**Letter Report for the Superconducting
Magnet Development Program**

April 1, 1977-June 30, 1977

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OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

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LETTER REPORT FOR THE SUPERCONDUCTING
MAGNET DEVELOPMENT PROGRAM

April 1, 1977-June 30, 1977

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Edited by W. A. Fietz and M. S. Lubell
Magnetics and Superconductivity Section
FUSION ENERGY DIVISION

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CONTENTS

ABSTRACT	v
1. INTRODUCTION	1
2. PROJECT REPORTS	1
2.1 DESIGN PROJECTS	1
2.1.1 The Next Step Program	1
2.1.2 Large Coil Program	1
2.1.3 ELMO Bumpy Torus Reactor Design	2
2.1.4 EBT-II Design Support	3
2.2 SMALL-SCALE EXPERIMENTS	3
2.2.1 Pulsed Parallel Field Experiment	3
2.2.2 Propagation and Stability Tests	3
2.2.3 Forced-Flow Experiment	4
2.2.4 Pulsed (Poloidal) Coils	5
2.2.5 Conductor Design and Tests, Mechanical Tests, and Facilities	5
2.2.6 Instrumentation	7
2.3 LARGE COIL EXPERIMENTS	7
2.3.1 Large Coil Segment Test Facility	7
2.3.2 LCS Conductors and Coils	8
2.4 PROJECTS BASED ON DISCIPLINES	8
2.4.1 Structural Analysis and Material Evaluation	8
2.4.2 Fabrication Development	8
2.4.3 Stability Analysis	9
2.5 PROJECTS PERFORMED BY SUBCONTRACTORS	10
2.5.1 Forced-Flow Magnets	10
2.5.2 Refrigerator and Liquid Handling System	10
2.5.3 Pump Development	10
3. DOCUMENTATION	11
3.1 ORAL PRESENTATIONS	11
3.2 PUBLICATIONS	11

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ABSTRACT

The results and accomplishments of the Superconducting Magnet Development Program (SCMDP) for the second quarter of the calendar year 1977 are summarized in this report. The presentations are arranged according to projects rather than the group organization by discipline of the Magnetism and Superconductivity Section. The design, procurement, and fabrication of the Large Coil Segment are well under way. Significant progress is reported on the conductor stability and loss experiments for both toroidal field coils and poloidal field coils.

LETTER REPORT FOR THE SUPERCONDUCTING
MAGNET DEVELOPMENT PROGRAM

M. S. Lubell, Program Manager

Period Ending June 30, 1977

1. INTRODUCTION

This Quarterly Report follows the format of the previous three. The numbering of the various sections however, has been chosen to provide continuity within this report rather than to correlate with previous reports. Where no activity occurred on a particular subject, the topic has been omitted completely.

This quarter has seen the real beginning of the Large Coil Segment (LCS) Test Program. Fabrication of the first coil case and bobbin is well under way, the winding facility has been set up and preliminary operation begun, and several conductors are in the manufacturing stage. The test facility has received the first part of a directive and construction is getting under way. At this time, it appears that the goal of testing the first coil in June 1978 will be met, assuming that the conductor ordered can be manufactured.

Although the LCS activities have become a major part of the program, they have not overshadowed the other work of the group. The design projects, small-scale experiments, and discipline projects continue to provide relevant engineering data and understanding of applications of superconductivity. Finally, the work of our subcontractors has shown substantial progress during this period.

2. PROJECT REPORTS

2.1 DESIGN PROJECTS

2.1.1 The Next Step Program (TNS)

Fusion Energy Division (FED) Personnel:

J. K. Ballou

The large costs of the ohmic heating (OH) system for The Next Step (TNS) were examined during the last quarter. The OH system costs are dominated by the power conversion equipment that must handle the large megavolt-ampere

(MVA) required to initiate the plasma and handle the magnetic energy stored in the OH magnet systems. There are three ways to solve the problem of the MVA needed for start-up: (1) the system can be designed for it and the large cost accepted; (2) other plasma initiation schemes can be used that will not require the OH system to supply the initiation voltage; or (3) an iron core, rather than an air core, can be used to reduce the MVA needed for a given amount of flux. The first approach has been used and the cost is high, even though the system can be built today. There is reason to believe that the cost of this approach will come down in the future, but not significantly. Other ways of initiating the plasma are under investigation at several locations, but the results are not ready yet. A preliminary investigation of the use of an iron core for TNS has been completed, and it appears that this option may reduce the initial MVA by about an order of magnitude. Further studies of the cost reductions are under way.

2.1.2 Large Coil Program (LCP)

FED Personnel: L. Dresner, W. A. Fietz,
C. G. Lawson, C. J. Long,
J. N. Luton,* W. C. T. Stoddart,
H. T. Yeh

The goal of the LCP¹ is to fabricate, test, and demonstrate reliable operation of superconducting coils which are large enough to prove the design principles, materials, and fabrication techniques proposed for the toroidal magnets of a tokamak fusion reactor. The LCP has strong interaction with industry, Union Carbide Corporation Nuclear Division (UCC-ND) Engineering, and the SCMDP, which provides ongoing support as required in areas of basic superconducting magnet technology. Overall LCP progress is reported separately² from that of the SCMDP.

In this quarter, the SCMDP assisted the LCP in conducting separate post-award meetings with the three teams [led by General Dynamics, General Electric Company (GE), and Westinghouse] whose

* Author.

proposals for LCP coil design and construction were successful. The meetings were held to answer the contractor questions, to clarify the technical specifications, and to discuss what we felt were the strong and weak points of the team's proposal, so that the Phase I work (conceptual design) could begin promptly and on the right track. At the request of the two unsuccessful proposers [Grumman Aerospace Corporation and Magnetic Corporation of America (MCA)], debriefing meetings were held to describe the strengths and weaknesses of the proposals as perceived by ORNL, with a view toward strengthening future proposals. Finally, the SCMDP also participated in an interim review of the Westinghouse Phase I effort.

In the second major area of LCP work, the SCMDP assisted the LCP in presenting conceptual design of the Large Coil Test Facility to an Energy Research and Development Administration/Division of Magnetic Fusion Energy review panel in April. Subsequently, we helped revise the design and testing plan to reduce costs (primarily by eliminating the liquid nitrogen refrigerator and the pulse coils at all but one test coil) and to provide a staged program in which each stage provided certain definite test data and had identified incremental costs. This latter requirement was met by including provisions for testing first one coil, then three, and finally six, with increasing degrees of realism.

REFERENCES

1. For a description of the LCP, see: P. N. Haubenreich, W. C. Anderson, J. N. Luton, and P. B. Thompson, *Plan for the Large Coil Program*, ORNL/TM-5824, Oak Ridge National Laboratory, Oak Ridge, Tennessee (February 1977), or *Fusion Energy Division Annual Progress Report for Period Ending December 31, 1976*, ORNL/TM-5275, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
2. P. N. Haubenreich, *Large Coil Program Progress Report, January-June, 1977* (in press).

2.1.3 ELMO Bumpy Torus Reactor Design

FED Personnel: H. T. Yeh

The emphasis in this year's ELMO Bumpy Torus Reactor (EBTR) magnet design is on optimization, improvements, and more detailed design. Some highlights of this year's design efforts are listed below.

- (1) The coil dimensions have been optimized to give the maximum access space between coils without violating the plasma constraints. This eases the problems of remote handling, divertor design, and diagnostics. The axial length of each coil is now reduced to 2.1 m.
- (2) Conductors are made of monolithic multifilamentary NbTi composite with built-up copper strips. More copper and a shorter slot size are used in the strip to improve both the cryostatic stability and the mechanical stability. The peak compressive stress in the winding is now reduced to 52.4 MN/m^2 (7.6 ksi).
- (3) Magnets are circular in shape and are made of tightly wound pancakes cooled by pool boiling helium. A fabrication procedure for coil winding and the attachment of electrical leads and cryogenic piping has been worked out. A detailed stress profile has also been computed. The peak stress and strain in winding are 136 MN/m^2 (19.7 ksi) and 0.11%, respectively. Both are within the design limits of the materials used.
- (4) The cryogenic load has been increased to 63.4 kW at 4.2 K (31.7 MW at 300 K), mainly due to the new eccentric shield design and the large conduction surface area structure support. The vapor-cooled lead loss, however, has been significantly reduced from previous designs (especially of tokamaks) by avoiding coil segmentation.
- (5) A flexible electrical connection scheme has been adopted. Coils are discharged in different ways according to whether a discharge is a normal operating discharge, a quench, or a lead/conductor failure. The

out-of-plane load during quench is minimized by reconnecting coils via switching into groups which interleave with each other.

2.1.4 EBT-II Design Support

FED Personnel: J. K. Ballou, C. G. Lawson,*
J. N. Luton, H. T. Yeh

Technical support of the EBT-II design was supplied in the areas of magnet design, protection, and refrigeration requirements.

The magnet parameters for the EBT-II are given in Table 1. The refrigeration requirements are 900 W at 4.2 K and 300 liters/hr of lead cooling.

Table 1. EBT-II magnet parameters

Major radius	4.88 m
Number of magnets	48 m
Mirror ratio	2.25 m
Magnet inner radius	0.176 m
Magnet outer radius	0.275 m
Magnet coil width	0.213 m
Magnet current	1500 A
Stored energy/magnet	0.83 MJ
Characteristic discharge time	≥ 2 sec
Terminal voltage	<500 V
Internal temperature rise	<77 K

2.2 SMALL-SCALE EXPERIMENTS

2.2.1 Pulsed Parallel Field Experiment

FED Personnel: L. Alley, J. R. Miller,
S. S. Shen,* W. H. Wagner

The superconducting torus for testing composite conductors under transient parallel field has been constructed and tested in zero background field. The self-field losses of the torus were measured as a function of current up to the design value of $I_m = 500$ A. Results for $I_m = 420$ A, corresponding to $B = 1.42$ T at the bore, are summarized in Table 2.

Table 2. Results from pulsed parallel field experiment for $I_m = 420$ A

Inductance	17 mH
Stored energy	3 kJ
Slow ramp hysteresis loss per cycle (3.5 mT/sec)	20 J
Coupling loss in exponential discharge mode	
$\tau = 2.17$ sec	12 J
$\tau = 0.78$ sec	28 J

These measurements provide basic data for one of the alternative methods of measuring the conductor losses inside the torus.

The winding of the first test cable conductor is currently under way. About 300 ft of 0.42- by 0.15-cm, 11-strand cable will be mounted inside the bore.

2.2.2 Propagation and Stability Tests

FED Personnel: L. Alley, L. Dresner,
J. W. Lue, J. R. Miller,*
J. P. Rudd

Last quarter, experiments to investigate vapor locking in restricted channels were described. These experiments were successfully completed during this report period. An important finding was that the stability margin for transient heat input into conductors cooled by boiling helium in restricted channels does not decrease monotonically. In fact, we find that the stability margin against transient heat input first decreases as the ratio of channel length to hydraulic diameter (L/D) increases, then increases with further increase in L/D . In very long channels, the stability margin may be larger than in freely boiling helium. We explain these results in terms of sharp pressure increase followed by gradual release in the restricted channels in such a way that both the heat transfer coefficient and the energy-absorbing capacity of the liquid helium are increased. We have gathered experimental evidence for the large pressure buildup and release in long channels and for the increased heat transfer

* Author.

coefficient during the pressure rise. Our complete findings were presented in a paper delivered at the International Cryogenic Engineering Conference, Boulder, Colorado.¹

Experiments on the stability of built-up conductors were also continued during this report period. Triplex samples were constructed with three identical superconducting composite strands and with two composite strands and one copper strand. Conductors of both classes contained very nearly the same fractions of superconductor and stabilizer but had quite different distributions. In each class, conductors were constructed to have (1) bare uninsulated strands, (2) tinned but not bonded strands, (3) tinned and bonded strands, or (4) fully insulated strands. A paper submitted to the Seventh Symposium on Engineering Problems of Fusion Research² presents a comparison of stability in these samples and compares the results with a theory on the effects of separating the stabilizer from the superconductor by a resistive barrier.

Some qualitative data were taken on transient heat transfer in pool boiling helium using samples prepared for the above experiments. Further, more definitive experiments are being planned to strengthen the interpretation of the preliminary results.

REFERENCES

1. J. W. Lue, J. R. Miller, and L. Dresner, "Vapor Locking as a Limitation to the Stability of Composite Conductors Cooled by Boiling Helium," paper presented at the Cryogenic Engineering Conference, Boulder, Colorado, August 2-5, 1977.
2. J. R. Miller, L. Dresner, and J. W. Lue, "Investigation of Current Transfer in Built-Up Superconductors," paper submitted to the Seventh Symposium on Engineering Problems of Fusion Research, Knoxville, Tennessee, October 25-28, 1977.

2.2.3 Forced-Flow Experiment

FED Personnel: L. Dresner, C. M. Fitzpatrick,
C. G. Lawson, J. W. Lue,*
J. R. Miller

During this report period we have continued our activities in all the areas reported before, namely, theoretical analysis, development of cabled conductors, flow and heat transfer apparatus construction, and forced-flow conductor stability assembly.

Theoretical analysis

A paper based on the refined optimization program and extensive parametric study was written by L. Dresner and J. W. Lue. It is entitled "Design of Force-Cooled Conductors for Large Fusion Magnets," and was presented at the Sixth International Conference on Magnet Technology, Bratislava, Czechoslovakia, August 26-September 2, 1977.

Cabled conductor development

Four more cabled conductors for forced-flow experiments were made during this report period, including one Nb₃Sn conductor. All the cables have approximately the same copper-to-superconductor ratio and helium space fraction. They differ in wire surface (bare, insulated, or solder-coated) and in strand distribution: (uniform superconducting composite, two superconducting and one copper strand per wire, or superconducting strands on the outside layer of the wire only). All cables were enclosed in brass jackets swaged down to fit the outer diameter of the cable. No additional compaction was done. Two industrial contracts were given to develop forced-flow conductors. One follows the same line as described above; the other uses a different approach in which the superconductor is monolithic and cooling channels are provided on two sides.

* Author.

Apparatus construction

The major part of the apparatus for measuring flow characteristics of the cabled conductor and the heat transfer coefficient has been constructed. A new set of heat exchanger loops is being built for this particular use. All the parts of the forced-flow stability test setup have been fabricated, including the pulse coil set for heating the test conductor, the test coil winding form, the heat transfer loops, and the current-coolant connectors. The low loss current leads for both the test conductor and the pulse coil have been delivered, and the entire setup is ready to be assembled.

2.2.4 Pulsed (Poloidal) Coils

FED Personnel: J. W. Lue, J. R. Miller,
J. P. Rudd, R. E. Schwall,*
S. S. Shen

During this quarter, we have completed stability testing of the model poloidal field (PF) coil conductors which were described in the last quarterly report. As expected, the solder-filled cable was more stable than the cables employing insulated or bare strands. The cable employing insulated stabilizing strands exhibited higher minimum propagating and maximum recovery currents than the cable with bare strands. The experiments also indicate that complete current transfer to and from the insulated copper stabilizer was achieved. Although the results must be regarded with some caution given the short sample length (~ 2 m), they indicate that further investigation of insulated cables is warranted.

Attempts to measure interstrand coupling losses in the model conductors were unsuccessful due to the presence of a large temperature-dependent paramagnetic moment. Subsequent measurements on a Faraday balance revealed a paramagnetic susceptibility ($\sim 1.9 \times 10^{-4}$ emu/g at 10 K) which is evidently due to the Cu-30% Ni alloy used in the mixed matrix conductor. Work is in progress to further characterize this susceptibility. Loss measurements were begun on a series of triplex cables. The objective of these measurements is to determine the effect of stabilizer distribution and transverse

electrical resistivity on loss. Although some basic calculations and experiments have been done in this area, the agreement between calculation and experiment is, in general, unsatisfactory.

During this quarter, design work on a high copper/superconductor, low loss, mixed matrix conductor was completed in collaboration with Intermagnetics General Corporation (IGC). Initial experiments to verify the fabricability of the conductor were begun.

A paper summarizing the results of the stability measurements on the PF coil model conductors and the initial loss measurements on the triplex cables was presented at the International Cryogenic Engineering Conference, August 2-5, 1977, Boulder, Colorado.

2.2.5 Conductor Design and Tests, Mechanical Tests, and Facilities

FED Personnel: W. A. Fietz,* J. R. Miller,
R. E. Schwall

Metals & Ceramics (M&C) Division Personnel:
D. S. Easton, D. M. Kroeger

Conductor design

Several minor modifications were made in the Toroidal field (TF) conductors being produced for use in the LCS program. These changes arose partly from application considerations such as insulating and winding, and partly as a result of manufacturing difficulties. A paper describing these and other TF conductor designs was presented at the Sixth International Conference on Magnet Technology, Bratislava, Czechoslovakia, August 26-September 2, 1977.

The first conductor which will be tested is similar to the LCP conductor proposed by General Electric. This consisted originally of 12 elements, each a compacted solder-filled strand cable, all wrapped about a center of steel coil which was split and insulated. The modifications on this conductor were to change to a solid core, to reduce the number of elements to 11, and to make solid elements instead of the compacted cable units.

* Author.

Another conductor being manufactured for LCS consists of seven insulated parallel compacted cable elements carried in a parallel untwisted configuration. Originally the elements were all identical, but in order to allow a particular insulation scheme to be used, three of the elements have a different aspect ratio from the other four. These elements will be insulated with a 50% coverage of insulation, while the other four will be initially uninsulated. The seven elements will then be bundled together and the entire assembly wrapped with a 50% insulation coverage.

Mechanical tests

This work is part of a broad program to study the effects of stress on the mechanical and superconducting properties of commercial superconductors. For the time period covered, the following investigations were undertaken.

(1) Three different multifilamentary Nb_3Sn conductors, obtained from the Atomic Energy Research Establishment, Harwell, England, in the unreacted state, were heat-treated to produce varying thicknesses of Nb_3Sn on the Nb filaments. Work was confined to these materials only. The conductors were:

- R-1: 0.43 mm in diameter, 1369 filaments (each 5.9 μm in diameter); twist pitch: 6.55 mm; vol % Nb: 25.7
- R-2: 0.495 mm in diameter, 1369 filaments (each 6.4 μm in diameter); not twisted; vol % Nb: 22.8.
- R-3: 0.43 mm in diameter, 1369 filaments (each 5.6 μm in diameter); twist pitch: 6.44 mm; vol % Nb: 22.8.

The reaction heat treatment was carried out in a muffle furnace with a flat temperature zone of 22 in., and the samples were kept straight to prevent any prestrain. Varying the time and temperature resulted in the following Nb_3Sn layer thicknesses.

Time (hr)	Temperature ($^{\circ}\text{C}$)	Nb_3Sn layer Thickness (μm)	Reacted (%)
1	700	0.41	24
2	700	0.59	34
8	700	0.7	39
24	700	1.2	61
50	700	1.5	72
156	700	2.42	94
162	600	0.81	44

(2) Visual examination was made of the samples taken to fracture and to varying amounts of strain at 4.2 K. The strain necessary to produce visible cracks varied from $\sim 0.5\%$ in the 2.42- μm -thick material to $\sim 2\%$ in the 0.59- μm -thick layer material. The cracks were often associated with diffusion voids in the matrix.

(3) Measurements of T_c were made on material both with and without the bronze matrix material. T_c was found to decrease as the thickness of the Nb_3Sn layer decreased. This occurred for material with and without a matrix. The T_c shows an increase upon removal of the matrix; this increase is greater for thin layered material (~ 2 K). I_c at zero stress and T_c (with matrix) data curves show the same general shape when plotted as a function of layer thickness.

(4) I_c and J_c at varying stress-strain levels were measured. It was found that increasing the volume of Nb_3Sn on the filaments by a factor of ~ 3 (layer thicknesses of 0.59-2.42 μm) resulted in only slight increases in J_c at zero stress while making the material more strain sensitive to cracking and J_c degradation. In all cases, J_c degradation of over 50% occurred prior to strain values that produced visible cracking.

I_c curves normalized to zero strain show increases in J_c at strains of $\sim 0.2\%$. A preliminary study at Case Western Reserve University (by Dr. L. J. Ebert and John Gayda) of stress states in these composites showed that the axial stress resulting from differences in thermal contraction would be nearly compensated for

with a tensile strain of 0.18%. However, these studies also show that because a triaxial stress state exists, the total stress on the filaments (axial, tangential, and radial) would never be zero at the same time.

(5) In cooperation with the Basic Energy Science Program in the Metals and Ceramics Division, a comparison was made of the variations in J_c , T_c , and $H_{c2}(0)$ with strain. By measuring $H_{c2}(T, \epsilon)$ near T_c in fields to 7 T the variation of $H_{c2}(0)$ with strain was derived. It was found that $J_c(\epsilon)$ showed little or no correlation with T_c but did appear to be more closely connected to $H_{c2}(0)$. Both J_c and $H_{c2}(0)$ values showed plateaus and even increases at strain values of ~ 0.2 to 0.5%, depending on the Nb_3Sn layer thickness.

(6) In cooperation with the Welding Group of the Metals and Ceramics Division, tests were made to evaluate the joint strength at 4.2 K of NbTi conductors joined with four different solders. A Sn-5% Ag solder had the highest shear strength at 300 K and the lowest at 4.2 K. A Pb-1.5% Ag-1% Sn solder had the highest strength at 4.2 K of the solders tested.

Facilities

The Injection into Microwave Plasma (IMP) mirror coils were assembled and tested successfully. This test confirms that these coils can be used as a 6-T short sample test facility to supplement the 8-T facility if needed. The 8-T coils are being wound and will be tested in the next quarter. Several current leads have been ordered, ranging up to 20,000 A. These will be used in the short sample test facility. Engineering work has been completed for installation of the 30,000-A, 20-V power supply and the 2000-A, 300-V bipolar supply, both of which are expected to be delivered in the next quarter.

2.2.6 Instrumentation

FED Personnel: J. F. Ellis, J. P. Rudd,
P. L. Walstrom*

Bids for the data acquisition system were received and the software design tasks for the system have been outlined.

An improved prototype voltage tap signal conditioning module has been developed and tested. An improved quench detection unit has also been constructed and tested. The units will be constructed on printed circuit boards and used in the LCS diagnostics.

A detailed plan for instrumenting the Impurity Study Experiment (ISX) magnet system was made and all necessary hardware was fabricated and was ready for installation at the end of this report period. This equipment will be used to measure the deflections of the toroidal field coil.

A ground fault detector was designed and a prototype built. The unit will be used to monitor ground faults in the LCS test facility.

2.3 LARGE COIL EXPERIMENTS

2.3.1 Large Coil Segment Test Facility

FED Personnel: P. L. Walstrom*

UCC-ND Engineering: P. B. Burn, J. S. Goddard,
L. W. Nelms, B. E. Nelson,
T. L. Ryan, R. E. Stamps,
R. C. Stewart, R. B. Wysor

Engineering design continued in all phases of the project during this quarter. The last background coil fabrication drawings were issued, and modifications to the coil cases to allow better coolant flow in their new orientation were completed and the coils shipped to the machine shop for further work.

A directive from ERDA-Oak Ridge Operations (ORO) for the UCC-ND portion of the facility was received. The cost plus fixed fee (CPFF) portion of the job requires approval of the Preliminary Proposal, which was at ORO awaiting approval at the time of this writing.

The vacuum system design is complete and fabrication drawings have been issued.

Specifications for a data scanner for monitoring facility variables have been issued for purchase.

* Author.

2.3.2 LCS Conductors and Coils

F&E Personnel: J. K. Ballou, W. A. Fietz*

UCC-ND Engineering: P. B. Burn, L. W. Nelms,
B. E. Nelson, R. C. Stewart

Two pool boiling conductors are still in the process of manufacture. These conductors have been described in the previous quarterly report and in Sect. 2.2.5 of this report. The delays in delivery are due in part to some minor design changes but will not affect the test schedule for LCS. Contracts for development work on other conductors, including forced-flow NbTi and Nb₃Sn, are expected to be issued soon.

Design and engineering of the first bobbin and coil case were completed and fabrication is proceeding on a schedule that promises delivery by July 15. The case is a welded construction of stainless steel which will allow three pancakes of about 20 turns each in a 12- by 30-cm winding cavity. Insulation details for the first coil are almost completed and will be as nearly as possible identical to the GE/IGC approach to be used in LCP.

2.4 PROJECTS BASED ON DISCIPLINES

2.4.1 Structural Analysis and Material Evaluation

F&E Personnel: W. H. Gray*

M&C Personnel: C. J. Long

UCC-ND Engineering: W. D. Cain, W. R. Hendrich,
W. C. T. Stoddart

Consultant: J. E. Akin (University of Tennessee)

A structural analysis of the Soviet T-10M tokamak toroidal field (TF) coil system has been performed. Two TF coil shapes were proposed, one oval, the other circular, both with 24 coils. The oval TF coil system has a 2.4-m major radius with a minor bore diameter of 2.5 m and a major bore diameter of 3.28 m. The circular TF coil system has a 2.5-m major radius with a 2.2-m-bore diameter coil. Both TF coil shape cross sections have the rectangular dimensions of 0.4 m by 0.26 m with a 0.36-m by 0.22-m winding cavity

symmetrically placed within the cross section and carrying a net current of 1.75 mA. This geometry produces a magnetic field of 3.5 T on axis, 2.4 m from the machine center line for each tokamak.

This study's goal was to determine which one of the TF coil shapes is the "best" design; that is, which one operates in a minimum stress configuration. The scope of the analysis covers only the in-plane force distribution produced by the magnetic field.

Based on the assumptions of the study, the oval TF coil shape appears to be superior to the circular TF coil shape. Further, the oval TF coil shape in its present design has a significant safety margin between working and yield stress.

The magnetic fields of the ISX tokamak have been measured and have also been calculated using the computer code GFUN3D, which includes saturable magnetic material. Magnetic field measurements were taken at the top of the number 1 toroidal field coil of the ISX device while the ohmic heating coils were energized with 437 A dc.

Calculations done by GFUN3D are in good agreement with measured values except in areas close to the iron transformer core corners. The probable reason for this is that GFUN3D assumes the B-H curve to be independent of flux direction, while in reality the iron core transformer is composed of grain-oriented material in which the B-H curve is highly dependent on flux direction. When the model was modified to approximate this directional dependency, the calculated magnetic fields compared favorably with the measured values.

2.4.2 Fabrication Development

F&E Personnel: R. L. Brown,* W. H. Wagner

UCC-ND Engineering: P. B. Burn, G. M. Henderson,
W. H. Kunselman, B. E. Nelson

Preparation for winding the first LCS coil has been the main goal for the large coil

* Author.

winding facility. The greatest time has been consumed in checking out and perfecting the winding equipment components. After winding and unwinding practice conductor, the weak features of some components have become apparent. Some minor alterations and new designs are under way. The greatest problem has been in maintaining sufficient tension in the conductor. Approximately 200 kg appears to be the most that can be reliably expected from the belt system we now have in the tensioner. A design using link chains is expected to eliminate many of our tension problems. We do not have either the resources or time to wind the first LCS coil as automatically as we would like. However, since there will only be 600 m of conductor, the slower winding will not be a significant part of the fabrication time. An interesting concept has been proposed for winding the LCS coil that uses bundle conductor consisting of seven individual conductors. A variation of the spliceless pancake method would be used and the bobbin would remain stationary. A dolly carrying the conductor would travel around the bobbin. Because this does not tie up existing equipment, some overlap in the fabrication time of the first two LCS coils could be possible.

A 28-cm, 4-pancake coil was wound using the spliceless method. Winding with this method proceeds very fast. An offsetting feature is the machine time needed to make polycarbonate plates. A mold to make the plates might be justified in a large coil. Drawings have been prepared for a pulsed test coil which will use 40 plates. It will have a 7.5-cm ID and a 24-cm OD, and will be 25 cm long.

2.4.3 Stability Analysis

FED Personnel: L. Dresner,* J. W. Lue,
J. R. Miller

A study has been carried out on the effect of the continuous resistive transition in composite superconductors on self-field instability.

Composite type II superconductors are known to develop resistance continuously rather than suddenly as transport current increases. This means that the distribution of current among the filaments in a composite conductor is determined not only by their inductive coupling but also by the longitudinal resistance they develop as they begin to carry current. The current distribution has been calculated in two cases, taking into account the continuous nature of the resistive transition: a composite clamped suddenly across a constant-current source and a composite charged with current at uniform rate. The results of the latter problem are used to show that slowly charged conductors are much more stable against self-field instability than indicated by purely inductive calculations. An abstract describing this work has been submitted to the Seventh Symposium on Engineering Problems of Fusion Research (to be held in Knoxville, Tennessee, October 25-28, 1977).

The stability of built-up conductors cooled by boiling helium has been studied. The conductors are composed of composite elements and pure copper elements that are soldered together. The reduction in the cold-end recovery current compared with that of another conductor, which contains the same amount of superconductor and copper but in which the copper is a continuous phase, has been calculated.

A paper entitled "Design of Force-Cooled Conductors for Large Fusion Magnets," by L. Dresner and J. W. Lue, was presented at the Sixth International Conference on Magnet Technology, Bratislava, Czechoslovakia, August 29-September 2, 1977. An abstract describing this work has been submitted to the Seventh Symposium on Engineering Problems of Fusion Research (to be held in Knoxville, Tennessee, October 25-28, 1977).

* Author.

2.5 PROJECTS PERFORMED BY SUBCONTRACTORS

2.5.1 Forced-Flow Magnets

FED Personnel: W. A. Fietz,* C. G. Lawson

Francis Bitter National Magnet Laboratory/
Massachusetts Institute of Technology Personnel:

M. O. Hoenig, A. Montgomery, D. B. Montgomery

On April 6 we encapsulated about 200 ft of dummy triplex cable in an aluminum sheath, 100 ft of NbTi cable in an aluminum sheath, and 100 ft of NbTi cable in a stainless steel sheath.

A dummy D-shape coil, wound using C-shaped channels and vacuum impregnation, has been tested for electrical breakdown (found to be 35 kV at 80 K) and structural integrity. The tests indicate a need for lateral support as well as a need to keep channels in close contact with the conductor tube. However, the structure is rigid and more than adequate to support the Lorentz forces expected in the first D-shape coil. Winding of the split pair field coils for the D-shape coil has been completed at MCA. The tubulated thermal shroud (6 K) and matching top plates (6 K and 78 K) have been completed by Dean Products of New York City. The Model 1400 CTI helium refrigerator has been received together with transfer lines, gas storage tanks, compressors, etc. Final design work has been started to permit assembly of equipment in the test stand by September 1, 1977.

One triplex conductor heavily soldered was prepared into a test coil. Initial dc tests indicated a severe current limitation. The problem was overcome by careful filling of the contact region with solder. Subsequent critical current measurements matched short sample values. A $3 \times 19 \times 1.05$ -mm NbTi cable, with a copper-to-superconductor ratio of 5:1 (identical to the first D-shape coil cable, but encapsulated in stainless steel) has been fabricated into a test coil. It has been subjected to dc tests as well as to supercritical and subcritical pulse tests using helium circulation. The Airco hybrid conductor has been soldered and cabled. It consists of 19 sets of triplets. Each triplet consists of one 50% NbTi, 50%

copper wire, and two ultrapure aluminum wires (copper sheathed). We have placed an order for a conductor utilizing 0.5-mm-diam strands, to be cabled in a $3 \times 3 \times 7$ configuration. Delivery was expected by August 15, 1977.

Assembly and testing of the backup bellows pump with reduced turnaround time is complete. Fabrication of current lugs and cable hydraulic T's has proceeded, using appropriate combinations of copper, stainless steel, and aluminum. The test equipment has been modified by the inclusion of a check valve upstream and a hand throttling valve downstream of the 5000-A test conductor coil. A hydraulic T placed at the midpoint of the coil allows for the measurement of pressure and temperature.

2.5.2 Refrigerator and Liquid Handling System

FED Personnel: C. G. Lawson*

UCC-ND Engineering: J. P. Kois, J. Schubert

A 3.5-K helium refrigerator and liquefier is being purchased from CTI Corporation. The coldbox is being fabricated and completion is expected by July 29. The compressor was received at Waltham, Massachusetts in May and completion of the test stand measurements is expected on schedule. The turbine expanders for the coldbox have been received at Waltham and will be shipped to ORNL with the refrigerator packages.

The work on the refrigerator installation package, including the liquid nitrogen system, cooling water system, and structural drawings, is proceeding more slowly than planned due to the impact of planning for the Large Coil Project. Accordingly, the operational acceptance test at ORNL is now anticipated by the end of March 1978.

2.5.3 Pump Development

FED Personnel: C. G. Lawson*

A purchase order has been placed for a cold helium pump to supply 5 to 20 g/sec of

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supercritical helium at 4.5 to ~ 7 K for a force-cooled loop. This pump will be used to develop measurement and control hardware for a force-cooled loop operating between 3 and 6 atm at the pump suction and discharge locations.

3. DOCUMENTATION

3.1 ORAL PRESENTATIONS

D. S. Easton, "Stress Effects in a Variety of Nb_3Sn Superconducting Composites," American Institute of Mining, Metallurgical, and Petroleum Engineers Spring Meeting, Atlanta, Georgia

D. S. Easton and D. M. Kroeger, "Stress Related Damage in Nb_3Sn Superconductors," International Cryogenic Engineering Conference, August 2-5, 1977, Boulder, Colorado

D. M. Kroeger, D. S. Easton, and A. DasGupta, "An Investigation of the Cause of Recoverable Current Degradation under Stress in Nb_3Sn Superconductors," International Cryogenic Engineering Conference, August 2-5, 1977, Boulder, Colorado

A. J. Moorhead, J. J. Woodhouse, and D. S. Easton, "Cryogenic Mechanical Properties of Solder Joints in a Nb-Ti Superconductor," International Cryogenic Engineering Conference, August 2-5, 1977, Boulder, Colorado

3.2 PUBLICATIONS

C. C. Koch and D. S. Easton, "Mechanical Behavior and Stress Effects in Hard Superconductors - A Review," *Cryogenics*, July 1977

A. J. Moorhead, J. J. Woodhouse, and D. S. Easton, *Soldering of Copper-Clad Nb-Ti Superconductor Composite*, ORNL/TM-5774, April 1977

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