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PROGRESS ON LARGE SUPERCONDUCTING TOROIDAL FIELD COILS*

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ABSTRACT

Large superconducting toroidal field coils of competing designs are being produced by six major industrial teams. In the U.S., teams headed by General Dynamics Convair, General Electric, and Westinghouse are under contract to design and fabricate one coil each to specifications established by the Large Coil Program. A facility for testing 6 coils in a toroidal array at fields to 8–12 tesla is under construction at Oak Ridge. Through an international agreement, EURATOM, Japan, and Switzerland will produce one coil each for testing with the U.S. coils. Each test coil will have a 2.5 x 3.5 m D-shape winding bore and is designed to operate at a current of 10 to 18 kA at a peak field of 8T while subjected to pulsed fields of 0.14 T applied in 1.0 s. There are significant differences among the six coil designs: five use NbTi, one Nb_3Sn; three are cooled by pool boiling helium, three by forced flow; five have welded or bolted stainless steel coil cases, one has aluminum plate structure. All are designed to be cryostable at 8T, with structural margin for extended operation. The three U.S. coil teams are almost or completely finished with detailed design and are now procuring materials and setting up manufacturing equipment. The non-U.S. teams are at various stages of verification testing and design. The GDC and GE coils are scheduled for delivery in the spring of 1981 and the others will be completed a year later. The 11-m diameter vessel at the test facility has been completed and major components of the test stand are being procured. Engineering and procurement to upgrade the helium liquifier-refrigerator system are under way.

1. Introduction

The practicality of fusion power from magnetically confined plasma depends upon the use of superconducting magnets to provide the principal component of the confining field. In the tokamak concept, the first power-producing reactor will require a toroidal field (TF) magnet having a major radius of more than 5 m, a peak field of 10 to 12 T, and about 10 to 20 GJ of stored magnetic energy. Because replacement of TF coils in such a machine would be extremely difficult, they must be very reliable. Continuity of reactor operation demands that the TF magnet remain superconducting or recover quickly and spontaneously from local normalcy produced by credible events, including the effects of superimposed pulsed fields from the plasma and poloidal windings. Meeting these requirements entails substantial development to insure that when design decisions on the TF magnet for a tokamak reactor are made in the mid-1980's, there will be an adequate basis. Because of its critical importance there must be a high degree of assurance of safe, reliable operation of the TF magnet but excessive design margins cannot be afforded because of the cost. Considering the state of the art today (one superconducting tokamak, T-7 in the Soviet Union, with a stored energy of 15 MJ), it is evident that substantial development is required before the mid-1980's when design decisions for a tokamak reactor (ETF, NET or INTOR) must be made.

Major efforts on the development of superconducting toroidal field coils for fusion is going on in at least six countries. In addition to T-7, the Kurchatov and Efremov Institutes are developing a 500-MJ toroidal magnet for T-15 which will use Nb_3Sn at 6 T. At Saclay and Grenoble, the French are developing coils using NbTi at 1.8 K and 9 T for possible use in TORE-II, a tokamak similar in size to T-15. The U.S. is constructing three large coils, to be tested at 8 T in the Large Coil Test Facility (LCTF) at Oak Ridge along with one coil each from EURATOM, Japan, and Switzerland. It is the design, development, and construction of these six coils and the LCTF that is the subject of the ten papers in this special session.

2. Objectives and Plan

The Large Coil Program (LCP) was established in 1976 as the central element in the U.S. development of toroidal field magnet systems.[1] The key objective is to develop an adequate base for choosing a superconducting toroidal magnet for a tokamak fusion reactor with assurance of performance, reliability, safety, and economy. Critical objectives along the way are:

- focus magnet research and development.
- mobilize U.S. industrial capabilities,
- produce practical, extrapolable coil designs,
- obtain design data and solve fabrication problems,
- demonstrate reliable operation at design conditions,
- define limits on individual coils and stretch capabilities of coil concepts, and
- provide information to system designers throughout the course of the program.

The approach in the LCP is to have three U.S. industrial teams design and build different test coils, for testing and demonstration under conditions closely resembling those in a tokamak reactor. Oak Ridge National Laboratory (ORNL), with guidance from the Department of Energy's Office of Fusion Energy (DOE-OFE), is managing the program and carrying out supporting research and development. The LCTF, being designed and constructed at Oak Ridge as part of the LCP, will accommodate six coils in a mutually supporting compact toroidal array. To be tested with the three U.S. coils will be one each from EURATOM, Japan, and Switzerland. Coil tests and exchange of information are governed by an International Energy Agency (IEA) agreement for collaboration in superconducting magnet development that exploits the unique capabilities of the LCTF.[2] The three U.S. industrial teams, chosen competitively from five proposals, are listed in Table 1, along with the participants in the IEA Large Coil Task (LCT).

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Table 1. Participants in US Large Coil Program and International Energy Agency Large Coil Task

U.S. Large Coil Program	
Sponsor and guide program	DOE-OFE
Direct and manage program	ORNL
Provide supporting R&D	ORNL
Design and manage construction of test facility	ORNL-UCC-ND
Design and fabricate test coils.	General Dynamics Convair with Intermagnetics General Co.
	General Electric Co. with Intermagnetics General Co.
	Westinghouse Electric Corp. with Airco
IEA Large Coil Task	
Operating agent	U.S. DOE, acting through ORNL
Other participants	EURATOM (KfK — Siemens) Japan (JAERI — Hitachi) Switzerland (SIN — Brown Boveri)

Complementing the Large Coil Program in the U.S. is the 12-Tesla Coil Program. This program is carrying out, on a smaller scale, development of large conductors suitable for use in tokamak TF coils at fields up to 12 T. Several conductors will be tested in 1-m diameter coils in the High-Field Test Facility at Livermore in the same time frame as the large coil tests at Oak Ridge. The combination of the results of the Large Coil Task and the 12-T program is expected to provide a sound basis for decisions on the TF coils for the tokamak Engineering Test Facility.

The LCTF was designed to permit practical modifications to allow testing of a full-size prototype of a reactor (TNS) coil.

3. Coil Specifications

The LCP test coil specifications were prepared by ORNL with the intent of insuring relevance of the fabrication and testing experience to tokamak magnet requirements. They were therefore based on conceptual studies of EPR and TNS both at ORNL and elsewhere in the U.S. Because the strategy of the LCP is to investigate different coil concepts, the specifications describe the required performance, the spatial envelope, and interface dimensions while leaving the internal design of the coil to each designer. A peak field of 8 T was chosen by a U.S. panel as the maximum consistent with several practical design options. The size of the test coils was set at 2.5 x 3.5 m bore on the basis of the gap in size to be bridged (Fig. 1) and considerations of technology and cost. The principal requirements of the specification are indicated in Table 2.

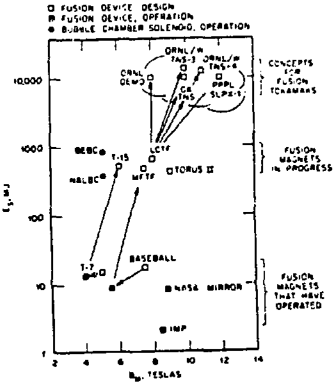

Fig. 1 Peak field and stored energy of superconducting magnets for bubble chambers (solid circles) and plasma confinement (solid squares).

Table 2. Features of test coil specifications

- Cryogenic stabilization
- Either NbTi or Nb_3Sn superconductor
- Produce 8 tesla peak field in a 6-coil torus with five similar coils at 80 percent of design current
- Operate stably at this peak field, with a superimposed pulsed field of 0.14 T in 1.0 sec., with simulated radiation heating
- survive grossly unequal current distribution among coils of the torus and other specified extended operations
- Conductor current in the range of 10–18 kA
- Stay within specified helium refrigeration limits
- Force transmission, helium supply, and power leads through precisely defined interfaces
- Design and manufacturing plan extrapolable to coils twice the bore dimension

Cryogenic stabilization was adopted as a criterion at the inception of the LCP in view of the importance of continuous magnet system operation in a reactor. The specifications place the responsibility on the LCP coil designer to define credible events within his coil and to design to assure its stability. As a minimum, U.S. coils are required to have the capability of recovering from any half-turn normal. (The non-U.S. coils are exempted from this latter requirement and others that are not essential to their performance as background coils.)

The specified peak field of 8 T is within the practical range of NbTi at 4.2 K but use of Nb_3Sn was allowed to encourage advances in design and manufacture of coils with the higher-field but less well-developed material. The pulsed-field magnitude is approximately that of the transients to be experienced during normal startup and shutdown of the plasma current in a large tokamak reactor that has some poloidal coils threading the TF coils. The conductor currents are in the range anticipated for reactor coils, so that nearly identical conductor can be used in the next generation coil designs. The limitation on refrigeration power and the interface specifications insure compatibility with the test stand and supporting systems.

The coil structure is required to withstand operation under extended test conditions, partly to permit a range of testing conditions to allow for exploration of the limits of superconducting operability and partly to accommodate large inequalities of TF coil currents imposed either in tests with a partial array or unintentionally. The various extended operating conditions specified are indicated in Table 3.

Table 3. Extended operating conditions

% OF DESIGN CURRENT	COIL NUMBER 1	2	3	4	5	6	PULSE FIELD
ALT A	110	90	90	90	90	90	NO
ALT B	100	100	100	100	100	0	NO
ALT C	140	*	*	*	*	*	NO
ALT D	110	90	90	90	90	90	YES
ALT E	140	0	0	0	0	0	YES

* *ALT C is a lone coil. ALT E is an array of six coils with only one energized.*

This table establishes limiting cases for coil structural design. (Actual test conditions will be specified using the defined combinations of coil currents for the various coils within the array.) Maximum in-plane loads are generated when operating in Alternates A and D; maximum out-of-plane loads, in Alternate B. Single coil loads, where the dominant effect is a circularizing tendency, are greatest in alternates C and E. These limits were derived from early consideration of superconducting margins and the capability of a coil to reach assumed critical current limits. These characteristics are defined in Fig. 2. An important element in these extended operating cases is the reduction permitted in specified structural design margins. The nominal design point, where the test coil is operated at 100% of its design current and the remaining five coils at 80% of their design currents, requires that the maximum stress level in the structural material of any coil not exceed a value of two-thirds of its minimum yield strength. For operation in the extended cases the coil designer is allowed to use a working stress up to the minimum yield point.

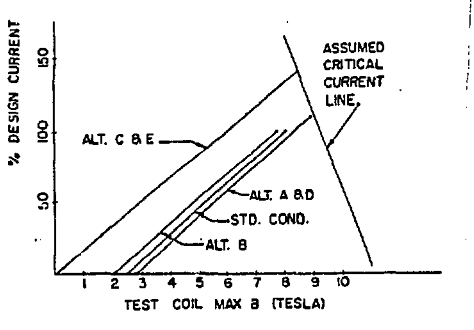

Fig. 2 Extended Operating Conditions Characteristics.

4. Coil Concepts

Each of the six test coils must meet the specifications prepared by ORNL to ensure reactor-relevant performance and compatibility with the LCTF. Otherwise, the specifications allow the coil design teams freedom to come up with what they consider the best solution to tokamak reactor magnet design and fabrication problems. The LCP coils are a considerable advance beyond previous experience and although several design options appear to be feasible, none could be chosen *a priori* as most promising. As a result, the designs that have been evolved for the six test coils are quite different (Table 4). Each of these designs is described in a subsequent paper in this session. It should be remarked here, however, that no insurmountable hurdle in any of the six concepts is evident and, although the proof can only come through construction and testing, there is confidence that the objective for which the LCP was created will be achieved.

5. Program Schedule

The present timetable for the LCP is indicated by Fig. 3. Indicated in this figure are the test coil deliveries and testing time allocations, first for two coils and later for the full six-coil torus. The facility activities are grouped by major Work Breakdown Structure (WBS) elements. The schedule is structured to allow for phased design and installation so that sufficient capability exists to support an early two-coil test program. Later modifications include the provisions for pulse field testing and forced-flow cryogenics necessary for full six-coil torus testing.

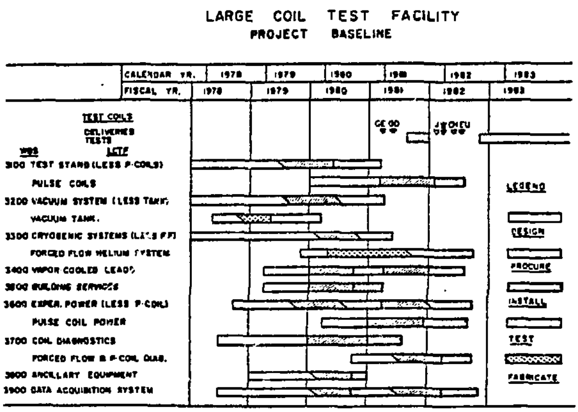

Fig. 3 LCP Schedule

Table 4. LCP Test Coil Features

	GD/CONVAIR	GENERAL ELECTRIC	WESTINGHOUSE	EURATOM	JAPAN	SWITZERLAND
Core bore (specified)	2.5 x 3.5 m	2.5 x 3.5 m	2.5 x 3.5 m	2.5 x 3.5 m	2.5 x 3.5 m	2.5 x 3.5 m
Peak field (specified)	8.0 T	8.0 T	8.0 T	8.0 T	8.0 T	8.0 T
Ampere-turns	6.65×10^6	6.98×10^6	7.36×10^6	6.62×10^6	6.76×10^6	6.6×10^6
Conductor current	10,200 A	10,450 A	17,800 A	11,000 A	10,210 A	15,000 A
Conductor material	NbTi	NbTi	Nb_3Sn	NbTi	NbTi	NbTi
Conductor configuration	Flattened cable in extended-surface copper bar	16 subelements, spiraled around copper core	Cable (insulated) strands) in square conduit	22 subelements, spiraled around CrNi core, inside rectangular conduit	Flattened cable in rough-surface surface copper bar	Solder-filled cable surrounded by He-filled copper cable in square conduit
Helium conditions	Pool boiling (4.2K, 1 atm)	Pool boiling (4.2K, 1 atm)	Supercritical, forced flow	Supercritical, forced flow	Pool boiling (4.2K, 1 atm)	Supercritical forced flow
Winding configuration	Edge wound in layers (14)	Flat wound in pancakes (7)	Laid in spiral grooves in 26 structural plates	Flat wound in pancakes (7)	Edge wound in pancakes (20)	Pancakes (12)
Structural material	304L stainless steel	316 LN stainless steel	2219-T87 plates A286 bolts	Stainless steel similar to 316 LN	304L stainless steel	Stainless steel similar to 316 LN
Structure configuration	Fully welded case	Welded case with bolted closure	Grooved flat plates, bolted	Welded case, bolted or welded closure	Welded case, bolted side plate closure	Bolted case

6. Conclusions

The need for fabrication and operating experience with large superconducting coils meeting the peculiar requirements of tokamak reactors will be met by the international program outlined in this paper. Competing industrial teams in four countries have considered a wide variety of design alternatives and have produced six different designs, all of which appear to be practicable. Confident choice of the optimal design for the toroidal field magnet of a large tokamak, however, will require experience with the fabrication and testing of these concepts.

The Large Coil Test Facility will provide capability for realistic testing of six coils with 2.5 x 3.5 m bore dimensions. It therefore has provided the basis for an international agreement through which a broad effort is being applied to one of the key development tasks in the way of practical fusion power from tokamak reactors.

The first six LCP test coils are designed to achieve 8 T reliably, but the basic coil structure and conductor concepts promise significant "stretch capability." The development of large conductors suitable for tokamak ETF magnets producing up to 12 T, in combination with the LCP results in large coil development, construction in industry, and testing, will provide future reactor projects with a range of options from which a toroidal field magnet design may be chosen. The LCTF has been designed to be adaptable for testing much larger coils, using the first LCP coils to provide the background magnetic field, and may later be employed to test ETF prototype coils.

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