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THE ROLE OF THE LARGE COIL PROGRAM IN THE DEVELOPMENT OF SUPERCONDUCTING MAGNETS FOR FUSION REACTORS*

P. N. Haubenreich,** J. N. Luton,** P. B. Thompson†

ABSTRACT

The central element in the Office of Fusion Energy's development of superconducting toroidal field magnets for fusion reactors is the Large Coil Program (LCP). Toroidal field coils in a tokamak reactor face special problems of heat generation by pulsed poloidal fields, demands for continuity of operation, structural design to handle the asymmetric in-plane loading and the out-of-plane forces repeatedly imposed, and space competition that makes high current densities desirable. Several design concepts have been advanced but large coils meeting tokamak requirements must be built and tested before an optimal choice can be made. This is being done through the LCP, in which three U.S. industrial teams are designing and will build one coil each to a common set of specifications. Coil specifications and test conditions were chosen to insure maximum relevance to fusion program needs. Each test coil will have a 2.5 x 3.5 m D-shape bore, will contain about 7 MA-turns, and must operate at a peak field of 8 T while subjected to pulsed fields up to 0.14 T in a test stand that can accommodate up to 6 coils in a compact toroidal array. Coils by General Dynamics/Convair and General Electric will use different NbTi conductors cooled by pool-boiling helium. The Westinghouse coil will use Nb_3Sn cooled by a forced flow of supercritical helium. These coils will be delivered in 1980 and 1981 for testing in the Large Coil Test Facility at Oak Ridge in a compact toroidal array with three coils from outside the U.S. These will be produced by EURATOM, Japan, and Switzerland for testing under an International Energy Agency agreement.

I. INTRODUCTION

Superconducting magnets will be essential for fusion power reactors to be economically attractive. A substantial body of superconducting magnet technology has been built up for other applications over the past 15 years, but the magnets that will be needed in a tokamak or mirror reactor will require major advances of various kinds.

A simple indication of the magnitude of the technology gap is seen in Fig. 1, where the stored magnetic energy, E_s, and peak field, B_M, of existing and proposed superconducting magnets are plotted. There is no large superconducting magnet (E_s > 10 MJ) that produces a peak field of more than 5.1 tesla. Magnets for ignited tokamak fusion reactors, on the other hand, must have stored energies on the order of 10,000 MJ and peak fields of 8 to 12 T. What cannot be so simply shown is the step up in complexity of design from the largest magnets today (circular bubble chamber magnets), with their relatively simple force distribution, shape, and conductor, to the fusion reactors' configurations of multiple coils, complex conductors with large asymmetric forces and (in the case of tokamaks) superimposed pulsed fields.[1,2] An intermediate step between today's technology and tomorrow's fusion reactor magnets is essential.

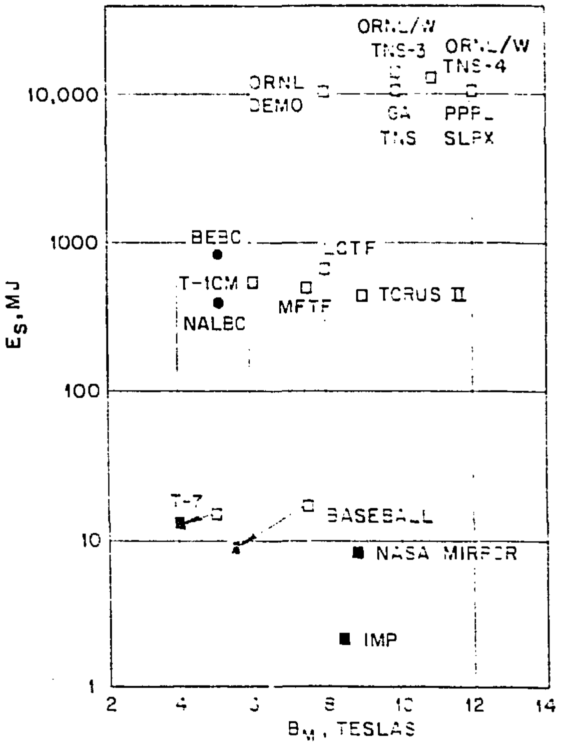

Fig. 1 Peak field and stored energy of superconducting magnets for bubble chambers and plasma confinement.

One route from existing technology to fusion reactor magnets is to build a series of superconducting confinement devices, each representing a significant step up in size and/or performance. For the past 6 to 8 years this route has been pursued with mirrors in the U.S. (Baseball-II and MFTF) and with tokamaks in the USSR (T-7 and T-10M). Evaluations and decisions in 1974-75 regarding superconducting tokamaks in the U.S. resulted in the adoption of a different plan for tokamak magnets.

Considering the fusion program schedule, its primary emphasis on tokamaks, and the costs and risks of integrating unproven technology into an operating confinement device, fusion program management decided to build the Tokamak Fusion Test Reactor with copper coils, meanwhile developing large superconducting toroidal field coils and demonstrating them on a suitable scale in a test stand. Thus the Large Coil Program (LCP) was established with the mission of providing the technology necessary for confident specification of the large, specialized superconducting magnet coils needed for the tokamak reactor to follow TFTR.

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**Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

†Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN 37830.

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II. OBJECTIVES AND PLAN

The objectives and strategy for the Large Coil Program were formulated in the context of a fusion program plan that envisioned the U.S. first superconducting tokamak to be an Experimental Power Reactor (EPR) designed and constructed in the 1980's. A variety of design options for toroidal field coils appeared to be open, but each involved a host of uncertainties, ranging from critical parameters of candidate materials through conductor production techniques and coil fabrication problems to the ultimate questions of performance, dependability and cost of coils of unprecedented size and complexity. A broadly based panel review late in 1975 emphasized the urgency, in view of the fusion program schedule and anticipated time requirements, to move quickly into the fabrication of large coils. The panel recommended that several different coils be designed and built by industrial teams, that they be a reasonable fraction of EPR coil size and otherwise directly applicable to the reactor coils. These large coils were to be tested under reasonably realistic conditions, in a test arrangement that minimized investment in background field coils.

Objectives of the LCP are listed in Table 1. The "key objective" is the essential end product. "Critical objectives" are necessary but subsidiary.

The program plan for the Large Coil Program was developed at the Oak Ridge National Laboratory (ORNL) with guidance from ERDA-DMFE.[3] Industrial capabilities are involved through cost-type contracts for the conceptual design, verification tests, detailed design, and fabrication of test coils. Program planning and management, technical guidance and evaluation of contractors' efforts, and directly supporting research and development are provided by ORNL, with review and approvals by DOE-OFE. An essential part of the LCP is design and construction of the Large Coil Test Facility (LCTF) at Oak Ridge for testing and demonstrating the reliable operation of the large coils.

Table 1. Objectives of Large Coil Program

Key Objective:

To develop a magnet technology base sufficient for commitment to a superconducting tokamak reactor through the design, construction, testing, evaluation and comparison of different large toroidal field coils that operate reliably at a peak field of 8 T and other conditions typical of a tokamak reactor magnet.

Critical Objectives:

- to focus DOE-sponsored superconducting magnet R&D on the crucial technology problems of large toroidal fusion magnets.
- to mobilize industrial capabilities for superconducting magnet design and fabrication,
- to translate superconducting magnet technology and industrial capabilities into practical coil designs that can be applied with only reasonable extrapolations to a tokamak fusion reactor toroidal magnet,
- to obtain results of design-specific verification tests needed for these and larger coils,
- to confront and solve fabrication problems in practical, cost-effective ways,
- to obtain data on fabrication costs and time requirements through actual experience in industrial shops,
- to verify design predictions and obtain data on coil behavior by operation of large test coils at specified design conditions including pulsed fields similar to those in a tokamak reactor,
- to demonstrate reliable operation of a large, multicoil superconducting magnet system including both bath-cooled and forced-flow-cooled coils,
- to explore limits of stable operation and demonstrate "stretch capability" of designs, and
- to promote industrial capability for and interest in competition for subsequent fusion magnet coils (either tokamak coils or higher-performance test coils).

III. TEST CRITERIA AND COIL SPECIFICATIONS

The basic criteria for the LCP coils and test conditions were chosen to insure relevance to tokamak reactor requirements. Similarity of force distributions to those in a tokamak, adaptability to the program's need to test several different coils, and costs were primary considerations in the selection of the coil test stand concept. The final choice was a compact torus of six test coils within a single large vacuum vessel, with provision for imposing a pulsed vertical field similar to that in a tokamak.

By the time the specifications for the LCP test coils were prepared late in 1976 the long-range reference had changed from the EPR to the somewhat smaller but still ambitious TNS, a D-T ignition test reactor that would be The Next Step after TFTR. The test coil specifications were designed to insure relevance of LCP experience and data to the TNS magnet requirements predicted by studies both at ORNL and elsewhere in the U.S.

In order to explore the concepts that appeared most promising from the standpoint of performance, fabricability, dependability and costs, the LCP coil specifications describe the required performance, some design criteria, and interface dimensions, but allow the contractors much freedom in the internal design of the coils. A specified spatial envelope dictates D-shaped coils, with bore horizontal and vertical dimensions of 2.5 x 3.5 m, leaving a reasonable factor of 2 scaleup to full-size TNS coils. Conductor currents must be in the range of reactor coils (10-18 kA) and the coil cross section is limited to constrain the winding design to achieve reactor-like current densities. All features of the design and manufacturing procedures are required to be applicable to reactor-size coils. A peak field of 8 T is specified to push the capabilities of NbTi at 4.2 K, but use of Nb_3Sn is also permitted in order to encourage advances in design and manufacture of coils with this material. In the interests of reactor-grade reliability, the designers are required to make their coils cryostatically stable. The specifications further require the coil to operate stably while subjected to a superimposed pulsed field of 0.14 T in one second and simulated radiation heating. The coil must be structurally capable of withstanding certain extended operating conditions including the out-of-plane loads encountered in testing a partial torus.

IV. COIL DESIGNS

In 1977 five industrial teams submitted proposals for test coil design and fabrication. Three were selected for cost-type contracts to produce one coil each: General Dynamics Convair Division with Intermagnetics General Corporation (IGC), General Electric with IGC, and Westinghouse Electric with Airco. GD and GE proposed concepts using NbTi cooled with boiling helium while Westinghouse proposed to use NbTi with forced flow cooling, with Nb_3Sn as an alternate. At the direction of the Office of Fusion Energy (OFE), Westinghouse later adopted Nb_3Sn for their coil.

The design concepts chosen by the three teams are quite different. General Dynamics uses a conductor consisting of a superconducting cable in a rectangular copper bar, edge wound in layers. General Electric's conductor is made of subelements spiraled around a core and is flat-wound in pancakes. In each of these coils a heavy stainless steel case serves as structure and helium vessel. The Westinghouse coil employs Nb_3Sn cable in a conduit, mounted in grooved plates which are bolted together to make up the coil structure. Cooling is by forced flow of supercritical helium through the cable interstices.

Table 2 presents a comparison of the principal features of the three U.S. coil designs.

As will be explained later, three foreign coils will be tested along with the U.S. coils. One each will come from EURATOM, Japan, and Switzerland. the EURATOM coil will use NbTi in subelements spiraled around a flat steel core, inside a steel channel, cooled by forced flow of supercritical helium. The winding will be spiral pancakes, potted in epoxy in a heavy stainless steel case. The Swiss coil will use a different conductor configuration, but will also have supercritical helium cooling, pancake winding, and a heavy case. The Japanese concept has not yet been chosen.

Table 2. LCP test coil features

	GD/CONVAIR[4]	GENERAL ELECTRIC[5]	WESTINGHOUSE[6]
Core Bore (specified)	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
Ampere-Turns	6.65×10^6	6.98×10^6	7.36×10^6
Conductor Current	10,200	10,450	16,000
Conductor Material	NbTi	NbTi	Nb_3Sn
Conductor Configuration	Cable in extended-surface copper strip	16 subelements spiraled around copper core	Cable (insulated strands) in square conduit
Helium Conditions	Pool Boiling (4.2K, 1 atm)	Pool Boiling (4.2K, 1 atm)	Supercritical Forced Flow (4-6K, 10 atm)
Winding Configuration	Edge wound in Layers	Flat wound in Pancakes	Laid in spiral Grooves
Structural Material	304L SS	316LN SS	2219-T87 Al
Structure Configuration	Welded Case	Bolted case	Grooved plates, bolted

V. TEST FACILITY

The Large Coil Test Facility (LCTF) will consist of a test stand which supports up to six test coils, another set of small coils that imposes a pulsed field on any selected test coil, a large vacuum tank which provides thermal isolation, and refrigeration, electrical, and data acquisition systems.[7]

The test stand, Fig. 2, supports the test coils from a central column mounted on a spider base which, together with its roller bearings and G-10 pads, gives a high thermal resistance to the vacuum tank bottom. The two "torque rings" which clamp the outer corners of the test coils are continuous so that fewer than six coils can be mounted and energized without modification of the test stand or use of dummy coils.

The pulsed field coils are a relatively small coaxial pair suspended in the bore of the toroidal coil being tested. In the reference mode of operation they produce a pulsed field with distribution and peak values approximating the poloidal field at the toroidal field coils in TNS. (Perpendicular and parallel components peak at 0.14 T.) By connection of both power supplies to one of the coils, considerably higher pulsed field over a smaller volume of the test coil can be produced. Design efforts are now concentrating on ways to relocate the pulse coils from one test coil to another without warming up the entire test array.

The cylindrical vacuum tank has an 11-m diameter, a flat bottom, domed head, and a nitrogen-cooled cold wall. The tank is sized and its base is designed to accomodate heavier test coils, either higher field or up to TNS size.

VI. INTERNATIONAL COLLABORATION

Fusion programs in Western Europe and Japan are also contemplating commitments to superconducting tokamaks in the next decade. The decision of the

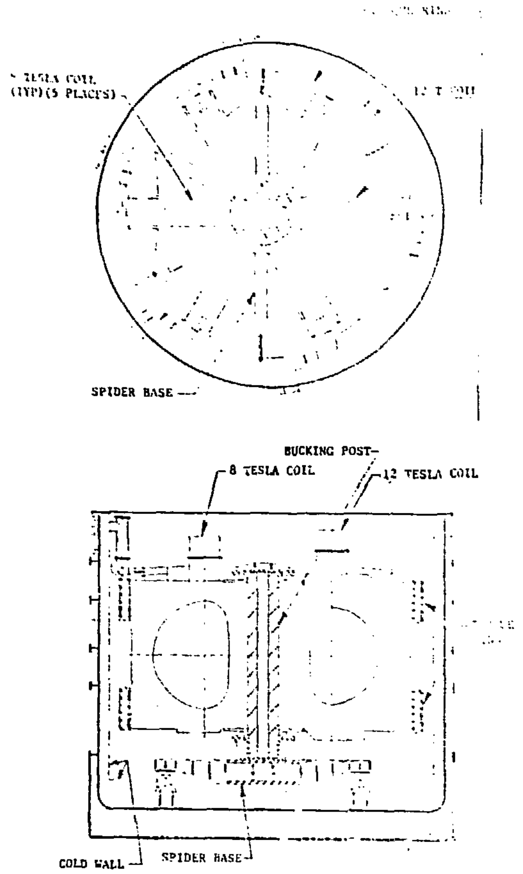

Fig. 2 LCTF vacuum tank and test stand.

U.S. to proceed with the LCP, including the construction of the 6-place test stand in the LCTF, came at an opportune time in the planning for superconducting magnet development in these countries. Recognition of the mutual benefits of simultaneously testing in the LCTF coils designed and built in several interested member countries led the International Energy Agency in 1976 to convene a committee of magnet experts to work toward that end. The result is the "IEA Implementing Agreement for a Program of Research and Development on Superconducting Magnets for Fusion Power," and its "Annex I - Large Coil Task."

The Implementing Agreement provides the basic framework for cooperation in magnet development among members of the IEA. Annex I provides that the U.S., as Operating Agent, will construct the LCTF at Oak Ridge and will test coils delivered there by the other Participants. Besides the U.S. Department of Energy, Participants are EURATOM, Japan, and Switzerland. All Large Coil Task (LCT) test coils must meet those portions of the U.S. LCP coil specifications that insure performance and dimensions compatible with the test array. Participants agree to exchange information obtained during the design, fabrication, and testing phases. Semiannual meetings of LCT project officers and the Program Executive Committee serve to coordinate the national efforts. Representatives of all Participants will take part in the coil installation, testing, and analysis of results.

The U.S. is represented on the Executive Committee by a member of DOE's Office of Fusion Energy. In the technical aspects of its role as Operating Agent, the U.S. acts through the Oak Ridge National Laboratory. The EURATOM effort is managed through the Kernforschungszentrum Karlsruhe, in collaboration with the Institute for Plasma Physics, Garching. Management of the Japanese and Swiss efforts is by the Tokai Research Establishment, JAERI, and the Swiss Institute of Nuclear Research.

VII. PROGRESS AND STATUS

General Dynamics, General Electric and Westinghouse began work in April, 1977 and by the end of that year had completed conceptual designs of the three different U.S. test coils. Since then they have been engaged in verification tests of crucial design features and manufacturing steps. Support R&D on conductor tests, instrumentation, and coil winding techniques is being carried out at ORNL. As of September, 1978 all three contractors are proceeding vigorously with detailed designs. Deliveries of the **two NbTi coils (by GD and GE) are planned for 1980; the Nb_3Sn coil (by Westinghouse) in 1981.**

EURATOM has selected, on the basis of preliminary design studies by three European firms, a conceptual design for its coil and conductor. The conductor is being developed by Vacuumschmelze and other supporting R&D is going on at KfK. Coil construction will be by a competitively selected European firm. Plans are to pretest the coil at KfK in 1981 and deliver it to Oak Ridge in 1982.

Japanese industries, including Hitachi, Mitsubishi, and Toshiba, who are now engaged in design of a smaller superconducting magnet test at Tokai, will compete for a contract to build the Japanese LCT coil. The Swiss LCT effort is jointly funded by the government and Brown Boveri Company. BBC will build the Swiss coil at its Zurich-Oerlikon works. Both the Japanese and Swiss coils are scheduled for delivery in 1982.

The design, procurement, and construction of the Large Coil Test Facility is proceeding on a schedule that will permit shakedown operations and partial testing of the first two coils soon after their arrival in 1980. The foundation has been prepared for the 11-m vacuum tank and the tank contractor (Pittsburgh-DesMoines Steel) is forming sections in shop in preparation for field erection. Major components of the helium refrigerator have been delivered and installation is under way. Procurement has been initiated on the central column of the test stand, a stainless steel hexagon, 6m long by 1m across the flats.

VIII. CONCLUSION

The Large Coil Program is well suited to the need to bring the nation's resources of superconducting magnet technology and industrial capabilities to bear on the especially demanding task of toroidal field coils for fusion reactors. Progress has been encouraging, and the U.S. fusion program is counting on the LCP to provide an adequate technology base for toroidal magnet systems producing peak fields up to 8 T or more. The existence of the Large Coil Test Facility at Oak Ridge stimulated productive international cooperation in superconducting magnet development. In 1982 it will be the site for an important and unique operation, the nose-to-nose testing of six huge superconducting coils designed to the same performance specification by six major industrial firms in four countries. The outcome of the program is expected to be a great advamce in the practical application of superconductivity and a major step toward useful energy from nuclear fusion.