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The Structural Design of Superconducting Magnets for the Large Coil Program

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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 20 years, several requirements for their application in fusion reactors are beyond demonstrated technology in existing magnets. The Large Coil Program (LCP) 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 U.S.A., Switzerland, Japan, and the Federal Republic of Germany. The significant structural mechanics concerns that are being investigated with the LCP are presented.

PREFACE

This document reflects the prephase II final design review status of the structural designs of the superconducting coils and testing facility of the Large Coil Program. Most of the information contained in this report is current as of February 1, 1979.

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 associated verification tests being performed.

An indication of the magnitude of the technology gap is seen in Fig. 1, where the stored energy E_S is plotted against the peak field B_M for existing and proposed superconducting magnets. The hollow squares represent proposed magnets, and the shaded squares represent operating superconducting magnets. There are no large superconducting magnet systems (a large magnet is defined as one with a stored energy of >10 MJ) that produce a peak field of >5.1 T. This dramatically illustrates some of the fundamental problems with applied

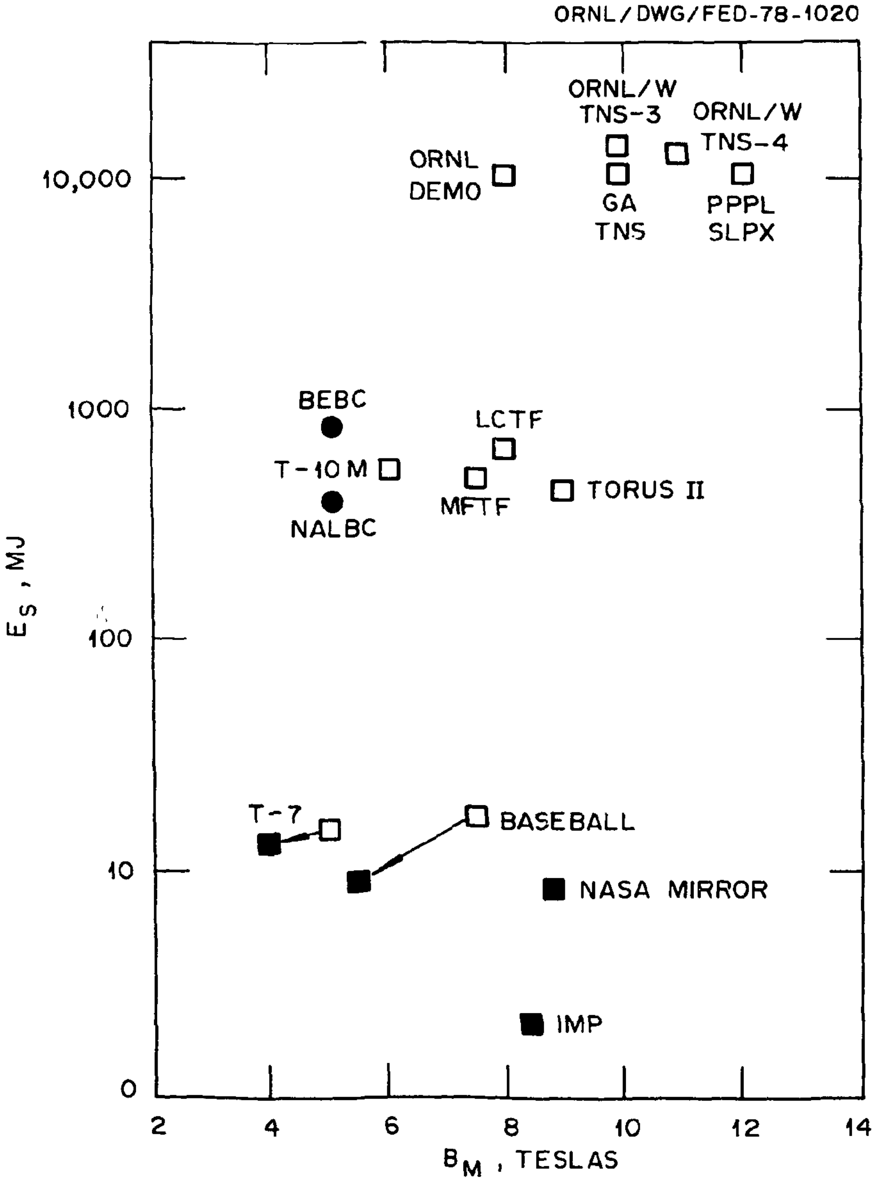

Fig. 1. Peak magnetic field (in T) vs stored energy (in MJ) for several large superconducting magnet systems. On this figure existing superconducting magnets are represented by shaded circles (for bubble chamber magnets) and by shaded squares (for systems with unique geometries or multiple magnets). Predicted or design values are represented by hollow squares.

superconductivity. Experience has shown that when large extrapolations either in size or in complexity are attempted, previously negligible phenomena often interfere with successful operation until the new problems are recognized and solved.

There are more than 1000 compounds and alloys as well as 26 elements that are known to exhibit the phenomena of superconductivity in conducive laboratory environments. Superconductivity is most influenced by magnetic field intensity. Each superconductor has a critical magnetic field value above which the superconductor becomes a normal conductor. The critical magnetic field is also a function of temperature.

For a variety of reasons, the most fundamental of which is the critical magnetic field intensity, only two superconducting compounds, niobium titanium (NbTi) and niobium tin (Nb_3Sn), are commercially available for magnet design. Practical engineering designs can use NbTi up to a maximum magnetic field of about 8 to 10 T. For Nb_3Sn the maximum is 18 T. On Fig. 1 all magnets to the left of the 8-T grid line were constructed of NbTi. The remaining two used Nb_3Sn.

Magnets for ignited fusion reactors, however, must have stored energies on the order of 10^5 MJ and peak fields from 8 to 16 T. What cannot be shown in Fig. 1 is the stepup in complexity of design from the largest magnets today (circular bubble chamber magnets such as BEBC and NALBC) with their relatively simple force distribution, shape, and conductor to the fusion reactor's configurations of multiple coils, complex conductors with large asymmetric forces, and, in the case of tokamaks, superimposed pulsed magnetic fields. An intermediate step between today's technology and tomorrow's fusion reactor magnets is essential.

One route from existing technology to fusion reactor magnets is to build a series of superconducting confinement devices, each representing a significant stepup in size and/or performance. For the past six to eight years, this route has been pursued with mirror fusion devices in the U.S.(Baseball-II and the Mirror Fusion Test Facility) and with tokamaks in the U.S.S.R. (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.

After 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 (TFTR) with resistive coils, meanwhile developing large superconducting toroidal field (TF) coils and demonstrating them on a suitable scale in a test stand. Thus, the 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.

2. THE LCP OBJECTIVES

The objectives and strategy for the LCP 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 TF 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, of moving quickly into the fabrication of large coils. The panel recommended that several different coils be designed and built by industrial teams and 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 objectives of the LCP are listed below.[1] The "key objective" is the essential end product. The "critical objectives" are necessary but subsidiary.

The key objective is 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 TF coils that operate reliably at a peak field of 8 T and other conditions typical of a tokamak reactor magnet.

The critical objectives are

(1) to focus DOE-sponsored superconducting magnet research and development (R&D) on the crucial technology problems of large toroidal fusion magnets;

(2) to mobilize industrial capabilities for superconducting magnet design and fabrication;

(3) 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;

(4) to obtain results of design-specific verification tests needed for these and larger coils;

(5) to confront and solve fabrication problems in practical, cost-effective ways;

(6) to obtain data on fabrication costs and time requirements through actual experience in industrial shops;

(7) 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;

(8) to demonstrate reliable operation of a large, multicoil superconducting magnet system including both bath-cooled and forced-flow-cooled coils;

(9) to explore limits of stable operation and demonstrate the stretch capability of designs; and

(10) to promote industrial capability for and interest in competition for subsequent fusion magnet coils (either tokamak coils or higher performance test coils).

The program plan for the LCP was developed at Oak Ridge National Laboratory (ORNL) with guidance from the Energy Research and Development Administration (ERDA; now DOE) and the Division of Magnetic Fusion Energy (DMFE; now the Office of Fusion Energy).[2] 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 direct support of research and development are provided by ORNL, with review and approvals by DOE. An essential part of the LCP is design and construction of the Large Coil Test Facility (LCTF) at ORNL for testing and demonstrating the reliable operation of the large coils.

3. THE LCP DESIGN SPECIFICATION

The basic criteria for the LCP coils and test conditions were chosen to ensure 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 instructions, the facility was designed such that after testing, it can be modified at minimum cost to test either coils for The Next Step (TNS) reactor or 12-T coils of LCP size.

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 deuterium-tritium (D-T) ignition test reactor that would be The Next Step after TFTR. The test coil specifications were designed to ensure the 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 dependability, fabricability, performance, and costs, the LCP coil specifications[3] describe the required performance, some design criteria, and interface dimensions but allow freedom in the internal design of the coils. The specified spatial envelope dictates D-shaped coils, with 2.5 x 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.

Concisely stated, the LCP technical specification requires the following.

(1) The test coil shall be operable at a peak field of at least 8.0 T at a design current of 10-18 kA in a six-coil, compact torus when five other such coils are at 80% of their design current.

(2) The designer must show that his coil is stable against effects on the conductor of all "credible" events. No design will be acceptable that is not capable of recovery from a sudden normalcy extending over any half turn.

(3) The coil must be within a spatial envelope defined in the technical specifications. The bore approximates a "D" while the outside of the coil case is rectangular in profile. The inboard straight edge bears against a central hexagonal post in the test stand and has a vertical tongue that fits a groove in the post to transmit part of the overturning moment from the vertical field that will be imposed. Structural

members that will be provided to transmit forces between adjacent coils will attach to the outer corners of the coil case. The structural, electrical, and coolant interfaces indicated in Fig. 2 are precisely defined in the specifications. The concept of the structure that will be provided as part of the test facility is depicted in Fig. 3.

(4) The design of the coil must be consistent with a postulated radiation environment equivalent to that expected in TNS. The stability analysis shall assume that the matrix material will be exposed to a fast neutron fluence of 0.5×10^{17} neutrons/cm^2. Insulation capable of operation after a dose of 10^7 rads must be used. The thermal design must accommodate a hypothetical nuclear heat source of 0.1 W/kg, with 0.5 W/kg at local "hot spots."

(5) The test coil must continue to operate in a cyclically imposed pulsed field with peak values of 0.14 T perpendicular to the conductor and 0.10 T parallel to the conductor, ramped up in 1 sec.

(6) The test coil shall be made with either a NbTi or Nb_3Sn superconductor.

(7) The design and manufacturing plan shall be extrapolative to coils of twice the bore dimensions.

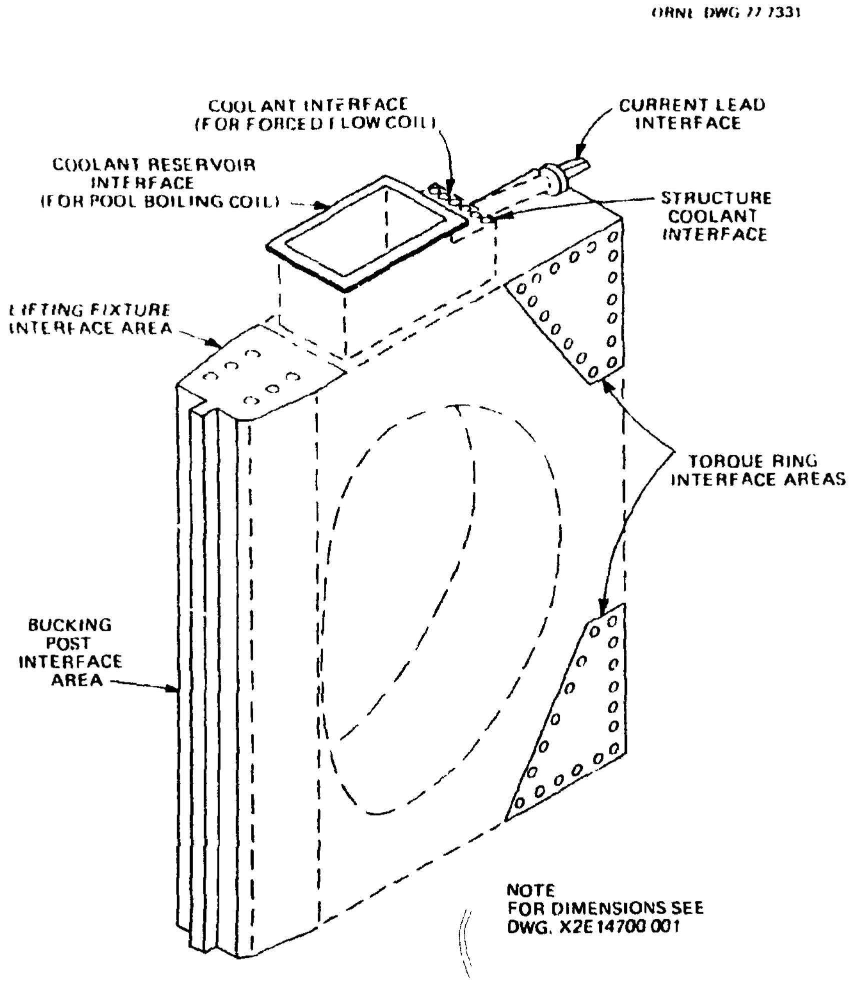

Fig. 2. Spatial envelope interface features of the LCP design specification.

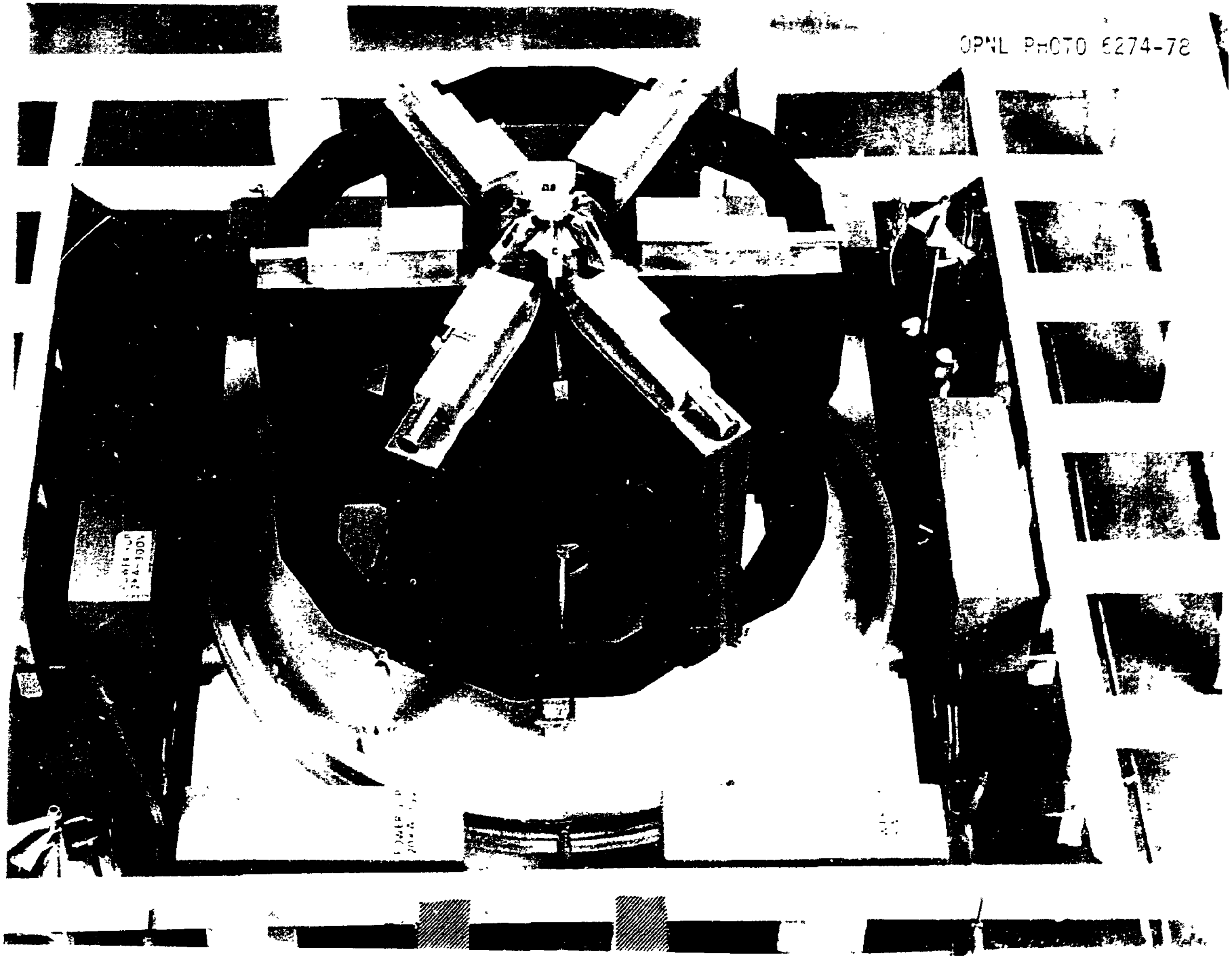

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Fig. 3. A model of the assembled LCTF.

(8) The test coil must survive grossly unequal current distributions among coils of the torus and other specified extended operations (see Table 1).

Cryogenic stabilization is a criterion established at the inception of the 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 ensure its stability. As a minimum, the capability of recovering from any half turn normal is required.

The peak field of 8 T was chosen to push the capabilities of NbTi at 4.2K. The use of Nb_3Sn 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 because of the need 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 ensures compatibility with the test stand and supporting systems.

Table 1. Design and extended[*] operations specified for the LCP[3]

Test	Coil number						Pulsed fields
	1	2	3	4	5	6	
Design	100[*+]	80	80	80	80	80	No
Extended A	110	90	90	90	90	90	No
Extended B	100	100	100	100	100	0	No
Extended C	140	0	0	0	0	0	No
Design	100	80	80	80	80	80	Yes
Extended D	110	90	90	90	90	90	Yes
Extended E	100	100	100	100	100	0	Yes
Extended F	140	0	0	0	0	0	Yes

[*] Expressed as percent of design current.

[+] The coil must meet all requirements in all positions of the design cases after having been exposed to the extended cases but need not remain superconducting during attempted operation as coil 1 in the extended cases.

Although they are not discussed here, the specification also covers instrumentation, heaters for testing stability and simulating radiation, electrical insulation requirements, helium conditions, cooldown time, operating cycles, and maximum weight.

4. THE LARGE COIL TEST FACILITY

The Large Coil Test Facility[4] (LCTF) will consist of a test stand that 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 that provides thermal isolation, and refrigeration, electrical, and data acquisition systems.

The test stand, seen in Fig. 4, supports the test coils from a central column mounted on a spider base that, together with its roller bearings and G-10 pads, gives a high thermal resistance to the vacuum tank bottom. The two torque rings that 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 TF coils in TNS. (Perpendicular and parallel components peak at 0.14 T.) By connection of both power supplies to one of the coils, a 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.

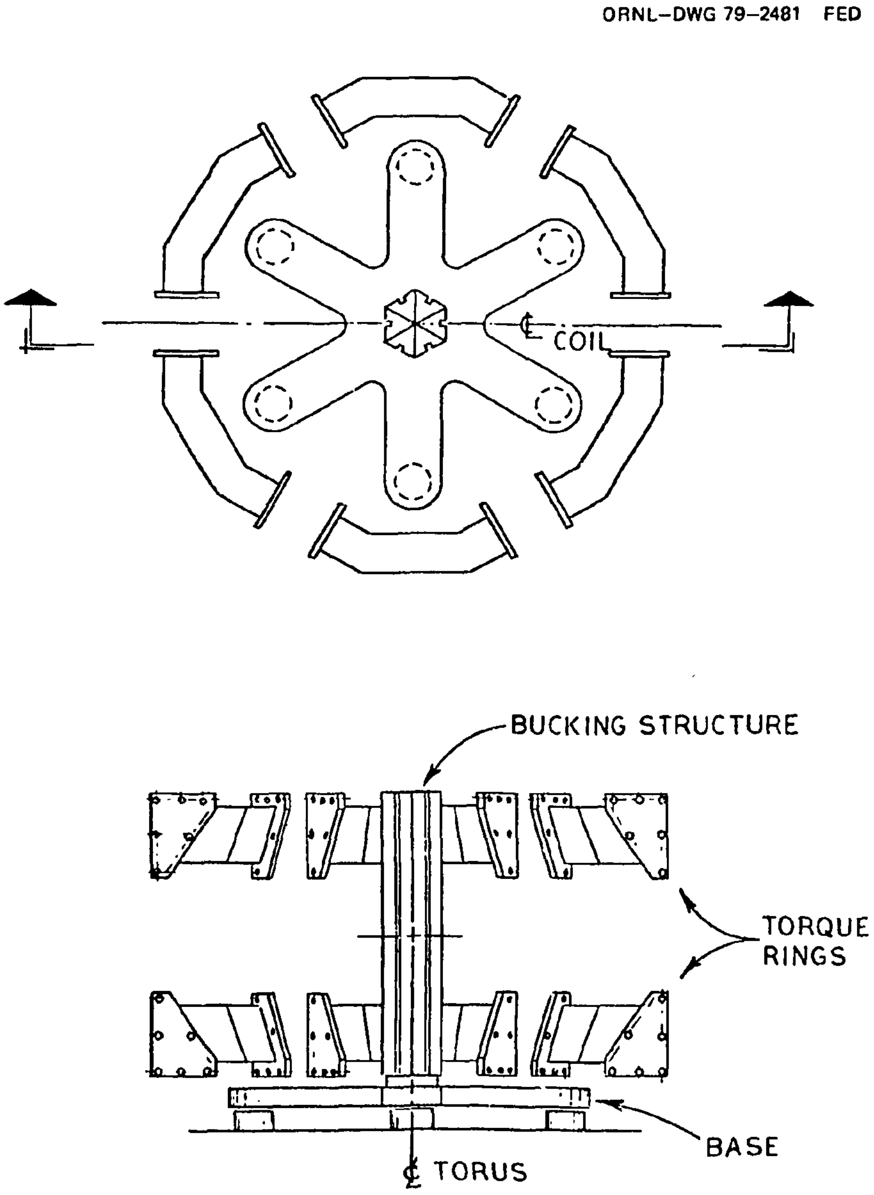

Fig. 4. The LCTF support concept showing the bucking post, torque ring, and spider base structures.

The cylindrical vacuum tank has an 11-m diameter, a flat bottom, a domed head, and a nitrogen-cooled cold wall. The tank diameter is sized and its base is designed to accommodate heavier test coils and to withstand zone 2 seismic loading.

The design, procurement, and construction of the LCTF are proceeding on a schedule that will permit shakedown operations and partial testing of the first two coils soon after their arrival in late 1980. The foundation has been prepared for the 11-m vacuum tank and the tank contractor (Pittsburgh-Des Moines Steel) is currently erecting the vacuum tank at ORNL 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, hexagonal prism, 6 m long by 1 m across the flats.

Structural testing and analysis of the entire test facility are currently being performed by Union Carbide Corporation Nuclear Division (UCC-ND) Engineering and Systems Analysis, Incorporated (SAI). Data from this analysis are 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.

5. 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 the LCTF coils designed and built in several interested member countries led the International Energy Agency (IEA) 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 ORNL 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 ensure 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. 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 (OFE). In the technical aspects of its role as operating agent, the U.S. acts through ORNL. The EURATOM effort is managed through the Nuclear Research Center in Karlsruhe in collaboration with the Institute for Plasma Physics in Garching. The Japanese and Swiss efforts are managed by the Tokai Research Establishment, JAERI, and by the Swiss Institute of Nuclear Research.

6. THE LCP COIL DESIGNS

In 1977 five U.S. industrial teams submitted proposals for test coil design and fabrication. Three were selected to produce one coil each: General Dynamics Convair Division (GD) with Intermagnetics General Corporation (IGC), General Electric (GE) with IGC, and Westinghouse Electric with Airco. General Dynamics and General Electric 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 OFE, Westinghouse later adopted Nb_3Sn for their coil.

The design concepts chosen by the three teams are quite different. Table 2 presents a comparison of the principal features of the three U.S. coil designs.

TABLE 2. LCP test coil features

	GD/Convair	GE	Westinghouse
Coil bore (specified)	2.5 × 3.5 m	2.5 × 3.5 m	2.5 × 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 A	10,450 A	16,000 A
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)	Pool boiling (4.2K)	Supercritical forced flow (4-6K)
Winding configuration	Edge-wound in layers	Flat-wound in pancakes	Laid in spiral grooves
Structural material	304L stainless steel	316LN stainless steel	2219-T87 AL
Structure configuration	Welded case	Welded and bolted case	Grooved plates, bolted

The GD concept[5] uses a conductor consisting of a NbTi superconducting cable soldered into a grooved, rectangular copper bar for stabilization (see Fig. 5). This composite conductor is 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 that is welded together (see Fig. 6). The conductor is cooled by pool boiling liquid helium at 4.2K and 1 atm.

The GE concept[6] uses a conductor consisting of NbTi superconducting subelements spiraled around a rectangular copper core (see Fig. 7). This composite conductor is flat-wound into pancakes. The coil case and bobbin are made from 316LN stainless steel and are assembled with bolts (see Fig. 8). The conductor is cooled by pool boiling liquid helium at 4.2K and 1 atm.

The Westinghouse concept[7] uses a Nb_3Sn superconducting cable in a conduit (see Fig. 9). The conductor composite is mounted into machined 2219-T87 aluminum plates. The plates are bolted together to make up the coil structure (see Fig. 10). The conductor is cooled by forced flow of supercritical helium at 4-6K and 10 atm through the interstices of the cable in the conduit.

Because of 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),

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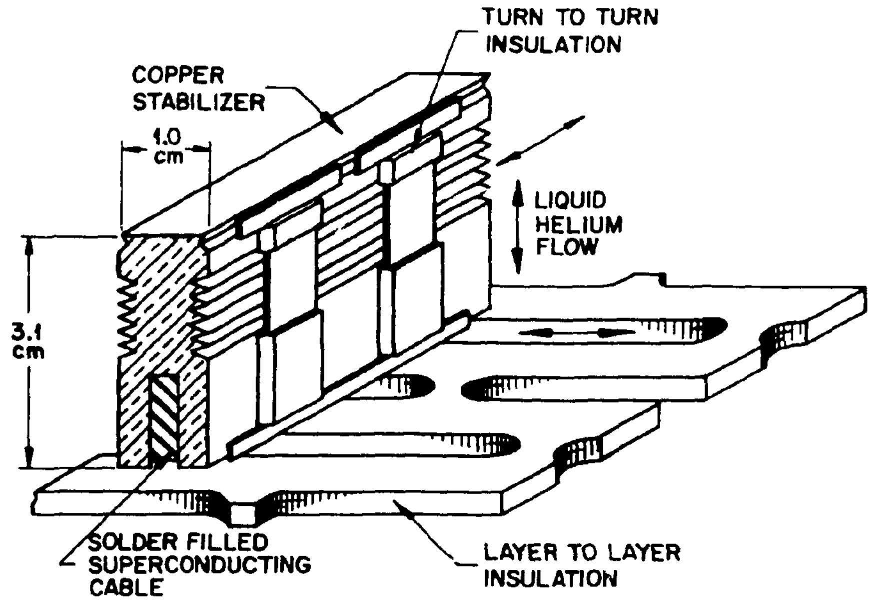

Fig. 5. The General Dynamics superconductor design concept for the LCP.

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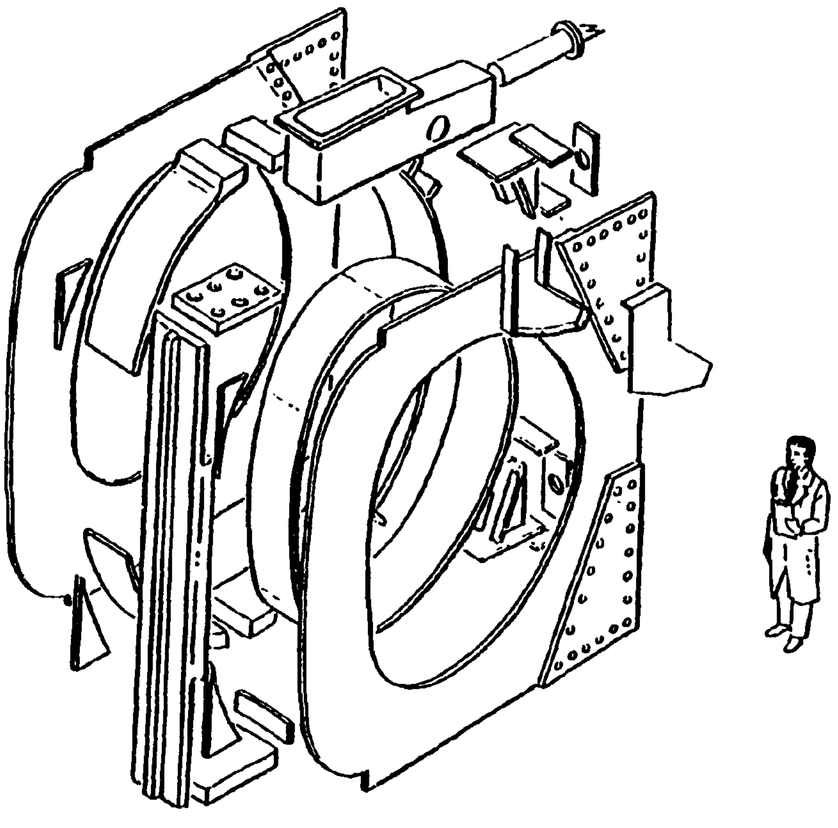

Fig. 6. The General Dynamics coil concept for the LCP.

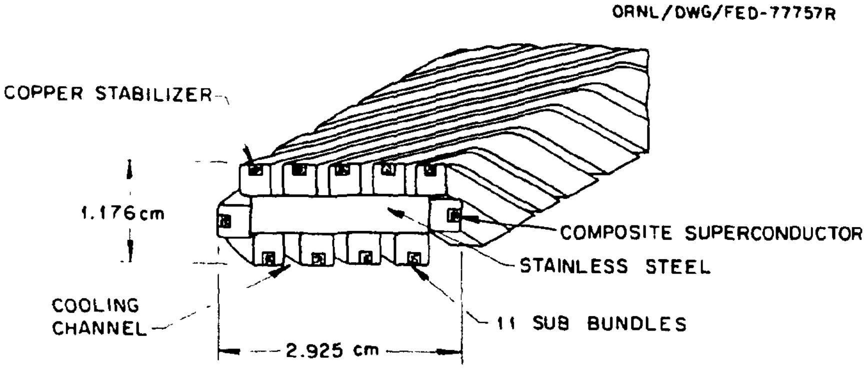

Fig. 7. The General Electric superconductor design concept for the LCP.

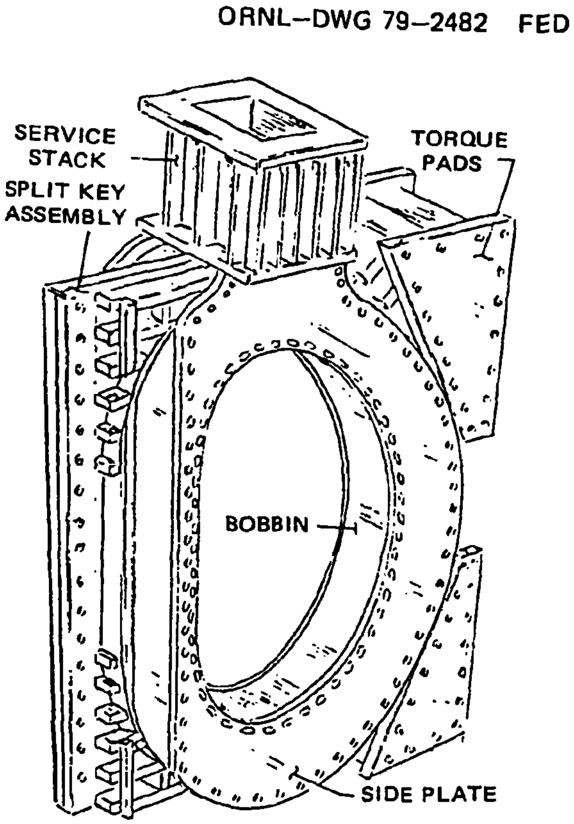

Fig. 8. The General Electric coil concept for the LCP.

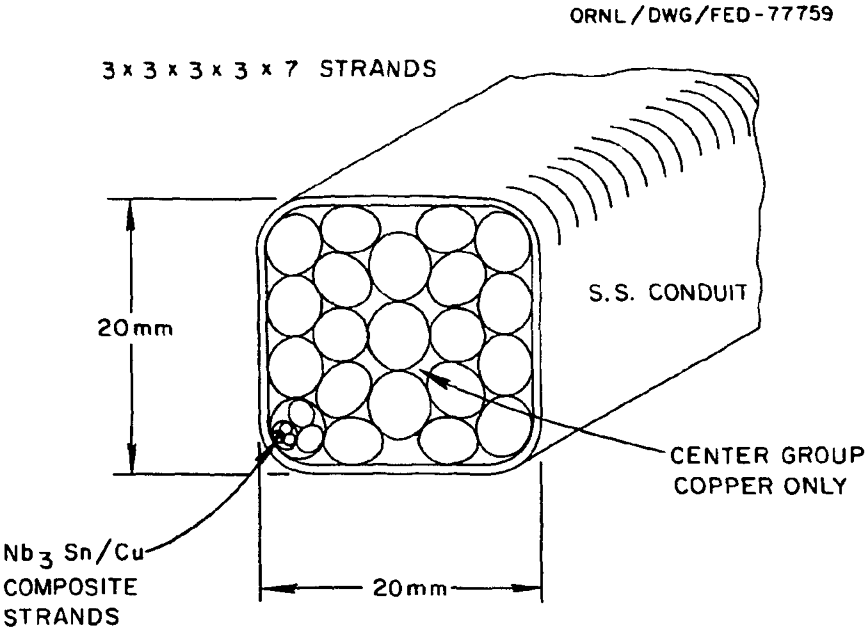

Fig. 9. The Westinghouse superconductor design concept for the LCP.

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 located inside a steel channel and 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 also a heavy case. The Japanese concept has not yet been defined.

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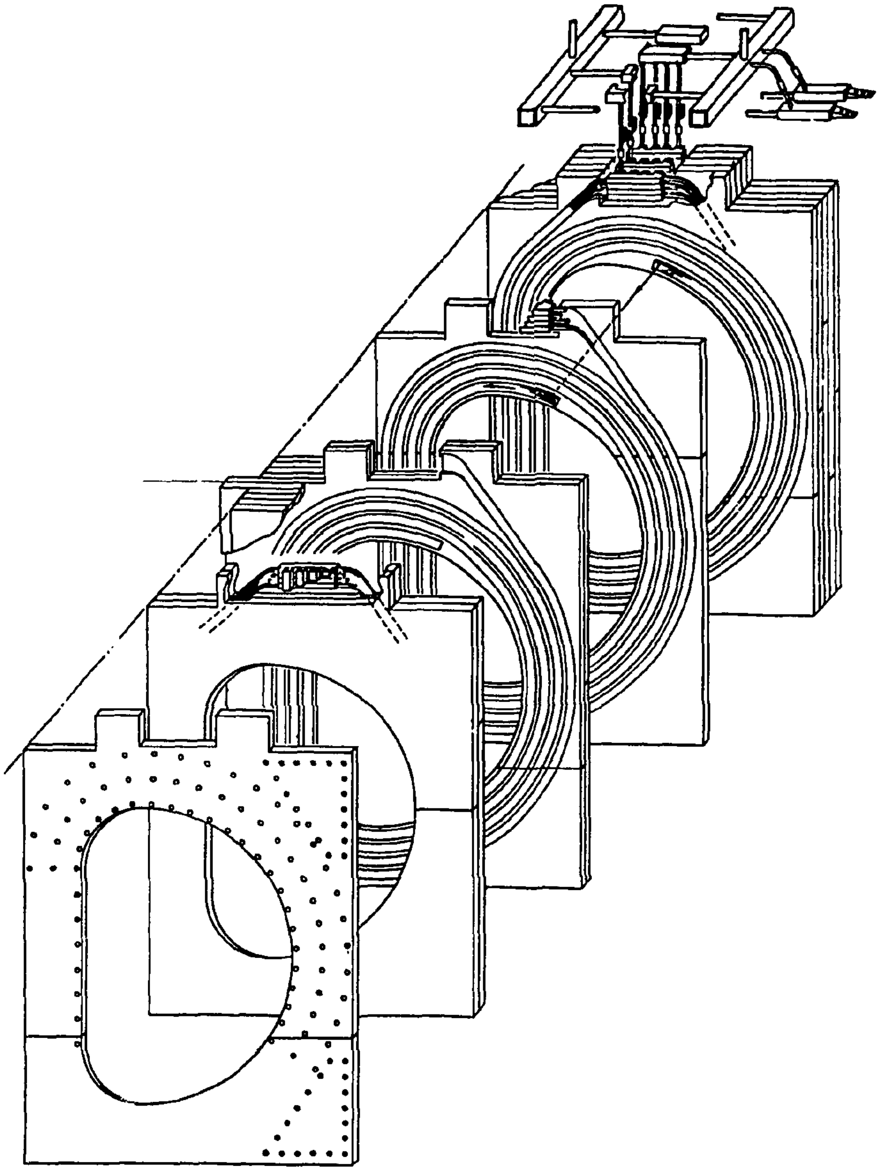

Fig. 10. The Westinghouse coil concept for the LCP.

7. TEST COIL STRUCTURAL ANALYSIS PERFORMED AS A BASIS FOR THE LCP DESIGN

In the design of magnet structures, normal operating conditions necessitate a structural analysis. Consideration must be given to loads that 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, most of the 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 GD finite element model[8] consists of plate elements that model the test coil case, rod elements that model the conductor winding pack, and boundary elements that model interfaces to other structure. Symmetry of the test coil about the horizontal axis is used (see Fig. 11). 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

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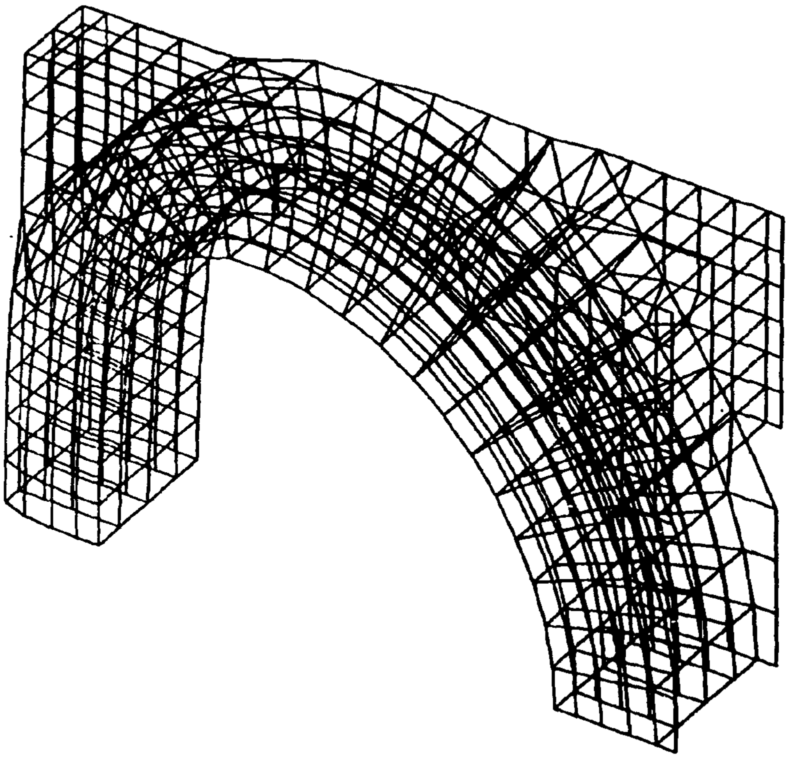

Fig. 11. The General Dynamics finite element model for their LCP coil.

section for the appropriate grade of conductor. Stiffness of the conductor winding pack in the radial direction is represented by radial connectors, which are active only during compression. 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.) A GD-modified version of the finite element code SAP,[9] GDSAP, is used for their structural analysis computer program.

The GE finite element model[10] consists of plate elements that model the test coil case, beam elements that model the conductor winding pack, and spring elements that model the coil case winding pack interaction (see Fig. 12). Nine hoop beam elements represent the conductor winding pack at a given cross section. From a mechanics viewpoint, the finite element models of these contractors are very similar, except for the use of beam elements (GE) or rod elements (GD) to model the conductor winding pack. General Electric is using the computer program ANSYS[11] to perform their structural analysis calculations.

The Westinghouse finite element model[12] consists of eight-node brick elements (see Fig. 13). One-quarter symmetry of the test coil about the horizontal axis and vertical midplane 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

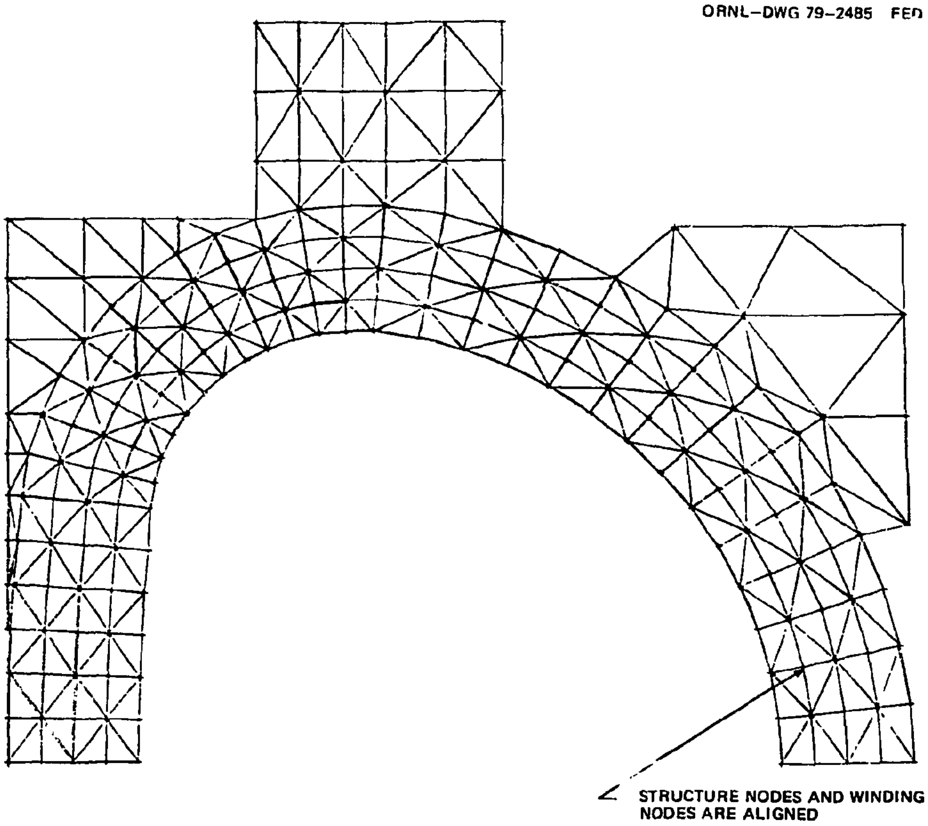

Fig. 12. The General Electric finite element model for their LCP coil.

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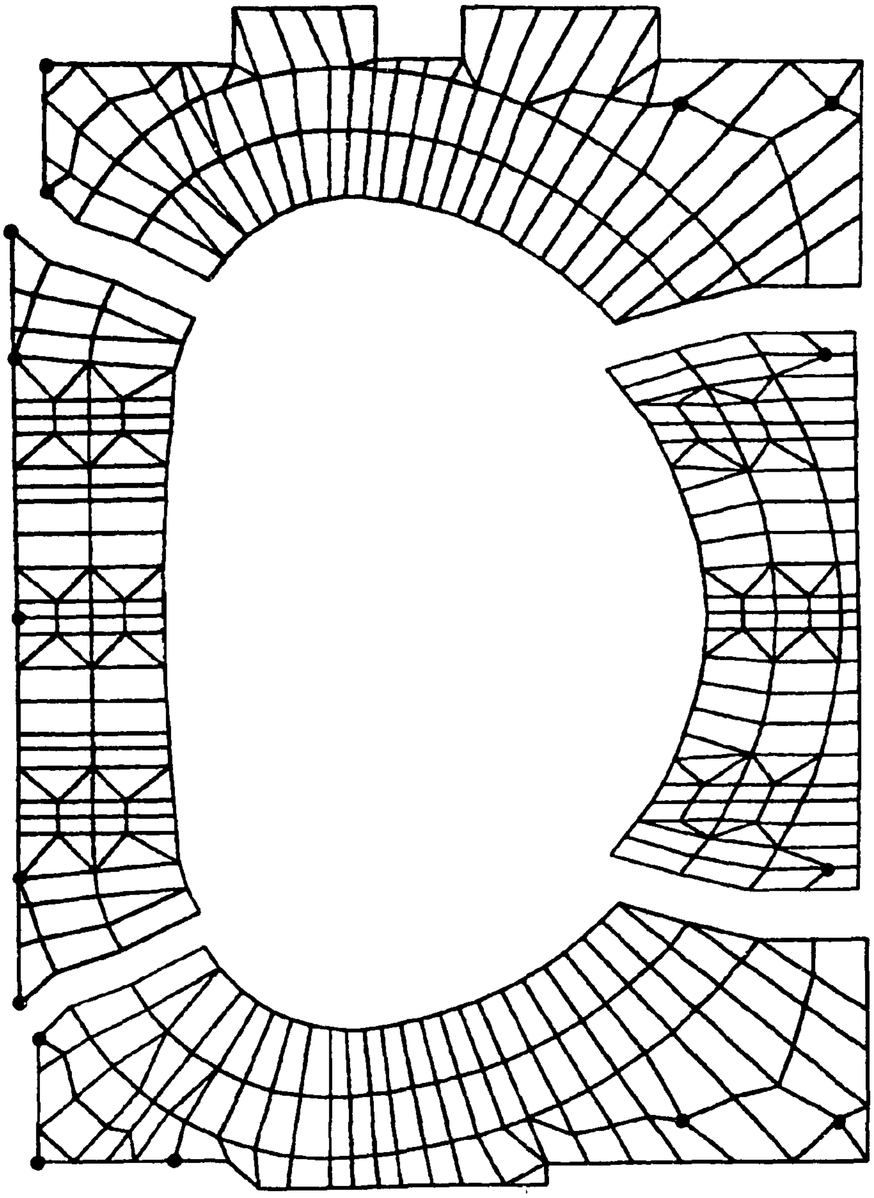

Fig. 13. The Westinghouse finite element model for their LCP coil.

matrix. Westinghouse is using their proprietary computer program WECAN[13] to perform their structural analysis calculations.

Finite element data-management complexities have required the development of a number of special purpose computer programs to automate the pre- and postprocessing 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[8] 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[10] and MAFCO-W,[14] 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.

8. LCTF STRUCTURAL ANALYSIS PERFORMED AS A BASIS FOR THE LCP DESIGN

The six toroidal coil designs have different structural stiffnesses and current densities that reflect different preferences in satisfaction of the LCP design specification. Evolving competitive designs are not necessarily available for free exchange between the coil manufacturers. Considering the influence of other coil manufacturers' designs, this problem of design/analysis has been resolved by the establishment of a scheme[15] that enables the coil designers to design their coils with a limited amount of knowledge regarding the LCTF system. This, in turn, allows ORNL to design the LCTF without detailed characterization of the various coils. The procedure involves the determination of the LCTF 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 LCTF structure in their detailed coil designs. This interface response is presented to the coil designers as displacements of all interface nodal grid points that are calculated by the LCTF system analysis. The coil designers may then use them as boundary condition displacements at the corresponding test coil interface nodal grid points.

Systems Analysis, Incorporated, is performing the overall structural analysis of the LCTF to support the sizing design calculations. They are using NASTRAN[16] for their structural analysis and TORMAC[17] for their magnetic load calculation. The NASTRAN finite element model for the LCTF is shown in Fig. 14. The finite element model includes the bucking post, the 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 LCTF. 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 UCC-ND 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), the quadrilateral (QUAD2) and triangular (TRIA2) membrane and bending plates, and the solid isoparametric (IHEX2) elements. In addition, multipoint constraints (MPC's) are utilized to represent the various subassembly 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

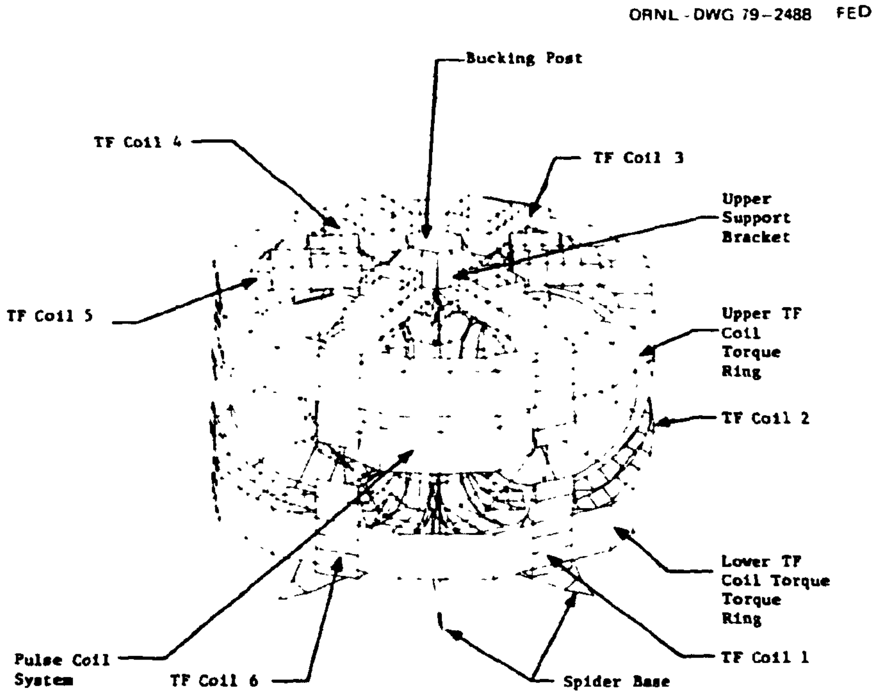

Fig. 14. The NASTRAN finite element model used by SAI to determine the macroscopic behavior of the LCTF.

for a total of 1526 elements. There are 1787 discrete grid points totaling 10,722 degrees of freedom (DOF; there are six DOF per grid point). Numerous multipoint and single-point constraints reduce the system to 7551 independent DOF. Utilizing a partitioning scheme available in NASTRAN, this system is further reduced to 861 DOF in the analysis set and 6690 DOF in the omitted set. The total run time on an IBM 370/195 computer system using 1700 kbytes 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. Approximately 10 CPU seconds are required to develop the global stiffness matrix and 30 CPU minutes are required 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 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 enough to determine the overall structural behavior.

9. VERIFICATION TESTING AS A BASIS FOR THE LCP DESIGN

As designing proceeded, contractors were asked to identify and formulate tests necessary tc 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 the behavior of the materials and devices at 4K.

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 the mechanical properties of structural materials, are likely to be of more general usefulness. Even for alloys with much prior use at 20K and below, including types 304 and 304L stainless steel and aluminum alloy 2219-T87, disagreements 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 GD and the type 316LN stainless steel selected by GE, 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.

As magnet design stabilizes somewhat, the number of such novelties should decrease and with it the number of verification tests. Better generic characterization of materials and devices would save time and materials by giving design teams necessary information at the start rather than near the end of the design cycle.

10. POTENTIAL AREAS FOR FURTHER INVESTIGATION

Because of 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 not being investigated as part of the LCP that will be addressed as the technological sophistication of applied superconductivity increases. 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 simplest 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. Because 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, cooling channels, and spacers, as well as the superconducting filamentary composite itself, should be modeled as a basic inhomogeneous 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 4K must be established. The material properties that 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 variants L and LN, type 310S 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_3Sn 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_3Sn superconductors. Also, electrical vs 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 that should be examined to ensure stable operation on the basis of magnetoelastic stability.[19] Although the magnetoelastic stability of the LCTF does not appear to be a problem, analytical methods should be incorporated into finite element computer programs[20] so that the magnetoelastic 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 the competition for computer resources from other groups within our organization. Techniques such as multilevel substructuring and multiglobal analysis will be needed as the sophistication of the finite element model of the LCTF increases.

11. 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 nested 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 the commercialization of nuclear fusion.

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