004449

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ABSTRACT

The international Large Coil Task (LCT), involving EURATOM, Japan, Switzerland, and the United States, is developing competing concepts of superconducting toroidal field coils. Six different coils will be tested together in the Large Coil Test Facility (LCTF). All Participants are collaborating in planning and will share all test data.

1. FUSION MAGNET DEVELOPMENT

Because of the importance of performance, reliability, and cost, and the magnitude of the development required, superconducting magnets have been widely recognized as a critical element of fusion technology. Superconducting coils have been used in a few plasma confinement experiments (e.g., Baseball II and Tokamak-7), but fusion reactor magnets will be huge in comparison with these small devices. For example, the toroidal field (TF) magnet in INTOR would operate at two to three times the field strength of Tokamak-7 and the stored energy (a measure of mass and cost) would be several thousand times as great. To cross the associated wide technology gap, fusion programs have chosen two distinct approaches:

- a. Intermediate size confinement experiments using superconducting coils are built and operated. Development efforts focus on a single design, meeting actual constraints of the specific device. Coil testing is incidental to device operation.
- b. Intermediate size test coils of various designs, meeting constraints typical of envisioned reactors, are built and tested over extreme ranges of conditions.

Well-known examples of the first approach are MFTF-8 in the United States, Tokamak-15 in the U.S.S.R., and Tore Supra in Europe. When development for these devices began about 1977, quite different configurations of conductor and coolant were chosen for their coils. MFTF-8 coils employ NbTi superconductor, cooled by a bath of helium at atmospheric pressure (4.2 K). Tokamak-15 designers went to Nb₃Sn superconductor, cooled by forced flow of two-phase helium. Tore Supra coils will use NbTi, cooled by superfluid helium at 1.8 K.

The second approach is represented by the Large Coil Task (LCT), which is developing competing concepts of superconducting TF coils through the testing of coils about 0.4 the size of those in INTOR /1/. Three LCT coils are bath-cooled, and three are cooled by forced flow of helium at supercritical pressure. Five coils use NbTi, one uses Nb₃Sn.

2. IEA LARGE COIL TASK

The LCT stems from several separate national programs of development that were drawn together because of the availability of the Large Coil Test Facility (LCTF) /2/.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy under contract No. W-7405-eng-26 with the Union Carbide Corporation.

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The U.S. involvement was an outgrowth of a decision to address and resolve problems of TF coils for fusion reactors by building and testing several different coils of substantial size. Oak Ridge National Laboratory (ORNL) was given the responsibility of managing the coil procurement, building a test facility, and conducting the test program /3/. Consideration of various testing schemes led to selection of a six-coil compact torus. ORNL prepared specifications and in 1977, competitively awarded contracts to teams led by General Dynamics Convair, General Electric, and Westinghouse Electric. Each was to design, to perform verification tests upon, and then to build one coil.

At the same time that the United States was initiating this work, other nations were considering how best to proceed with scaleup of TF coil development. Under the auspices of the International Energy Agency (IEA), member countries and agencies began considering modes of cooperation centering around use of the LCTF. This led to a formal agreement defining the LCT, under whose terms Euratom, Japan, and Switzerland are designing and building one coil each to be tested with the three U.S. coils. Design data, certain manufacturing information, and test results are being shared among the Participants. The U.S. Department of Energy, acting through ORNL, is the operating agent for the LCT. The Euratom coil project is being managed by Kernforschungszentrum Karlsruhe (KfK), with Siemens AG as the principal industrial contractor. The Japan Atomic Energy Research (JAERI) manages the Japanese project, with Hitachi, Ltd. manufacturing the coil. The Swiss Institute for Nuclear Research manages the Swiss project, in which Brown Boveri and Company is an industrial partner.

3. LCTF DESCRIPTION

3.1 Test Stand

The LCTF test stand /4/ is depicted in fig 1. Coil bore dimensions are 2.5 x 3.5 m, overall height of the array is 8.9 m, and total weight with six coils in place is 360,000 kg. Test coils, each weighing about 40,000 kg, are attached to the bucking post through upper and lower collars. Centering forces are transmitted from each coil to a face of the hexagonal bucking post. The pulse coils impose field transients and overturning moments on the test coils resembling those in a tokamak. Out-of-plane forces are resisted by torque rings at the top and bottom of the coil array. The test coils and bucking post operate in the temperature range of 4-5 K, cooled internally by liquid helium. The torque rings and gravity base are also helium-cooled. Heat conduction through the support structure is limited by roller mounting on liquid-nitrogen-cooled plates on the six pedestals. Convective heat transfer is prevented by operation of the test stand in a vacuum inside an 11-m-diam tank. Radiant heat transfer from the tank walls to the test stand is blocked by a "cold wall" cooled with liquid nitrogen to 77 K and blanketed with reflective super-insulation.

3.2 Cryogenic Systems

The helium system must meet varied requirements of several modes of operation with different test coils /5/. During filling, helium can be liquefied at 15 g/s. During controlled cooldown and warmup, 300 g/s of helium gas can be supplied at any temperature between 300 K and 80 K, with the flow distributed to minimize thermal gradients. During operation, liquid is provided to the bath-cooled coils and other components at 4.2 K as required to replenish boiloff. Simultaneously, the force-flow coils are provided with 300 g/s of

Fig. 1. Cross section of the LCTF test stand in the 11-m diameter vacuum vessel. Pulse coils move on a circular track to any chosen test coil.

helium at 1.5 MPa and 3.7 K, with the flow passing through the three coils in series, in parallel, or combinations. Operation of the cryogenic system is integrated with coil testing, and flows and heat loads vary, depending on the test. A typical condition is 12.5 g/s of liquefaction, with 1470 W of refrigeration at 3.6 K, and 170 W of refrigeration at 4.2 K. At this condition, the helium compressors require 1500 kW of electric power to the compressors, and 620 L/h of liquid nitrogen is boiled off from the helium coolers in the cold box and purifier.

3.3 Coil Power and Protection

Each of the six coils is provided with a separate 12-V dc power supply, allowing independent control of currents. Three power supplies are rated at 16 kA and three at 25 kA. Protection is provided by a reliable system for rapidly deenergizing coils upon any of several signals implying potentially damaging conditions. Such conditions are a non-superconducting zone in a coil or an abnormal helium level or pressure in a coil or vapor-cooled current lead. In such events, a breaker opens the power supply circuit, forcing the current through an external resistor where the energy (up to 100 MJ per coil) is harmlessly dissipated.

3.4 Instrumentation and Data Acquisition

Each coil incorporates between 180 and 220 sensors. These include voltage taps, resistance thermometers, thermocouples (for cooldown), pressure taps, level probes, strain gages, and displacement transducers. All are brought to the outside of the vacuum tank. The data acquisition system (DAS) provides signal conditioning for about half the total

number of sensors at any one time. The allocation of channels to each coil depends upon whether it is being especially tested or is serving temporarily as a background coil.

Coil data are stored in microcomputers operated in a ring buffer mode to preserve data before and after initiation of significant transients. A central minicomputer provides for display and archival storage of data. The original, limited display capability is being expanded to improve accessibility of data to LCT participants. Capability for extensive analysis is not provided at the LCTF site but exists nearby in Oak Ridge. Up to 500 channels of facility data (other than the coils) can be stored and selectively displayed for the operators /6/.

4. COIL SPECIFICATIONS

Test coil specifications were intended to ensure compatibility with the facility and relevance of the fabrication and testing experience to tokamak magnet requirements. Otherwise, the design teams were given freedom to come up with their own solution to design and fabrication challenges.

The specifications require that each coil be capable of producing a peak field of 8.0 T while in a six-coil torus with five similar coils at 80 percent of design current. The field requirement was chosen to be within the practical range of NbTi at 4.2 K, but use of Nb₃Sn was allowed to encourage development of the higher field but less well-developed material. Cryogenic stabilization was adopted as a criterion in view of the importance of continuous magnet operation in a reactor. Each coil designer had to identify credible events within his coil and design to ensure stability. The coils are also required to survive grossly unequal current distributions among the coils of the torus and other specified extended conditions without damage. The coils must tolerate a superimposed pulsed field of 0.14 T in 1.0 s, which were the conditions anticipated when the specifications were written. (Some of the coils are designed to tolerate much higher field transients without excessive heating, reflecting different views about ultimate applications.) Conductor currents were required to be in the range of 10 - 20 kA, to ensure that the manufacturing processes could be used directly for conductors for much larger coils.

5. TEST PROGRAM

The first goal of the LCT test program is to obtain conclusive data from tests that are sufficiently extensive in conditions and time to demonstrate that each coil, as designed and built, is capable of meeting all specified requirements. It is likely that some coils will prove to be capable of operating to even higher fields and currents. A second goal, therefore, is to determine the actual margins that have been achieved in design and construction by testing beyond the specified nominal design conditions. The extent of such extended testing will be determined by agreement between the coil's supplier and ORNL.

In general, testing is to be accomplished by increasing operating parameters cautiously. At each upward step, sufficient data will be taken for comparison with values predicted by designers before another step is taken. The coil that is entering a new operational regime will be temporarily designated as the "test coil" and will have as many of its diagnostic signals processed as deemed necessary to provide assurance of safety and to permit evaluation of performance. Signals from the other coils will be monitored to guard against unexpected, undesirable conditions.

The test program will follow an outline formally adopted by the LCT executive committee.

The schedule is conformed to the realities of coil deliveries. During the first period of operation in 1983, the only coils available will be bath-cooled, and the facility will be completed only to the extent required to test them without pulsed fields. The end of this period of operation will be dictated by the achievement of satisfactory facility operation and the approaching deliveries of the remaining coils. While these coils are being installed, the facility construction will be completed to allow testing with a full six-coil array, with pulsed fields. Six-coil tests should begin in 1984 and continue for about 2-3 years.

Long-range plans for the LCTF use are not firm. The vacuum tank and supporting systems were designed to be adaptable for testing either larger or higher field coils.

6. CONSTRUCTION AND INSTALLATION

LCTF design and construction project management are by the engineering organization at Oak Ridge, with major construction by contractors. Non-U.S. Participants in LCT provide equipment that is required for their coils but is not included in the scope of the original U.S. construction project. Installation of the coils, the pulse field system, and certain other experimental equipment will be managed by ORNL.

7. OPERATIONS AND ANALYSIS

Because of the long times required for cooldown and warmup from cryogenic temperatures, the LCTF will be operated continuously for long periods of time using four crews, each consisting of a supervisor and two operators. The Head, LCTF Operations, has overall responsibility for safe and efficient operation of the facility in furtherance of the test program. An analysis group will be responsible for detailed planning of experiments and will participate in and analyze coil experiments. Day-to-day decisions on schedule and procedures (within the framework of the Test Programme document approved by the LCT executive committee) are made by an on-site steering committee, on which all LCT Participants are represented. Non-U.S. personnel are integrated in the analysis group. The operating crews are all ORNL staff members, formally trained and certified for their jobs.

8. STATUS AND SCHEDULE

The Japanese coil was the first one completed, having been delivered to JAERI in October 1981. It was successfully tested at full current in JAERI's Superconducting Engineering Test Facility in June 1982. As of 1 September 1982, it was being prepared for shipment to the LCTF. Meanwhile, winding of the General Dynamics coil is nearly finished. LCTF construction for bath-cooled coil testing is on schedule for completion in November 1982. Facility acceptance tests and preliminary coil tests are planned for the first half of 1983. All construction is to be completed by the end of 1983. The other coils, now in various stages of construction, are expected at the LCTF between July 1983 and March 1984. Testing of the full array is scheduled to begin in July 1984.

9. CONCLUSIONS

Design and manufacture of the six LCT coils has been quite instructive. There appears to be no fatal flaw in any of the concepts, but proof must await operation in the LCTF. International collaboration among LCT Participants has been quite effective. It is reasonable to expect that through the Large Coil Task, fusion reactor projects can confidently select from among several proven concepts the designs, materials, and manufacturing capabilities for the superconducting TF coils that will be needed for practical fusion power.

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