**Letter Report for the Superconducting
Magnet Development Program
December 1, 1975-March 1, 1976**

MASTER

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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LETTER REPORT FOR THE SUPERCONDUCTING
MAGNET DEVELOPMENT PROGRAM

December 1, 1975 - March 1, 1976

Engineering Sciences Department
Thermonuclear Division

MAY 1976

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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LETTER REPORT FOR THE SUPERCONDUCTING
MAGNET DEVELOPMENT PROGRAM

Period Ending 1 March 1976

H. M. Long, Program Manager

M. S. Lubell, Assistant Program Manager

J. K. Lovin, Program Monitor

I. INTRODUCTION

During this report period, the Fourth Quarterly Progress Report (period ending September 1, 1975) was issued as ORNL/TM-5184. Both the FY 1975 Annual Report (period ending June 1, 1975) and the Fifth Quarterly Progress Report (period ending December 1, 1975) will soon be published as ORNL/TM-5019 and ORNL/TM-5259, respectively. In addition, the Program Plan (ORNL/TM-5109) was revised in January 1976, and a summary of the Engineering Sciences Department activities for CY 1975 was prepared for the Thermonuclear Division Annual Report. The revised program plan will be issued to the distribution of the original plan in the forthcoming reporting period. These documents, together with this Letter Report, describe the accomplishments and evolution of the SCMDP toward the present activities. The overall program consists of: (1) the basic program focused on fabrication of Large Coil Segments, i.e. thin coils, for the toroidal magnetic field system, (2) fabrication of small-scale pulsed coils for the poloidal field system, and (3) the industrially fabricated toroidal field coils of the Large Coil Project. The Large Coil Segments are essentially full size large coils in bore and winding depth but have fewer total ampere turns. They are therefore thin coils which exhibit most of the winding and fabrication problems expected for large coils. Continual work in refining the Experimental Power Reactor (EPR) reference system and initiation of the design of magnet systems for the Demonstration Reactor (DEMO) help provide the overall focus for the SCMDP activities.

The following acronyms are used in this report:

CTR - Controlled Thermonuclear Reactor
DEMO - Demonstration Reactor
EBTR - ELMO Bumpy Torus Reactor
EPR - Experimental Power Reactor
LCP - Large Coil Project
LCS - Large Coil Segment
LVDT - Linear Variable Differential Transformer
MF - Multi-Filament
OH - Ohmic Heating
SCMDP - Superconducting Magnet Development Program
SCR - Silicon Control Rectifier
TF - Toroidal Field

II. PROGRAM OBJECTIVES

The program plan issued as ORNL/TM-5109 is being revised. A January 1976 version with concise, clear statements of the objectives, philosophy, and key issues will soon be available for distribution.

The goal of the Large Coil Project (LCP) is to utilize the experience and creativity existing in industry from conceptual design through fabrication of large EPR-relevant coils. When completed the industrially fabricated coils will be assembled in a test facility to provide a demonstration of the viability of superconducting magnets for EPR's.

Concurrently with LCP, ORNL will, in the basic program, undertake the design, fabrication, and testing of Large Coil Segments which are similar in bore to the coils produced in the LCP but much reduced in cross section and amp-turns. The small-scale experiments performed by the SCMDP staff and subcontractors are in direct support of the preceding activities as well as the poloidal field requirements. The initial pulsed field coil measurements will be on a small scale and are aimed principally at selecting the conductor and winding configuration that can satisfy the rate of rise requirement with acceptable losses. The development activities will enable ORNL to provide guidance, technical input, and evaluation of the industrial participation in the LCP. In addition to the close cooperation with industry and the continuing cooperation with other national laboratories by means of subcontracts, use of well-documented computer programs, and loan of superconducting material, the SCMDP staff has initiated discussion with representatives of the IEA and Euratom on means to foster and encourage international cooperation on the development of superconducting magnets for tokamak fusion devices.

III. IMPLEMENTATION

The following changes in personnel have occurred. E. L. Woods and R. W. Derby have assumed new positions with General Atomic and Magnetic Engineering Associates, respectively. G. W. Donaldson has finished his sabbatical and returned to his university duties in Australia. There are no immediate plans to replace these valuable employees, due to a lack of funds.

The newly formed Large Coil Project (Subprogram I) is being managed by P. N. Haubenreich who continues in his position as technical projects manager reporting directly to the division director. J. N. Luton is the assistant project manager and also continues as subprogram manager of the coil design activity. P. B. Thompson and W. C. Anderson of the Engineering Division, have assumed the position of principal engineer (responsible for providing the technical information and coordinating the drafting), and project engineer (responsible for overall coordination of cost and scheduling), respectively.

The construction of the new labs which are so vital for the program has not been completed and is not likely to be finished before the end of the next quarter.

Of those milestones which remain in FY 1976, three of them came up at the end of this period and two of them were met on or just before the promised date. The pressure-drop experiments on the cable conductor in a hollow conduit have been initiated, and reliable measurements have been taken. The design of a number of conductor configurations suitable for the Large Coil Segments has been completed, and specifications will be sent out to industry for evaluation and comment prior to the solicitation of bids. The signing of a contract for a helium refrigerator has been held up pending a third solicitation of bids on identical proposals. It is anticipated, but not certain, that all the purchasing and legal requirements will be satisfied before the end of March and that a contract will be signed with the successful low bidder.

IV. PROGRAM STAFF AS OF 1 MARCH 1976

Scientific (Monthly)

J. K. Ballou	J. K. Lovin
R. L. Brown	M. S. Lubell
L. Dresner	J. W. Lue
J. F. Ellis	J. N. Luton
W. A. Fietz	J. R. Miller
K. J. Froelich	J. W. Pearce
W. H. Gray	R. E. Schwall
P. N. Haubenreich	S. S. Shen
C. G. Lawson	J. E. Simpkins
C. J. Long	P. L. Walstrom
H. M. Long	H. T. Yeh

Technical (Weekly)

L. Alley	J. P. Rudd
C. M. Fitzpatrick	W. H. Wagner
E. C. Moore	

Consultants†

J. E. Akin
W. F. Gauster
H. Pih

Engineering Division†

E. L. Allred	E. F. Marguerat
W. C. Anderson	J. R. Moore
P. B. Burn	S. J. Sosnowski
W. D. Cain	W.C.T. Stoddart
G. M. Henderson	P. B. Thompson
J. P. Kois	

V. SUBPROGRAM REPORTS

A. Systems Design

Personnel: H. M. Long*, J. K. Lovin, M. S. Lubell,
J. W. Lue

The major activities during this reporting period were coordination and control of the SCMDP, and participation in the EPR design and DEMO study.

Program Monitor. Budget estimates were made for FY 76, 76a, 77 and 78. These estimates were incorporated into the 189 forms for the SCMDP. In addition checks were made to ensure that charges against the program were valid. Several changes were implemented to reduce future costs. These were necessary to bring program spending in line with allocated funds.

Systems Design. Work was directed towards four major areas during this period. Each of these areas is briefly discussed in the following paragraphs.

TF Coil Shape. Work continued on the study of the choice of a TF coil shape. A method of finding a constant tension "D" shape that takes into account a finite number of coils and finite coil cross section has been evaluated. It has been found that the "oval" shape originally proposed for the reference design can have constant tension over 80% of the winding with a minor modification. The reduction of magnetic energy storage is more than 20% for the oval-shaped as compared to the D-shaped constant tension coil. A method has also been developed which will determine the shape

of a bending stress minimized coil with point supports, i.e. concentrated reactions.

TF Coil Protection Scheme. A magnet protection scheme that conceptually appears to meet the widely varying requirements has been put forth as a base for detailed consideration. It consists of dividing the 20 coils into 4 groups symmetrically distributed along the torus. The five coils in each group will be connected in series. Each group will be charged by an independent power supply, and will be forced to discharge if any one of the individual coils fails.

Ohmic Heating System Study Meeting. A meeting of the OH system study held in Austin, Texas, on February 12, 1976, was attended. Some conclusions reached at the meeting were:

- The power supply requirements agreed to by the three design groups (ANL, GA, and ORNL) have a rise time of between 0.5 to 2 sec and a stored energy of 1 to 2 GJ.
- There is quite a difference in the current and voltage ratings for the three OH coil designs. They range from 25 kA to 400 kA and 6 kV to 150 kV.
- GA and ORNL feel that an initial voltage spike from the OH circuit is necessary, even with some form of pre-ionization.
- Although all three EPR reference designs used a homopolar generator power supply, concerns about whether it can serve the purpose were raised. Several attendees pointed out that solid state rectifiers and motor generator sets may be a viable alternative.

DEMO Reference Size. The input of the magnet scaling laws from this subprogram to the plasma engineers has resulted in a set of plasma parameters for the first iteration. This requires a magnetic field of 5.2 T at the center of the plasma which has a 10.5 m major radius and a 3.5 m minor radius. The maximum field at the magnet winding is 11 T, the same as that used in the EPR reference design. This machine is expected to generate a fusion power of 2000 MW(th). Preliminary calculation using 20 TF coils resulted in an "oval" shape of 12 m horizontal bore diameter and 15.5 m vertical bore diameter. The magnetic energy stored in the TF coil system is about 100 GJ, a factor of 4 larger than the EPR reference design.

B. Coil Design

Personnel: J. N. Luton*, J. K. Ballou, W. H. Gray

Consultant: W. F. Gauster

Designs continued to be developed for practical and reliable superconducting coils to produce the stationary and pulsed fields of future large toroidal fusion machines. Particular progress was made in developing a design for the LCS (thin coils), improving our design tools, completing the pulse coil program plan, and conserving financial resources by performing relevant work for projects outside the SCMDP.

† Employed only on a part time basis.

* Program Manager

* Subprogram Manager

Conductor Configurations. In small monolithic or compacted conductors, the surface-to-volume ratio is large, and the conductor can be cooled sufficiently by having a fraction of its edges exposed to a pool of liquid helium. The remaining portion of the edge is normally covered by the load-bearing interspiral spacer whose interconnected channels contain helium and allow two-dimensional flow. However, as the conductor is made larger, this edge cooling is not sufficient for cryostability. Moreover, in a large conductor it is not economical to process the bulk of the copper as matrix for the superconducting filaments, so that a large conductor is customarily built up of multifilamentary composite plus plain copper strips. Several conductor arrangements were suggested in which this additional copper is formed so that the cooling surface is greatly increased. The arrangements are superficially different and allow for different methods of manufacture, but all provide the additional cooling surface by having the cooling passages primarily within the conductor rather than within the insulating spacer.

Some of the configurations appear well suited for use with either monolithic or compacted stranded conductor. Preliminary calculations indicate that a conductor utilizing the largest monolithic superconductor available commercially is conservatively cryostable at 3200 A (2500 A/cm² overall) in a field of 7.5 T. The size limitation based only on cooling surface area for marginal cryostability gives a current of about 30,000 A at 2500 A/cm² and 7.5 T.

In addition to providing large cooling surfaces, the configurations are sturdy, use commercially available monolithic or stranded conductors, isolate the superconducting filaments thermally from surfaces which might experience frictional heat inputs, give a less compliant coil than does the usual construction, and have smooth flat mating surfaces for facilitating insulating, winding, and force transmittal. The arrangements will be among those considered for the Coil Segments and the Large Coil Test Facility.

PLASS Code. The computer code PLASS (Pulse Losses in Axisymmetric Superconducting Systems), which calculates total pulse losses in a superconducting coil, has been revised to extend its capabilities in two ways. First, the current is no longer restricted to a fixed time schedule; an arbitrary pulse can be handled by a piecewise linear substitution. Second, currents in the coils need not all be the same; up to three circuits with independently varying currents are allowed.

Poloidal Coil System. Work on the EPR poloidal coil system has been directed toward identification of the needed development areas. The task areas include: (1) development of lower-cost manufacturing methods for high-performance conductors; (2) selection, testing, and possible development of suitable non-metallic structural materials; (3) determination of the most suitable cooling scheme for the magnets; and (4) possible development of the cryogenic equipment needed. The identification of these tasks is the first step toward the goal of a working coil system.

EBTR Magnet Design. Preliminary magnet design for an ELMO Bumpy Torus Reactor (EBTR) has begun. So far the results indicate a need for high-field magnets with about 10 T in the high field region of the windings. It also appears that noncircular coil shapes are not necessary because the fields are nearly symmetrical in the windings; the field on the inside radius of the coil varies only about 1% around the coil. The construction

method described for the ORNL reference tokamak EPR appears adequate for the EBTR coils. In the present EBTR the coils themselves appear to be a less difficult task than the tokamak EPR toroidal field coils. However, there may be significant problems (e.g., coil heating and irradiation) arising from the requirement of a small radial gap between the coil and the plasma.

C. Conductor Selection and Test

Personnel: W. A. Fietz*, L. Alley, J. W. Lue, J. R. Miller, J. P. Rudd, R. E. Schwall, S. S. Shen, W. H. Wagner

Metals & Ceramics Division: R. J. Beaver, D. S. Easton, R. E. McDonald

Argonne National Lab: E. S. Fisher, S. H. Kim

Westinghouse: M. S. Walker, G. R. Wagner

During this reporting period the mechanical tests on MF Nb₃Sn continued and several activities with NbTi conductor were initiated. The pulse coil winding facility was set up and a model coil of the first winding concept was completed. Apparatus for testing bifilar pancakes was finished and operated. A test of a NbTi solenoid was conducted and analyzed under pulse conditions. Conductor designs for LCS tests were prepared and analyzed. The last major area of effort was experimental cable compacting. These and other areas of involvement are briefly discussed in the following paragraphs.

Tensile Properties of MF Nb₃Sn. The mechanical testing of MF Nb₃Sn has continued using new samples supplied by Airco and IGC. These new samples include larger cables from IGC and other monolithic configurations from Airco. The most recent data show improved performance for the monolithic conductor with a slight increase in current density for strains up to about 0.1%. For higher strains current density decreased as in earlier samples.

Pulse Coil Testing. The winding equipment for the ventilated pulse test coil has been set up, and a model coil wound. An existing 5 cm bore coil, 15 cm in length, with a design field of 5.2 T at 400 A, is being tested. The conductor in this coil is a 35-strand braid with 15 μ m filaments and a copper-to-superconductor ratio of 2.

The coil was successfully tested to design field and is being cycled at a rate of 1 T/sec to 4 T and back to zero. An electric method has been developed to measure transient voltage losses directly. This method can be used to determine heat losses during cycling, and can be used for quench detection, since it is very sensitive to changes in the effective conductor resistance. A detailed analysis of the pulse losses in the coil is being carried out.

Conductor Designs for Large Coils. Conductors capable of carrying 10 kA at 7.5 T and operating in pulse fields of 0.5 T/sec have been designed and analyzed. Four different configurations have been proposed, three for pool-boiling application, and one for forced-flow operation. These conductor designs form the basis of a forthcoming request for price quotation by industry. The conductors will be wound for testing as Large Coil Segments.

* Subprogram Manager

Conductor Stability Test. Apparatus for examining the propagation and recovery of normal zones in a superconductor in a realistic coil environment has been constructed and tested. The apparatus utilizes a bifilar wound pancake sample of up to 23 cm OD. The pancake can be oriented at any angle relative to the applied vertical fields, allowing investigation of such effects as cooling channel orientation. In addition, the effect of cooling channel geometry can be studied because cooling channels can be interchanged without rewinding the pancake.

Experiments with this apparatus are under way. Preliminary results appear to be reasonably well understood, but are incomplete. Data have been collected in both the propagation and recovery regions of current, and in applied background fields from zero to 5.5 T. Comparison is being made with data taken with the simpler longitudinal propagation apparatus reported previously (ORNL/TM-5259).

Westinghouse has progressed to the completion of phase I, the initial study phase, while apparatus for phase II is currently under construction. Phase II will consist of the measurement of conductor stability under simulated operating conditions.

Cable Compacting. Tests of a series of cable samples which have been rolled to different thicknesses have been completed. The tests demonstrated that the cables showed no degradation in critical current until the conductor was reduced to about half its original thickness. In this state the total conductor thickness was only 15% greater than one of the original strands of the cable. These tests indicate that NbTi conductors can be very severely deformed before degradation occurs, and that compacted multistrand conductor designs are feasible for large coils.

Cyclic Stress Effects. This work is being performed under subcontract to ANL. Experimental work on the increase of electrical resistivity in copper with constant strain cycling has been completed. These tests have confirmed the role of annealing texture in determining the resistivity change under cyclic loading. Samples of C101-grade copper (RRR=230) showed a resistivity increase of 15 nΩ cm after 500 cycles at 0.3% strain. This is a 200% increase over the residual value of 7.5 nΩ cm, which is about half the magnets' resistive effect (30 nΩ cm and 8 T).

Work on phase II, cyclic loading effects on composite superconductors, is well under way. Equipment has been assembled and the first samples have been prepared. The test will consist of a cyclic push-pull loading with periodic measurement of conductor critical current without warming the sample.

D. Radiation Effects on Superconducting Coils

This subprogram has not been staffed as a full-time project because of funding limitations. However, a brief survey¹ of published investigations of fast-particle irradiations at low temperature was conducted. The purpose of the study was to scope the areas of concern for likely CTR magnet materials. The materials-related topics included in this survey are:

- Irradiation of NbTi alloys with fast neutrons, protons, deuterons, and electrons.
- Irradiation of A-15 components (mainly Nb₃Sn) with fast neutrons, deuterons, and oxygen atoms.
- Irradiation of Cu and Al with fast and thermal neutrons.

- Irradiation of insulators with neutron and gamma rays.
- Irradiation of structural materials with neutrons.

One of the results derived from this study is that for fast-neutron fluences up to approximately 5×10^{18} n/cm² ($E > 0.1$ MeV), it appears that the problem of degradation of important superconducting parameters ($J_c(H)$, H_{c2} , T_c) by radiation damage for NbTi alloys and Nb₃Sn is minimal. Above this fluence, $J_c(H)$ for NbTi material can be decreased significantly. A similar degradation is expected for $J_c(H)$, H_{c2} , and T_c for Nb₃Sn.

The results of this study have been used to address the question of radiation damage for an EPR-1 magnet system for short periods (~1 year) of 100 MW operation. Specific results of the study include: (1) a recommendation to account for the increase in resistivity of Cu and Al components due to radiation damage over the reactor life; and (2) the finding that no appreciable damage is expected to accumulate in superconductor material.

Reference

1. J. F. Guess et al., A Survey of Radiation Damage Effects in Superconducting Magnet Components and Systems, ORNL-TM-5187, Oak Ridge National Laboratory, Oak Ridge, TN (Dec. 1975).

E. Coil Protection, Eddy Current Shielding, and Power Supply

Personnel: H. T. Yeh*, L. Dresner

Computer Sciences Division: K. H. Carpenter

Progress was made towards solving technical problems related to the quenching, protection, eddy current shielding and power supplies of tokamak EPR superconducting magnets. Specific accomplishments are discussed in the following paragraphs.

Perturbation Expansion with Separated Time Dependence for Eddy Current Calculation. The perturbation expansion technique which was developed earlier (see the Fifth Quarterly Progress Report, ORNL/TM-5259) for the eddy current calculation has been implemented for the case of rectangular thin plates and thin cylindrical shells. For the test cases, linear ramp time-dependence of an external dipole field was used. Other cases may be treated by modifying the subroutines. Results derived for coaxial geometries may be compared with results for the lumped circuit solution. Good agreement for the steady state was obtained. The agreement in the calculation of the transient behavior (time variation) of the eddy currents is about 15%. The main uncertainty is in fitting a ramp time function by a polynomial with finite terms. The edge charge (boundary effect) was found to modify the eddy current pattern significantly.

Coil Protection Experiment. Assistance is being provided to Conductor Selection (Subprogram C) with the pulsed magnet ac loss experiments. The model coil protection system reported earlier (ORNL/TM-5259) has been integrated into the experiment. A sample holder for persistent switches has been fabricated and the Hall probe inside was used to monitor the magnetic field attained by the 5 cm bore, 5 T pulsed magnet.

* Subprogram Manager

Two types of persistent switches developed for protection circuitry have been designed and fabricated. One type used manganin wire, while the second used a strain gage as the source of heat input to trigger the switch to go from superconducting to normal state. The inductive voltage (~ 10 V) developed during charging and discharging the magnet has been sufficiently compensated for (a factor of several hundreds), so that only a small (~ 10 mV) voltage, mainly due to ac loss, is observed. This demonstrates that the method of compensation by using a small pick-up coil at the current leads of the magnet is a viable way of quench-detection.

Stability-Optimized Force-Cooled Conductors. A computer program was previously written that calculates the temperature-time history of a uniformly pulse-heated composite conductor, cooled by super-critical helium in forced convection. The program determines whether the conductor recovers to the superconducting state or not. This earlier program required a time-consuming trial-and-error process to determine the maximum temperature to which the conductor could be raised and still recover to the superconducting state. By integrating backwards rather than forwards in time, it is possible to determine the maximum temperature for recovery without trial and error in a single integration. This option has been added to the earlier program.

Using the improved program described above, it has been possible to optimize conductors with respect to stability by varying the copper-to-superconductor and the metal-to-helium ratios simultaneously. These stability-optimized conductors allow a given stability level to be maintained and the pressure drop and pumping losses to be reduced.

Specific Heat of Nb₃Sn at Low Temperatures. Data are available on the specific heat of Nb₃Sn at zero magnetic field. Using a thermodynamic analysis described in ORNL/TM-5184, this data has been extended to non-zero values of the magnetic field. An earlier program for the calculation of specific heats and enthalpies has been extended to include Nb₃Sn.

Current Transfer Between Cable Elements. A study has been carried out of the stability of a stranded cable containing two different kinds of strands — composite multifilamentary strands and strands of pure copper. The conductor was found to be less stable than a conductor containing composite multifilamentary strands of the same amount of copper and superconductor.

F. Structural Analysis and Material Tests

Personnel: W.C.T. Stoddart*, C. F. Fitzpatrick, K. J. Froelich, W. H. Gray, C. J. Long

Engineering Division: W. D. Cain

Metals & Ceramics Division: D. S. Easton

Consultants: J. E. Akin, H. Pih (Univ. of Tennessee)

Lockheed: J. A. Mayhall, C. T. Welch

Mechanics Research: N. E. Johnson, R. M. Pardue

The Structural Analysis and Material Tests subprogram is gathering and developing necessary technology and information in the area of mechanical or structural features of superconducting magnets. The information

developed in this subprogram is being generated through analytical and experimental studies in support of the other subprograms of the SCMDP.

Mechanical Behavior of Laminated Composite Beams.

A study was initiated in December of the mechanical behavior of laminated composite beams. The experimental portion of this study has completed a series of tests of simply-supported copper and steel beams of various geometries. The geometric variables include section depth and number of layers. The beams have been tested using two epoxy bonding formulations as well as three non-bonded cases. The non-bonded beams used Mylar, Teflon, and Kapton films to separate the copper layers of the beam. After the completion in December of a series of tests to develop the deflection measurement system, the entire series of beam geometry tests was performed during January. The results of these experiments are now available to check the validity of the analytical methods being studied. The analytical portion of this study has shown that the accuracy of the results of two-dimensional finite element analysis can be changed from acceptable to unacceptable by increasing the aspect ratio (length/width of individual elements) or by rapidly changing material properties. This is not a new result in finite element analysis, but simply verification of a previously known situation. The adjustment of the geometry of the finite element mesh used is within the control of the analyst, while the material properties are dictated by the problem being analyzed. This would seem to indicate that analytical models may be significantly influenced by the size of the epoxy bonding layers in the beam and could involve computer costs higher than for homogeneous materials. To minimize this problem two approaches are being considered. The first is based on a classical theory of elasticity using stress functions, while the second is based on a specially developed finite element for laminated beams. The results of these analytical studies will be reported next quarter.

Mechanical Heat Sources in Superconductors. An experiment was completed which investigated the temperature rise in a superconductor specimen due to mechanical behavior. A series of tests at room temperature and 4 K on OFHC copper and a monolithic NbTi/Cu conductor was performed in the absence of a magnetic field. The room-temperature tests appear to correlate well with classical linear thermoelastic theory. The cryogenic tests of the copper specimen are also well supported by this theory. The behavior of monolithic NbTi/Cu conductor is not as well explained. This is due to the previously observed departure from linear elastic behavior at low strains. The results of these tests are being studied, and a report is being prepared.

Optimized Toroidal Field Coil Shape. The previously reported (ORNL/TM-5259) procedure for determining the shape of toroidal field coils with minimal bending stress has been extended to consider the effect of a discrete number of coils. This extension is based on the simplified procedure for determining force per unit length developed by Ron Moses and Warren Young¹ of the University of Wisconsin. This provides an easy-to-use program to investigate idealized coils with continuous or discrete supports.

Structural Analysis of EPR. The structural analysis performed to support the ORNL-EPR scoping study has been placed in report form. The analysis made extensive use of the NASTRAN computer code, and the report contains valuable information to anyone expecting to use this computer program for structural analysis of tokamaks.

* Subprogram Manager

Reference

1. R. W. Mosses, Jr. and W. C. Young, "Analytical Expressions for Magnetic Forces on Sectorial Toroidal Coils," paper presented at the Sixth Symposium on Engineering Problems of Fusion Research, San Diego, CA (Nov. 18-21, 1975).

G. Cryogenics and Refrigeration

Personnel: C. G. Lawson*, J. K. Lovin

Engineering Division: J. P. Kois

National Magnet Lab: M. O. Hoenig, Y. Iwasa,
D. B. Montgomery

The environment of the superconducting magnet must be established and maintained at temperatures of 3 to 5 K in the magnet coils. The efforts of this subprogram were directed toward ensuring that this environment is maintained for all operating modes of the magnet system.

Pressure-drop measurements have been made on cable-type conductors with helium gas at 300, 90, and 80 K. These data have been correlated on dimensionless coordinates to make them applicable to liquid helium in similar cables.

The two initial proposals for a 3.5 K liquid helium refrigerator have been evaluated, and negotiations via the purchasing department have continued with the two bidders throughout the quarter. A formal response to identical specification with no exception allowed is scheduled for March 2.

Development of Force Cooled Cable Conductors. The Francis Bitter National Magnet Laboratory is developing a cable-in-a-conduit winding for a superconducting magnet under subcontract to the SCMDP. Pressure-drop measurements were made with helium gas flowing through a sample of cable conductor 3.05 m (10 ft) in length. The cable was made from 19 wires with each wire made of a set of 3 strands. The fluid occupies about 50% of the conduit area.

The pressure-drop flow measurements were cast into the form of a conventional plot of friction factor versus Reynolds number. Preliminary evaluation of the data indicates a smooth transition from laminar to turbulent flow, and that values of the friction factor in the turbulent flow region are about 3.5 times higher than would be calculated on the basis of the smooth-tube friction-factor relation utilizing the hydraulic diameter of the cable and conduit.

Purchase of 3.5 K Liquid Helium Refrigerator. Two proposals were reviewed last quarter (November 1975) to supply a 3.5 K helium refrigerator and liquefier operating at 866 W and 118 l/hr. Both proposals were technically acceptable, given minor revisions to assure the capability of operation with refrigeration at supercritical pressure and subcritical temperatures. Negotiations have continued with both manufacturers during the last quarter, and a request has been sent out to submit the best and final price by March 2 with no exceptions allowed on a final set of specifications.

Support for ELMO Bumpy Torus Fusion Devices. General support in the area of magnetics and cryogenics has been supplied to the ELMO Bumpy Torus Reactor (EBTR) preliminary conceptual design. This support is charged

to that project. The EBTR is a series of continuous mirror devices arranged in a high aspect-ratio (toroidal radius/plasma radius) circle. The field bulges between mirrors are the bumps. The plasma resides in the bumps and is heated initially by microwave energy. The machine is an inherently steady-state device from the magnet point of view, since no large driving or heating pulses are required. The elimination of these pulses reduces the amount of energy deposited in the coils and appears to facilitate natural convection cooling of the magnet coils.

Analytical Modeling. Work, at a low level, was continued on extending the capabilities of ORNL's computer program THERM, a digital thermal analyzer. The graphic package is now operational. The user has several options available for selecting and grouping nodes to plot and defining titles and scales. An optional grid is also available. Some additional changes were necessary in the program's restart procedure to avoid loss of some data in the event of termination due to exceeding the maximum run time.

Temperature histories from the model of a "typical superconductor" were plotted using the new graphic package. This greatly reduced the man-hours required to obtain these plots, and avoided possible plotting errors. These histories are being analyzed to identify trends and potential problem areas. This study will be documented during the next reporting period.

H. Coil Fabrication

Personnel: R. L. Brown*, J. F. Ellis, C. M. Fitzpatrick, K. J. Froelich, C. J. Long

Engineering Division: E. L. Allred, P. B. Burn,
G. M. Henderson, E. F. Marguerat, S. J. Sosnowski

Electric Shop: H. F. Clayton, J. F. Monday

Large superconducting magnet systems will be needed if fusion reactors are ever economically successful. New and improved fabrication techniques which are reliable and not exorbitant in cost must be developed for these large magnet systems. The goal of this subprogram is to identify areas that need improvement and develop methods for implementing these improvements. It is considered cost beneficial to fabricate coils in at least one intermediate size before fabricating full-sized coils (6 - 10 m bores).

At Oak Ridge a 3 m TF coil-winding facility has been designed and is presently partly assembled. The layout and some component photographs have been reported previously (ORNL/TM-5184). The winding table, practice bobbin, tension device, conductor straightener, and spool dereeler are complete but untested. Designs for electrical power and tension controls are also complete. The system will be used for winding the Large Coil Segments.

Pulsed coils have some unique fabrication problems. The conductor will most likely be braided to permit extra cooling surfaces and suppression of eddy currents. Braided conductors cannot be expected to resist hoop stresses or transmit high compressive forces. Furthermore, the conductor must be held firmly in place to prevent generation of frictional heat. Potting or wet winding coils in epoxy has been a preferred method for small coils cooled at their outer surfaces. However, potting of large coils is much more difficult to do

* Subprogram Manager

* Subprogram Manager

reliably and differences in contraction on cool-down may cause cracks. In addition, potting of large coils will be time-consuming, expensive, and make it impossible to repair the coils. A method of both cooling and structurally supporting a cabled or a braided conductor is needed. Several concepts for fabricating unpotted coils have been proposed, and one small coil using copper braids has been fabricated to investigate a new winding scheme. Several small superconducting test coils are planned.

A container box for making explosively welded splices has been designed. Construction of the box and test-welding of splices will proceed when funding can be justified.

I. Large Coil Project

Personnel: P. N. Haubenreich*, J. N. Luton

Engineering Division: W. C. Anderson, J. R. Moore,
P. B. Thompson

The Large Coil Project (LCP) was created with the goal of early fabrication of large EPR-relevant toroidal field coils, utilizing the capabilities of industry under the direction of the SCMDP. Progress consisted of (1) resolution and approval of project objectives, (2) planning of major activities over the 4-year life of the project, and (3) technical work on early tasks. Plans are to let contracts within the year for design and fabrication of coils by industry, to be completed and ready for testing early in 1980. Conceptual design, planning of tests and preliminary contract negotiations were started during this report period.

EPR TF Conceptual Studies. Ranges of requirements on the EPR TF magnets have been defined by scoping studies at ANL, GA, and ORNL that produced reference conceptual designs of complete reactors. Based upon this work, ERDA-DCTR in December began preparations to let three contracts to qualified industrial groups to do conceptual studies of TF magnet systems meeting EPR requirements. The purpose is to permit selection of reference points for subsequent design of test coils in the LCP. The LCP staff drafted the work statement for the contracts, which are to be handled by ERDA-ORO with technical input from ORNL and DCTR. In cooperation with the three EPR teams, project personnel summarized EPR magnet requirements in the form of a set of guidelines and criteria to be provided to the contractors.

Each of the three contractors will be required to consider two cases: one with an 8 T peak field, and the other with a peak field as high as practicable in the range 11-16 T. All designs must be cryostatically stable and be protected against damage in any credible event. The coil sizes are 7.5×11.25 m for the 8 T magnet and 6.8×10.2 m for the higher field case. The contractor may choose either a "D" or "oval" shape. The designs must ensure reliable operation in specified pulsed fields and radiation environments typical of those found in the EPR scoping studies.

An advertisement was run in the February 20 Commerce Business Daily soliciting qualifying statements from interested firms.

Comparison of Testing Arrangements. Earlier work in coil testing (Subprogram J) was extended, with the goal of providing an adequate basis for choice of testing arrangements during the next quarter. General

requirements are that test coils representing the two or three most promising EPR concepts, large enough to prove EPR coil fabrication procedures and designs, be fabricated by industry and be tested by ORNL under conditions closely simulating those in the EPR. Early indications are that the test coil must be about 3×5 m in size. Test conditions would include the same peak magnetic field (7.5 or ≥ 11 T), equivalent stresses and strains in the winding, similar spatial distribution of fields, forces and stresses, pulsed fields, and simulated radiation heating. Other important considerations in the choice of testing arrangements include cost, investment in nonprototypic background coils, convenience in testing several different coils, and compatibility with existing facilities.

Field and force distributions in test coils and total inventories of superconductor were calculated for the three leading candidate test arrangements: a 6-coil compact torus, a cluster test, and a "split-eccentric" test. The last-named requires the least total amount of conductor to produce peak fields, but force distributions are least like those in the EPR and there is substantial investment in background coils. The compact torus concept is based upon the availability of 6 test coils, possibly of several different candidate designs but compatible dimensions.

Site Considerations. Requirements of a test site were defined. Prominent among them are cryogenic and vacuum facilities and equipment capable of handling coils 40-50 tons in weight. Prospective sites owned by ERDA or NASA were identified for further consideration.

J. Coil Testing and Evaluation

Personnel: P. L. Walstrom*, J. F. Ellis, E. C. Moore,
J. E. Simpkins

Instrumentation & Controls Division: J. W. Reynolds

The Coil Test and Evaluation Subprogram has as its major concerns the evaluation and development of an instrumentation and data acquisition system for coil testing and the design of coil test facilities.

The basic evaluation tests of the moving coil (coreless) LVDT reported previously (ORNL/TM-5259) were concluded. Five working units were fabricated. In the magnetic field sensitivity tests, maximum nonlinearity measured 0.1% over a gaging range of 1 cm. The output increased 0.3% in a 4 T magnetic field and 1% in a 7 T field in the worst orientation. In most proposed applications, the effect will be considerably less, due to a more favorable orientation in the field. Dynamic testing of the device by driving the center coil back and forth sinusoidally over the gaging range showed a virtually flat response up to 100 Hz. An assortment of mounting hardware and linkages was designed and tested for mechanical backlash. It exhibited values of 5 to 30×10^{-6} m, depending on the coupling used.

A potentially troublesome noise problem in carrier amplifier systems was investigated. The problem arises when a periodic noise voltage contains harmonics which coincide with the carrier frequency (e.g. 60 Hz SCR spikes and a 3 kHz carrier). The harmonic mixes with the carrier and produces beat notes as the relative phase of the harmonic and carrier varies. The noise signal can be present when sensors are closely coupled capacitively to the windings (e.g., a strain gage cemented to the windings, etc.). A possible solution

* Project Manager

* Subprogram Manager

is to phase-lock the carrier to the line at a frequency which is not a low harmonic of the line voltage.

A literature survey of pressure sensors which are potentially operable in high magnetic fields and at low temperatures is being performed, and a number of candidates have been selected for testing. Of the commercially available sensors studied, a device operating on a variable capacitance principle appears to be the most promising. If necessary, however, the moving coil LVDT described earlier could be coupled to a diaphragm for pressure measurements.

A method of making a separate superconducting sensor (ORNL/TM-5259) which does not require a groove in the magnet conductor was developed, and an experiment to test the new configuration is being prepared. The detector circuit is in the shape of a ribbon which is formed by rolling out a circular NbTi filament. Carbon thermometers made by vacuum deposition were investigated, but a completely satisfactory film was not obtained. A method of making films reported in the literature, which uses a carbon colloid suspension in a dissolved organic polymer, gave mechanically rugged films, but the resistance ratio was too low.

Bids for an online data acquisition system for coil testing were sent out and returned. We have elected to purchase part of the system (the portion which met specifications) from the successful bidder and to purchase the remainder of the system from other sources, pending approval.

VI. LIST OF MAJOR PURCHASES

1. Aluminum Corporation of America: Aluminum-stabilized conductor.
2. Intermagnetics General Corporation: Cryostabilized compacted rectangular cable.
3. Leeds & Northrup: Recorder.
4. Falk Corporation: Reducer for winding machine.
5. American Manufacturing Company: Elevating table.

VII. VISITORS*

December 18-19	Carl Henning (ERDA-DCTR)
December 29	Denis Markiewicz (Intermagnetics General Corporation)
February 4	Eric Stern, Robert Patsco, Anthony Favale, and Michael D'Agostino (Grumman, Long Island, NY)
February 5	Dan Deis (Lawrence Livermore Laboratory)
February 10	D. Bruce Montgomery and Mitch Hoenig (MIT-National Magnet Laboratory)
February 17	Joseph R. Heim (Fermi National Accelerator Laboratory)

* This list does not include discussions with job applicants or meetings and discussions with staff members of other ORNL divisions.

VIII. STAFF TRIPS*

<u>J. K. Ballou</u>	
February 11-12	Ohmic Heating, Power Supply, & Coil Review, Austin, Texas
<u>W. A. Fietz</u>	
February 3	LLL Program Review, ERDA-DCTR
February 23	Review of Battelle Hydrostatic Extrusion Program, ERDA-DCTR
February 25	Coordination Meeting for Procurement of Superconductors, Chicago, Illinois
<u>P. N. Haubenreich</u>	
January 14-15	ERDA-DCTR
January 21-22	Fusion Power Coordinating Committee Meeting, LASL
February 25-26	Thermonuclear D & T Programs Review, ERDA-DCTR
<u>C. G. Lawson</u>	
February 2-3	MIT-National Magnet Laboratory
<u>C. J. Long</u>	
December 3-4	ASTM/ASME/MPC Joint Committee J1 on Effect of Temperature on Material Properties, Houston, Texas
<u>H. M. Long</u>	
January 14-15	ERDA-DCTR
January 25-31	IEEE Power Engineering Society 1976 Winter Meeting & Tesla Symposium, New York
February 2-4	LLL Program Review, ERDA-DCTR
February 13	Alcoa Technical Center, Monroeville, Pennsylvania
February 25	Thermonuclear D & T Review, ERDA-DCTR
<u>M. S. Lubell</u>	
February 3	LLL Program Review, ERDA-DCTR
February 12-13	Materials Review & Long Range Research & Development Needs, ERDA-DCTR
February 25-26	Thermonuclear D & T Review, ERDA-DCTR
<u>J. W. Lue</u>	
February 24	Discussion on EPR Design, ERDA-DCTR
<u>R. E. Schwall</u>	
December 3-5	Los Alamos Scientific Laboratory

* This listing includes only permanent staff members of the SCMD program and does not include consultants or members of other divisions or external contractors.

W. C. T. Stoddart

January 16	Lockheed-Huntsville
January 19-21	Safety and Protection Workshop, Brookhaven National Laboratory
February 4-5	MHD Channel Review, Argonne National Laboratory

H. T. Yeh

January 19-21	Safety and Protection Workshop, Brookhaven National Laboratory
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