THE STRUCTURAL DESIGN OF SUPERCONDUCTING MAGNETS FOR THE LARGE COIL PROGRAM

W. H. GRAY, W. C. T. STODDART, C. J. LONG
Oak Ridge National Laboratory,
P.O. Box Y, Bldg. 9204-1 MS 14, Oak Ridge, Tennessee 37830, U.S.A.

Abstract

Fusion reactor designs based on magnetic confinement will require the use of superconducting magnets to make them economically viable. For a tokamak fusion reactor large magnetic field coils are required to produce a toroidal magnetic confinement volume. Although superconductors have been used for approximately twenty years, several requirements for their application in fusion reactors are beyond demonstrated technology in existing magnets. The Large Coil Program is a research, development, and demonstration effort specifically for the advancement of the technologies involved in the production of large superconducting magnets. This paper presents a review of the status of the structural designs, analysis methods, and verification tests being performed by the participating LCP design teams in the USA, Switzerland, Japan, and the Federal Republic of Germany. The significant structural mechanics concerns which are being investigated with the Large Coil Program are presented.
1. Introduction

The economic viability of fusion power reactors depends upon the timely development of large superconducting magnets. Over the past 20 years a substantial resource of superconducting magnet technology has been developed for magnets other than tokamaks, but toroidal fusion magnets will require significant advances. Thus the Large Coil Program (LCP) was established with the mission of providing the technology necessary for confident specification of the large, specialized superconducting magnets needed for tomorrow's tokamak fusion reactors.

The key objective of the LCP is to develop a superconducting magnet technology base sufficient for commitment to a tokamak fusion reactor through the design, construction, testing, evaluation, and comparison of different large toroidal magnetic field coils. This paper presents a review of the status of the structural designs, analysis methods, and verification tests being performed.

The objectives and strategy for the Large Coil Program were formulated in the context of a fusion program plan that envisioned the first superconducting tokamak in the U.S. 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.

The program plan for the Large Coil Program was developed at the Oak Ridge National Laboratory (ORNL) with guidance from ERDA-IMPE. Industrial capabilities were incorporated 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-ETM. 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.

2. The LCP Design Specification

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. In accordance with DOE-ETM
instructions, the facility was designed such that after the 8T tests, it can be modified at minimum cost to test either TNS coils or 12T coils of LCP size.

In order to explore the concepts that appeared most promising from the standpoint of dependability, fabricability, performance, and costs; the LCP coil specifications describe the required performance, some design criteria, and interface dimensions, but allow much freedom in the internal design of the coils. The specified spatial envelope dictates D-shaped coils, with 2.5 by 3.5 m horizontal and vertical bore dimensions, respectively. Fusion reactor relevant currents (10-18 kA) must be carried by the conductor and the coil cross section size is limited to achieve approximate reactor current densities. All features of the design and manufacturing procedures are to be applicable to reactor-size coils and are to be fully documented.

Cryogenic stabilization is a criterion established at the inception of LCP to enhance reliability of magnet system operation. The specifications place the responsibility on the seller to define credible events within his coil and to assure its stability. As a minimum, capability of recovering from any half-turn normal is required.

The peak field of 8 T was chosen to match EPR requirements and to push the capabilities of NbTi at 4.2 K. The use of Nb$_3$Sn was allowed to encourage advances in design and manufacture of coils with this higher-field but less mechanically forgiving material. The pulsed field magnitude is a value reasonably attainable in a large tokamak reactor with some poloidal coils threading the TF coils or with some type of magnetic shielding for the TF coils. Survival of drastic "fault" conditions was required partly to permit a range of test conditions and partly because of uncertainty in the feasibility of limiting inequalities of TF coil currents in a tokamak. The conductor currents are in the range anticipated for reactor coils, so the same conductor could be used. The limitation on the interface specification insure compatibility with the test stand and supporting systems.

3. The Large Coil Test Facility

The Large Coil Test Facility will consist of a test stand which supports up to six test coils, a pair of smaller coils that impose a pulsed field on any selected test coil, a large vacuum tank which provides thermal isolation, and refrigeration, electrical, and data acquisition systems.

The test stand 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 such 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 design 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.

---

N 2.2/4
Structural testing and analysis of the entire test facility is currently being performed by UCC-ND Engineering Division and Science Applications Incorporated (SAI). Data from this analysis is being supplied to test coil contractors in the form of torque ring and bucking post interface deflections and forces. The contractors can use this data to simulate their coil's toroidal test environment.

4. International Collaboration

Fusion programs in Western Europe and Japan are also contemplating commitments to superconducting tokamaks in the next decade. The decision of the U.S. to proceed with the LCP, including the construction of the six-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 in the background positions and dimensions compatible with the test array. Participants agree to exchange information obtained during the design, fabrication, and testing phases.

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 Nuclear Research Center, Karlsruhe, in collaboration with the Institute for Plasma Physics, Garching. The Japanese and Swiss efforts are managed by the Tokai Research Establishment, JAERI, and by the Swiss Institute of Nuclear Research, respectively.

5. The LCP Coil Designs

In 1977 five U.S. 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 Nb3Sn as an alternate. At the direction of the Office of Fusion Energy (OFE), Westinghouse later adopted Nb3Sn for their coil.

The design concepts chosen by the three teams are quite different. Table 1 presents a comparison of the principal features of the three U.S. coil designs.

The General Dynamics concept uses a conductor consisting of a NbTi superconducting cable soldered into a grooved rectangular copper bar for stabilization. This composite conductor is edge wound in layers on the bobbin. Three grades of conductor are used by
varying concurrently the sizes of the copper stabilizer bar and the superconducting cable. The coil case and bobbin are made from elevated-nitrogen 304L stainless steel which is welded together. The conductor is cooled by pool boiling liquid helium at 4.2 K and 1 atm.

<table>
<thead>
<tr>
<th>Feature</th>
<th>GD/CONVAIR</th>
<th>GENERAL ELECTRIC</th>
<th>WESTINGHOUSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Bore (specified)</td>
<td>2.5 x 3.5 m</td>
<td>2.5 x 3.5 m</td>
<td>2.5 x 3.5 m</td>
</tr>
<tr>
<td>Peak Field (specified)</td>
<td>8.0 T</td>
<td>8.0 T</td>
<td>8.0 T</td>
</tr>
<tr>
<td>Ampere-Turns</td>
<td>6.65 x 10⁶</td>
<td>6.98 x 10⁶</td>
<td>7.36 x 10⁶</td>
</tr>
<tr>
<td>Conductor Current</td>
<td>10,200 A</td>
<td>10,450 A</td>
<td>16,000 A</td>
</tr>
<tr>
<td>Conductor Material</td>
<td>NbTi</td>
<td>NbTi</td>
<td>Nb₃Sn</td>
</tr>
<tr>
<td>Conductor Configuration</td>
<td>Cable in extended-surface copper strip</td>
<td>16 subelements spiraled around copper core</td>
<td>Cable (insulated strands) in square conduit</td>
</tr>
<tr>
<td>Helium Conditions</td>
<td>Pool boiling (4.2K, 1 atm)</td>
<td>Pool boiling (4.2K, 1 atm)</td>
<td>Supercritical forced flow (4-6K, 10 atm)</td>
</tr>
<tr>
<td>Winding Configuration</td>
<td>Edge wound in layers</td>
<td>Flat wound in pancakes</td>
<td>Laid in spiral grooves</td>
</tr>
<tr>
<td>Structural Material</td>
<td>304L stainless steel</td>
<td>316LN stainless steel</td>
<td>2219-T87 Al</td>
</tr>
<tr>
<td>Structure Configuration</td>
<td>Welded case</td>
<td>Welded and bolted case</td>
<td>Grooved plates, bolted</td>
</tr>
</tbody>
</table>

The General Electric concept uses a conductor consisting of NbTi superconducting subelements spiraled around a rectangular copper core. This composite conductor is flat-wound into pancakes. The coil case and bobbin are made from 316LN stainless steel and are assembled with bolts. The conductor is cooled by pool boiling liquid helium at 4.2 K and 1 atm.

The Westinghouse concept uses a Nb₃Sn superconducting cable in a conduit. The conductor composite is mounted into machined 2219-T87 aluminum plates. The plates are bolted together to make up the coil structure. The conductor is cooled by forced flow of supercritical helium at 4-6 K and 10 atm through the interstices of the cable in the conduit.

Due to the complexities of formalizing international agreements, such as the LCT, data on non-U.S. test coil designs are minimal. The following summary represents current (December 1978), but undocumented, data about the Japanese and European test coils. All three coils will use NbTi. The EURATOM coil will use 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 round solder-filled cable conductor in a square conduit, cooled by supercritical helium forced through the corner voids, pancake winding, and a heavy case. The Japanese concept has not yet been defined.

6. Test Coil Structural Analysis Performed as a Basis for LCP Design

In the design of magnet structures normal operating conditions necessitate a structural analysis to be performed. Consideration must be given to loads which induce stresses during manufacturing, cooldown, and energization. Less obvious, but still important, are loads produced by gravity, transient thermal gradients, and internal pressure, as well as loads generated by the extended operational capability specified for each test coil. The three U.S. design teams are addressing these problems using similar methods with dissimilar details.

To date the most effort has been directed toward the linear elastic structural response of a contractor's test coil to the body forces generated by the cross product of the current density and magnetic field (Lorentz forces). Because of the complexity of the structure, large finite element models have been used by the contractors.

The General Dynamics finite element model uses a test coil case, rod elements which model the conductor winding pack, and boundary elements which model interfaces to other structure. Symmetry of the test coil about the horizontal axis is used. Nine rod elements represent the conductor winding pack at a given cross section. Using the rule of mixtures, each rod is assigned axial properties that represent one-third of the cross section of the grade of conductor of which it is a part. Stiffness of the conductor winding pack in the radial direction is represented by radial connectors, which are active during compression only. To date the conductor winding pack has been assumed to be frictionless. (Plans have been made to evaluate this assumption as the design evolves into the final phase.) GDSAP, which is a General Dynamics-modified version of the finite element code SAP, is used for their structural analysis computer program.

The General Electric finite element model consists of plate elements which model the test coil case, beam elements which model the conductor winding pack, and spring elements which model the coil case-winding pack interaction. Nine hoop beam elements represent the conductor winding pack at a given cross section. From a mechanical viewpoint, except for the use of beam elements (GE) or rod elements (GD) to model the conductor winding pack, the finite element models of these contractors are very similar. GE is using the computer program ANSYS to perform their structural analysis calculations.

The Westinghouse finite element model consists of eight-node brick elements. One-quarter symmetry of the test coil about the horizontal axis and vertical mid-plane is used. The conductor winding pack and aluminum structure, which are assumed to be homogeneous, are represented by 16, eight-node brick elements at a given cross section. The rule of mixtures, as well as spatial position, was used to determine each element's elastic constitutive matrix. Westinghouse is using the computer program WECAN to perform their structural analysis calculations.

Finite element data-management complexities have required development of a number of special-purpose computer programs to automate the pre- and post-processing of a model. Each contractor has developed a suite of programs to calculate the body force that arises
from the interaction of the current and the magnetic field. General Dynamics uses a suite of programs based on MAGIC to perform their magnetic force calculations. MAGIC is characterized as a filament numerical method; that is, a conductor winding cross section is replaced by a bundle of conducting infinitesimal cross-sectioned filaments. General Electric and Westinghouse use suites of computer programs based on BARC-6 and MAFCO-W, respectively, to calculate magnetic fields and forces. These programs use finite cross section representations of conductor windings and numerically integrate the resulting elliptic integral equations.

At the present time little data is available on the analysis methods used by the European and Japanese design teams.

7. LTCF Structural Analysis Performed as a Basis for LCP Design

The six toroidal coil designs have different structural stiffnesses and current densities which reflect different preferences in satisfaction of the LCP design specification. Evolving competitive designs are not necessarily available for free exchange between the coil manufacturers. This problem of design/analysis, considering the influence of other coil manufacturers' designs, has been resolved by the establishment of a scheme that enables the coil designers to design their coils with a limited amount of knowledge regarding the LTCF system. This, in turn, allows ORNL to design the LTCF without detailed characterization of the various coils. The procedure involves the determination of the LTCF structural behavior at its interface with any selected test coil; for the purposes of this analysis, the coils are assumed to be identical. The resulting interface response would then be available to the coil designers to represent the behavior of the remaining LTCF structure in their detailed coil designs. This interface response is presented to the coil designers as displacements of all interface nodal grid points which are calculated by the LTCF system analysis. The test coil designers may then use them as boundary condition displacements at the corresponding test coil interface nodal grid points.

SAI is performing the overall structural analysis of the LTCF to support the sizing design calculations. They are using NASTRAN for their structural analysis and TORMAC for their magnetic load calculation. Their NASTRAN finite element model includes the bucking post, pulse coil structural system, and the upper and lower toroidal coil torque rings, all of which are modeled with beam elements. The six test coils are identically modeled with beam and plate elements. The simple but large beam and plate element model was deemed sufficient to evaluate the overall macroscopic structural behavior of the LTCF. This model does not attempt to solve for the stresses arising from the complex behavior of detailed structural elements such as the conductor winding pack and areas around notches, corners, and holes. (Details such as these are being addressed in separate analysis efforts being performed by UCCND-Engineering.) The beam element utilized in the finite element model references the appropriate area, shear factors, and bending and torsional inertia for its representative cross section in each structural component. The beam elements of the test coils reflect only the significant areas of the coil case for bending and torsion. The cross-sectional area of the conductor is accounted for only to resist the hoop tension.

The various component models combine the NASTRAN beam (BAR), quadrilateral (QUAD2) and triangular (TRIA2) membrane and bending plates, and solid isoparametric (IHX2) elements.
In addition, multi-point constraints (MPC's) are utilized to represent the various sub-
assembly interface reactions. Once assembled, the LCTF finite element model, with six
identical toroidal coils and the pulse coil system, contains 288 BAR, 20 IHEX2, 972 QUAD2
and 246 TRIA2 elements for a total of 1,526 elements. There are 1,787 discrete grid points
totaling 10,722 degrees of freedom (DOF; six DOF per grid point). Numerous multi-point and
single-point constraints reduce the system to 7,551 independent DOF. Utilizing a parti-
tioning scheme available in NASTRAN, this system is further reduced to 861 DOF in the
analysis set and 6,690 DOF in the omitted set. The total run time on an IBM 370/195 computer
system using 1700 kilobytes of memory for a six coil static structure analysis is 40 central
processing unit (CPU) minutes for a cold start and 15 CPU minutes for a restart. Approx-
imately 10 CPU seconds are required to develop the global stiffness matrix and 30 CPU minutes
to perform the necessary matrix partitioning and reduction to obtain the upper and lower
matrices of the constrained stiffness matrix for subsequent back substitution.

The test coil finite element model has a one-to-one correspondence with the TORMAC
magnetic force model. The fields and forces developed by TORMAC are based on a closed loop
of straight line segments carrying an electric current. The magnetic fields and forces are
evaluated at the conductor cross sectional center line with the values being an average
across the section. While this does not develop the maximum magnetic fields on a local
basis, it predicts the forces adequately to determine the overall structural behavior.

8. Verification Testing as a Basis for LCP Design

As design proceeded, contractors were asked to identify and formulate tests necessary
to ensure the viability of their concepts. These "verification tests" covered all aspects
of the designs, including structural and mechanical concerns. Some reflected unique features
of the individual designs, but others showed gaps in the general knowledge of materials'
and devices' behavior at 4 K.

Among the design-specific structural verification tests are weld-distortion tests
representing a portion of the assembly, investigation of load transfer across bolted joints
in the Westinghouse bolted-plate concept, and measurement of mechanical properties of the
conductors. While these add to the sum of knowledge about superconducting magnets, they
will be difficult to apply quantitatively to other designs unless relevant features are
identical.

Other verification tests, such as those on structural materials' mechanical properties,
are likely to be of more general usefulness. Even for alloys with much prior use at 20 K
and below, including types 304 and 304L stainless steel and aluminum alloy 2219-T87, dis-
agreements about design-minimum properties have required supplemental testing, often on the
particular heat to be used for the LCP. More novel formulations, such as the high-nitrogen
type 304L chosen by General Dynamics and the type 316LN stainless steel selected by General
Electric, place design teams in even more critical need of data. Because they offer solutions
to design problems, however, one can expect to see these alloys used again in superconducting
magnets; the information taken for the LCP will reduce the amount needed for the next use.

9. Potential Areas for Further Investigation

Due to practical budgetary constraints, only questions judged to be critical relative
to attainment of the LCP goals are currently being addressed. There are, however, numerous areas of interest which are not being investigated as part of the LCP which will be addressed as the technological sophistication of applied superconductivity matures. Several, but by no intention a complete group, of these noncritical questions are discussed below.

All the structural analysis done to date for the LCP is based upon the most simple of material property homogenization techniques. These techniques in most problems will yield acceptable overall deflections and stresses. However, they do not predict the behavior of the most fundamental part of the toroidal coils, the windings. As most structural analysis computer programs are capable of modeling orthotropic materials, work should be done to determine the composite orthotropic material properties of the candidate winding packs for the LCP. A conglomerate of superconducting cables, copper stabilizers, insulations, reinforcing cores, and cooling channels, as well as the superconducting filamentary composite itself, should be studied as a basic inhomogeneous model unit for intermediate scale homogenization. Techniques for introducing conductor slip\(^{18}\) should be explored as well as the effects of local temperature gradients upon intermediate scale homogenization.

For both the designer and analyst engineering minima for the important mechanical properties of commonly used structural alloys at 4 K must be established. The material properties which are most important are the tensile and compressive yield and ultimate strength, the percent elongation, the reduction in area, and the fracture toughness. Candidate materials such as type 304 and 316 stainless steel with the variants L and LN, type 310S and 21-6-9 stainless steel, and 2219 aluminum alloy in several tempers, should have the above material property characterization. Fabrication methods and weld properties for the above structural alloys should be determined.

The superconductor Nb\(_3\)Sn is strain sensitive. Its ability to superconduct is a function of strain level. This phenomenon should be characterized for several of the commercially available Nb\(_3\)Sn superconductors. Also, electrical versus mechanical tradeoffs in the amount of cold-work in the copper stabilizer for a superconductor should be established.

Manufacturing tolerance, imprecise magnet alignment, and installation imperfection are a few of the numerous unknowns which should be examined to insure stable operation on the basis of magneto-elastic stability.\(^{19}\) Although the magneto-elastic stability of LCTF does not appear to be a problem, analytical methods should be incorporated into finite element computer programs in order that the magneto-elastic stability of magnetic systems can be analyzed.

In fact, special techniques for handling the finite element models for the LCTF will have to be devised. At present, performing a finite element structural analysis on the LCTF with the unrefined model may take weeks of calendar time because of the size of the problem and competition from other groups for computer resources. Techniques, such as multi-level substructuring and multi-global analysis, will be needed as the sophistication of the finite element model of the LCTF increases.

10. Prospects

The U.S. fusion program is depending upon the LCP to provide adequate technology for superconducting toroidal magnet systems. The LCTF has stimulated international cooperation in superconductivity. Sometime in 1982 the LCTF will be the location of a unique event,
the simultaneous operation of six superconducting toroidal coils nestled nose-to-nose in a compact torus. This event will culminate a project to construct six magnets designed to the same performance specification by six major industrial firms in four countries over a time span of six years. The outcome of the program is expected to be a great advance in the practical application of superconductivity and a major step toward commercialization of nuclear fusion.

References


3. UCC-ND Technical Specification No. TS 14700-01 Rev. B.


