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ORNL/TM-5820

# Letter Report for the Superconducting Magnet Development Program June 1, 1976–October 1, 1976

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OAK RIDGE NATIONAL LABORATORY

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Price: Printed Copy $4.00; Microfiche $3.00

ORNL/TM-5820

Contract No. W-7405-eng-26

# LETTER REPORT FOR THE SUPERCONDUCTING MAGNET DEVELOPMENT PROGRAM

June 1, 1976 - October 1, 1976

Edited by M.S. Lubell and L. Dresner
Magnetics and Superconductivity Section
FUSION ENERGY DIVISION

Date Published - April 1977

MASTER

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
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# ABSTRACT

The results and accomplishments of the Superconducting Magnet Development Program for the period June 1, 1976-October 1, 1976 are summarized in this report. The presentations are arranged according to projects. A new format has been adopted for convenience in reporting. Only projects which have reached some milestone or completed tasks are discussed.

# LETTER REPORT FOR THE SUPERCONDUCTING MAGNET DEVELOPMENT PROGRAM

Period Ending 1 October 1976

M. S. Lubell, Program Manager

## 1. INTRODUCTION

The format for presenting the results and accomplishments of the Superconducting Magnet Development Program will be changed starting with this report. Instead of discussing the work of each group separately as in the past, we are arranging material according to projects. We hope thus to avoid some of the redundancy that occurred previously when aspects of the same work were presented in more than one group report. The new format was adopted only for convenience in reporting and should not be construed as a criticism of the group structure. It reflects the way the day-to-day activities are carried out — a way which permits flexibility in organizing assignments (sometimes short-term) involving personnel from more than one group. Not every project will be reported in each letter report; only those projects which have reached some milestone or completed some task will be discussed. Others, which are either inactive or else progressing satisfactorily without having yet reached a definite conclusion, will be omitted. It should also be understood that some projects are short-term and will be discontinued when they have served their purpose. New ones will be created as the need arises.

This report period was not only a fiscal transition quarter but also a transition quarter insofar as the composition of the staff is concerned. K. J. Froelich, C. J. Long, J. K. Lovin, and J. E. Simpkins all left the SCMDP. Karl Froelich terminated from ORNL to return to school and pursue a career in the medical profession. With his considerable mechanical skill he no doubt will make a fine M.D. Joe Long transferred to the Metals and Ceramics Division, but will continue to work half-time on our problems related to structural materials. The rest of his time will probably be taken up with a new project also of interest to us — that of characterizing insulation materials at cryogenic temperatures after prolonged neutron irradiation. Juan Lovin transferred to the Division Director's staff to create a management information system for the Fusion Energy Division. His engineering, organizational, and budgetary talents will be sorely missed. Jesse Simpkins remains in the Fusion Energy Division and will continue his work on vacuum deposition, thin film, and plating for the diagnostics group of the ISX Project, which has a strong interest in characterizing the material of the first wall. Please note that during this report period the Engineering Sciences Department and Thermonuclear Division underwent name changes to become the Magnetics and Superconductivity Section and Fusion Energy Division, respectively.

The following acronynms are used in this report:

SCMDP — Superconducting Magnet Development Program
ISX — Impurities Study Experiment
EPR — Experimental Power Reactor
TNS — The Next Step Program
TF — toroidal field coils
PF — poloidal field coils
OH — ohmic heating
EBTR — ELMO Bumpy Torus Reactor
PLASS — Pulsed Losses in Axisymmetric Superconducting Solenoids
M&S — Magnetics and Superconductivity Section
MCDT — moving coil displacement transducer
PLT — Princeton Large Torus
ECDT — eddy current displacement transducer
LCP — Large Coil Program
IMP — Injection into Microwave Plasma
FBX — fusion burning experiment
SCORE — Superconducting ORMAK
ORMAK — Oak Ridge Tokamak
FED — Fusion Energy Division

## 2. MAGNETICS AND SUPERCONDUCTIVITY PERSONNEL as of 1 October 1976

Section Head
M. S. Lubell
Systems Design
J. W. Lue
Coil Design
J. N. Luton
J. K. Ballou
Conductor Test and Selection
W. A. Fietz
J. R. Miller
R. E. Schwall
S. S. Shen
L. Alley, Jr.
W. H. Wagner
Coil Protection and Eddy Current Shielding
H. T. Yeh
L. Dresner
Coil Test and Evaluation
P. L. Walstrom
J. F. Ellis
J. R. Rudd
Structural Analysis and Materials Evaluation
W.C.T. Stoddart[†]
W. H. Gray
Cryogenics and Refrigeration
C. G. Lawson
C. M. Fitzpatrick
Coil Fabrication
R. L. Brown

## 3. PROJECT REPORTS

### 3.1 DESIGN PROJECTS

### 3.1.1 Experimental Power Reactor (EPR)

FED Personnel: J. K. Ballou, R. L. Brown, C. G. Lawson, J. W. Lue,[*] H. T. Yeh

Engineering Division: R. B. Easter, W.C.T. Stoddart

The report of the 1976 Oak Ridge Tokamak Experimental Power Reactor (EPR) Study was finished during this period. The magnet system in this revised design is more self-consistent, simpler, and partially optimized. Details of the EPR magnet system are documented in ORNL/TM-5574. A summary of the toroidal field coil system was presented at the 1976 Applied Superconductivity Conference in a paper entitled "Toroidal Field Coil System of the Oak Ridge EPR Reference Design," by J. W. Lue and J. N. Luton. Other published papers and reports on EPR work include:

> H. T. Yeh and J. W. Lue, *The Interaction and Protection of Superconducting Poloidal Field Coils and Toroidal Field Coils in a Tokamak Experimental Power Reactor*, ORNL/TM 5542, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1976).
>
> W. H. Gray and J. K. Ballou, "A Computer Program to Calculate Composite Conductor Losses in Pulsed Poloidal Coil Systems," paper presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976.

### 3.1.2 The Next Step Program (TNS)

FED Personnel: J. K. Ballou, J. W. Lue,[*] H. T. Yeh

The TNS study is aimed at design of a deuterium-tritium fueled ignition machine to be operated in the mid-1980's. Some preliminary design work has been performed, but most of the work has been done on scoping the various alternatives and on sensitivity analysis.

The number of toroidal field (TF) coils required was examined. The number of TF coils affects the field ripple, which in turn affects losses in the plasma. A 16-coil system will have the same field ripple as a 20-coil system with a bore smaller by 80 cm. The larger bore system more readily permits inclusion of a divertor system and increases the access for beam ports.

Magnets cooled by supercritical helium in forced flow offer the possibility of operation at higher fields with no change in the stability margin resulting from a change in the coolant flow rate. For example, an NbTi coil designed

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[†] Engineering Organization

[*] Author

for an 8-T field at 4.0 K can produce a field of 9 T at 3.36 K with four times the pumping power and 10 T at 2.68 K with sixteen times the pumping power. The stability margin is the same for all three cases. Lower pumping power losses can be obtained if in fact the same stability margin is not needed. Experiments will be necessary to determine the proper safe operating value; our calculations may be too conservative. This flexibility cannot be achieved in a magnet cooled by pool-boiling, because one cannot maintain the same stability at a higher field by lowering the temperature of a magnet cooled in a bath of helium.

The expected low duty cycle in TNS consists of high, fast nuclear heating pulses at comparatively long intervals. The following pulsed cooling scenario was proposed for use in designing the TF coils. The TF coils are pancake-wound, and the supercritical helium enters through the inner, high-field turn and exits from the outer, low-field turn. At the start of the plasma current, the helium flow rate is increased such that the nuclear heat accumulated during the helium transit through the first turn is less than the superconductor stability margin (flow velocity ∿1-2 $\mathrm{ms}^{-1}$). As soon as the plasma shuts down, the helium flow rate is reduced just enough to keep stable operation (flow velocity ∿0.5 $\mathrm{ms}^{-1}$). Because power is proportional to the 2.75 power of the helium flow velocity, this nonuniform helium flow is advantageous.

A study of the poloidal field (PF) coil system was performed, comparing systems with and without decoupling coils of the kind used in the EPR design. It was found that although the peak power requirement without the decoupling coils will be slightly higher, the ohmic heating (OH) coil current can be substantially reduced. Therefore, it is recommended that no decoupling coils be used in the TNS poloidal field coil system.

The charging and discharging history of the OH coils received attention in this reporting period. In order to eliminate the costly and problematic secondary energy storage and transfer system for the OH coils, a scheme different from that used in the EPR design was conceived. This new scheme consists of precharging the OH coil before start-up, discharging the OH current through a series of dump resistors to near zero current during the 1- to 2-sec start-up phase, and slowly reversing the current during the burn. The power supply now only needs to supply power during the burn and reset. For short burn times, the current flow in the OH coils remains high for only a very short time. This same scheme can be adapted to either superconducting or resistive coils.

### 3.1.3 Elmo Bumpy Torus Reactor (EBTR)

FED Personnel: H. T. Yeh*

Input was provided during this quarter on the magnet system of the Elmo Bumpy Torus Reactor (EBTR) Reference Design.[1] Some highlights of the design are summarized as follows.

- The magnets are designed so they can be built with current state-of-the-art technology.
- The magnet system is modular; one size can be used for reactors with different major radius/power output. Two versions of the reactor are being considered: 48 coils with a 60-m major radius and 24 coils with a 24-m major radius.
- A monolithic built-up conductor is used. The core is composite multifilamentary NbTi; copper strips with holes punched in them are soldered to the composite. The conductor is cryostatically stable.
- A high operating current (25 kA) is used to reduce the terminal voltage during discharge. Each turn has four conductors, each carrying 6.25 kA, interleaved along their wide face to create a symmetrical spiral winding.
- The magnets are wound of circular pancakes cooled by pool-boiling helium.

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*Author

- Tight winding without potting is preferred, and interleaved structural strips are not necessary because a 5-cm stainless steel wall around the winding is sufficient to support the magnetic stress.
- Quenches are detected by voltage taps placed on each coil. Any inductive signal is compensated for by pickup coils from the power supply. The stored energy is to be discharged externally in dump resistors, one for each coil. During discharge, switches will disconnect the coils from the power supply and from each other. All coils are discharged simultaneously. The terminal voltage is limited to 1 kV, and the internal temperature to 100 K.

### Reference

1. D. G. McAlees et al., *Elmo Bumpy Torus Reactor Reference Design*, ORNL/TM-5669, Oak Ridge National Laboratory, Oak Ridge, Tennessee (1976).

## 3.2 SMALL SCALE EXPERIMENTS

### 3.2.1 Pulsed Parallel Field Experiment

FED Personnel: J. R. Miller, S. S. Shen*

Experimental investigation of losses in twisted multifilamentary composites when exposed to pulsed longitudinal fields was continued using existing apparatus. Losses were studied both by measurement of dynamic resistivity during a longitudinal pulse and by sensitive temperature measurement of the surface of a potted sample. The variation of losses with applied transverse field, sample transport current, and longitudinal pulse ramp rate was investigated. Results were reported by J. R. Miller and S. S. Shen at the 1976 Applied Superconductivity Conference, Palo Alto, California.

It was verified that for a large conductor ($\gtrsim$1000 A @ 7 T) the coupling loss without transport current may not be as large as expected owing to incomplete saturation of the composite. However, in most practical applications, where the conductor carries transport current not far from its critical value, the loss increases as $(I_T/I_c)^2$ and can be represented by a saturation model.

Design was completed for a larger scale version of the existing experimental apparatus. The new version will accommodate conductors of larger cross section and will incorporate superconducting pulse field windings to allow biasing of the longitudinal field. Conductor for the pulse windings was purchased and tested.

### 3.2.2 Propagation and Stability Tests

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

A computer program was written to calculate propagation velocities. The program includes:

- the temperature variation of the thermal conductivity of the matrix,
- the temperature variation of the specific heats of both the matrix and the superconductor,
- the temperature variation of the heat transfer coefficient in steady-state pool-boiling, and
- the latent heat of the superconducting normal transition in a magnetic field.

The theory underlying the program and a comparison with some data of Miller and Donaldson were written up in ORNL/TM-5543, *Propagation of Normal Zones in Composite Superconductors*, by L. Dresner. A paper with the same title and author has been accepted for publication in Cryogenics.

The stability of various conductor designs in realistic coil environments was studied experimentally. The velocity of propagation or

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*Author

contraction of a normal zone, the full recovery current, and the minimum propagating current were measured in a coil segment. The dependence of these quantities on background field, transport current, electrical insulation, size and orientation of the cooling passages, and proximity of other conductors were studied. The measurements were compared with the theory described above. This work was presented at the Applied Superconductivity Conference in a paper entitled "Investigation of Stability of Composite Superconductors in Typical Coil Configurations," by J. R. Miller, J. W. Lue, and L. Dresner.

A new numerical program was developed to calculate the full recovery current of conductors partially covered by a periodic array of thermally insulating strips. Experiments are planned for comparison with calculations performed with the program.

Work on stability-optimized, force-cooled conductors reported in previous quarterly progress reports was written up and presented at the 1976 Applied Superconductivity Conference in a paper by L. Dresner entitled "Stability-Optimized, Force-Cooled, Multifilamentary Superconductors."

### 3.2.3 Pulse (Poloidal) Coil Development

FED Personnel: J. K. Ballou, W. H. Gray, R. E. Schwall,* S. S. Shen, H. T. Yeh

A program to develop pulsed superconducting coils for use as PF coils of future tokamaks is being pursued. The goal of this program is to provide the technology upon which design of superconducting PF coils for TNS could be based.

Although the initial ORNL design for a PF system for CPR employed forced cooling, much of the basic work on conductor design has been done on conductors cooled by pool-boiling helium, and we have focused our work in this direction.

In the period covered by this report, a method for measuring losses in superconducting coils was developed and used to measure losses in three small coils, a computer program was written to calculate losses in solenoidal coils, three papers[1,2,3] were presented at the Applied Superconductivity Conference, bids were solicited for a 2000-A, 300-V bipolar power supply, and the pulsed coil test equipment was moved to a more permanent location in the Magnetics and Superconductivity (M&S) laboratory.

The loss measuring scheme (described in Refs. 1 and 2) is an adaptation of a method first proposed by Wilson.[4] The inductive component of the coil terminal voltage is compensated by adding to it a signal proportional to dI/dt (the time derivative of the magnet current). The resulting voltage waveform [designated as $\Delta V(t)$], which is indicative of the flux change in the conductor, is digitized and stored. A signal proportional to the magnet current is also digitized and an "average coil magnetization" [$M(t) = \int \Delta V\, dt$] is calculated. The loss per cycle (Q) can be obtained from

$Q = (1/K_0) \quad I\, \Delta V\, dt$,

or from

$Q = (1/K_0) \quad M\, dI$,

where

$K_0$ is a calibration factor.

While the basic method used is quite commonly employed, the implementation here offers several advantages.

- The coil voltage waveform is preserved. This can yield considerable information about the specific loss mechanisms involved and is especially useful in studying conductor motion in coils.
- Any errors introduced by analog multipliers are eliminated because all signal processing is done digitally.
- A convenient digital file of test data is available for later detailed analysis and comparison with theory.

In order to perform a meaningful analysis of loss measurements on coils and to design for minimum loss, one must account for the variation in magnetic field over the winding volume and

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*Author

for the variation of field-sensitive material properties. A computer program, PLASS (Pulsed Losses in Axisymmetric Superconducting Solenoids), was written to compute losses in solenoids; it takes into account the actual field distribution in the coil and uses local, field-dependent values for such parameters as critical current and matrix resistivity. This program has been used to evaluate various conductor configurations, to evaluate the losses in the PF coils in the ORNL EPR design, and will be used to compare calculations based on various theoretical tests described above.

The power supplies currently available to the M&S Section do not allow our existing pulsed coils to be tested to their design limits. Neither do they permit the bipolar mode of operation presented in the three EPR reference designs. To provide some capability in this area we have prepared and bid a specification for a 2000-A, 300-V bipolar power supply. This device, which should be delivered in the first quarter of CY 1977, will permit the bipolar operation at or near the $B_{max} = 7$ T, $\dot{B}_{max} = 7$ T/sec suggested in the EPR designs. Discharge mode operation on a unipolar cycle is also possible.

Near the end of this reporting period the growth of other projects made it necessary to dismantle the loss-measuring system and move the experiment to another location. While the move will undoubtedly consume some time, the new location offers better facilities and should permit a rapid changeover to the 2-kA, 300-V supply when it is delivered. It is expected that a number of modifications and improvements will be made during the next quarter and that tests will resume in the later part of this period.

### References

1. S. S. Shen and H. T. Yeh, "Analysis of Pulse Loss Measurement on NbTi Solenoid," paper presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976.
2. R. E. Schwall, "ORPUS-1, A Pulsed Superconducting Solenoid," paper presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976.
3. W. H. Gray and J. K. Ballou, "A Computer Program to Calculate Composite Conductor Losses in Pulsed Poloidal Coil Systems," paper presented at the Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976.
4. M. N. Wilson, Cryogenics <u>13</u>, 361 (1973).

### 3.2.4 Instrumentation

FED Personnel: P. L. Walstrom,* J. F. Ellis, J. E. Simpkins
Engineering: J. S. Goddard
Consultant: H. Pih (University of Tennessee)

Platinum-8% tungsten strain gages were investigated for use in magnet testing. Our experiments showed that the temperature coefficient of apparent strain of these gages is a factor of 20 less than for Karma alloy gages at 4.2 K. This feature makes the platinum gages much less sensitive to thermal fluctuations and self-heating effects than the Karma alloy gages.

A uniform-strain cantilever beam apparatus was designed and under construction at the end of this report period. The apparatus will be used for determination of gage factor, for measurement of magnetoresistance at varying strain levels to 7.5 T, and for fatigue cycle tests of strain gages and cements. Beam displacement is measured by a moving coil displacement transducer (MCDT) developed previously by the SCMDP staff.

Thermal shock tests were performed to evaluate cements for strain gage application in magnet testing. The tests consisted of monitoring the apparent strain of the gage initially at room temperature, while it was plunged into liquid helium, and then when it was removed from the helium bath and warmed up to room temperature in a dry nitrogen atmosphere. Each gage/cement/substrate combination was cycled in this fashion

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*Author

at least ten times. In addition, bend tests were performed after the cycling in order to determine if the gage was adhering well to the substrate. Two epoxy cements from Micromeasurements Corporation, AE-10 and AE-15, were found to survive the above tests, while Eastman 910 cement failed. Microscopic examination showed cracking of the 910 cement.

Thermistors (Keystone Carbon Co.) were tested for low temperature use in high magnetic fields. The results of previous investigations were confirmed (i.e., the temperature error due to applied field is small — about 0.01 K at 8 T), but difficulties were experienced with contact failure and aging effects. It is hoped that these devices can be used for precise measurement of coolant temperature in the field in tests of force-cooled magnets, but further work is needed before they can be used with confidence in coil testing.

Assistance was provided to the Princeton Large Torus (PLT) beam line development effort in the form of field mapping of their charged-particle sweeping magnet.

An eddy current proximity detector was developed for noncontacting measurements of small displacements in the presence of high magnetic fields at ambient or cryogenic temperatures. The device was developed after a search of commercially available units failed to find a unit with no ferromagnetic materials. The eddy current detector will be used for displacement measurements in extremely constricted geometries, such as measurement of the displacement of the inner turn of the windings with respect to the bobbin. When operated with a signal conditioning unit developed for it, it has a sensitivity of 0.15 V/mm dc output over a range of 7 mm with a linearity of ±1.3%. The device is suitable for use with a "target" material of any high conductivity material such as aluminum or copper, but had not yet been tested in liquid helium in a high magnetic field during the report period.

An eddy current displacement transducer (ECDT) was developed for measuring small displacements in high magnetic fields at ambient or cryogenic temperatures. The device is intended to be a functional extension of the MCDT to smaller dimensions. It differs from the MCDT in that coupling between fixed primary and secondary coils is varied by movement of a copper slug which effectively acts as a diamagnetic material at the excitation frequency of 2.7 MHz. The prototype has a 0.95-cm outer diameter and a 5.1-cm length; the gaging range is 7.5 mm with a linearity of 2.5% and a sensitivity of 400 mV/mm with the same electronics as for the eddy current proximity detector. This device also had not been yet tested in a high magnetic field in liquid helium during this report period.

A prototype voltage tap signal conditioning system was designed and under construction during the report period. Direct analog compensation of voltage tap signals for the inductive signal component is performed by the system. The inductive signal is obtained from Rogowski coils which produce a voltage proportional to the rate of change of current in each independent circuit.

A Rogowski coil with a coaxial current bus and electrostatic and magnetic shielding was designed and fabricated. The device offers roughly a twenty-fold reduction in pickup noise over an unshielded device and is being used in the pulsed coil program in pulse loss measurements. Still better noise rejection is expected with proposed design improvements.

A liquid helium bath calibration facility for MCDT's and other displacement transducers was designed and built. Using this apparatus, the details of the behavior of the magnetically induced vibrations in the MCDT were examined and a method of greatly reducing their effect (to 0.1%) by selection of a particular phase angle was developed.

## 3.3 LARGE COIL EXPERIMENTS

### 3.3.1 Large Coil Segment Test

FED Personnel: P. L. Walstrom[*]
Engineering: P. B. Burn, J. R. Moore, B. Nelson

The conceptual design of the Large Coil Segment Test was completed by SCMDP staff and

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[*] Author

Engineering personnel. The facility has been incorporated into the Large Coil Program (LCP). The segment test coils will be 2-3 m in diameter, about the same as the LCP coils, but will have a considerably smaller cross section — typically 12 × 20 cm. A background field, which when added to the self-field of the test coil results in a total field of approximately 8 T over a 1-m length of the test coil windings, is produced by four racetrack-shaped $Nb_3Sn$ tape coils salvaged from the IMP facility. The test and background coils are placed in a "bell-jar" type vacuum chamber for thermal isolation. The current plan calls for using the ORMAK tank when it becomes available in April 1977 after shutdown of the ORMAK facility.

## 3.4 PROJECTS BASED ON DISCIPLINES

### 3.4.1 Structural Analysis and Materials Evaluation

FED Personnel: J. K. Ballou, C. M. Fitzpatrick, K. J. Froelich, W. H. Gray, C. J. Long
Engineering: W. D. Cain, W.C.T. Stoddart[*]
Consultants: J. E. Akin, A. R. Moazed (University of Tennessee), C. W. Trowbridge, J. Simkin (Rutherford High Energy Laboratory)

In the area of analytical developments, several results reached the point of documentation or were presented in papers. Three papers were written on the subject of the calculations of losses in composite conductors exposed to pulsed field environments. The loss mechanisms considered include conductor hysteresis, superconductor coupling, stabilizing material eddy currents, structural material eddy currents, and thermoelastic dissipation. The calculational procedure involves integrating the losses over the coil winding volume, thus taking into account the spatial variation of magnetic field. A computer code, PLASS, was written to perform these calculations. This more accurate procedure shows two interesting results. The first is that the losses are about half of the earlier estimated levels when thermoelastic dissipation is neglected. The second is that the thermoelastic dissipation may be the largest loss mechanism for some conductors during the early life of a pulsed coil. These results are discussed more fully in papers by J. K. Ballou and W. H. Gray presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976, and the American Nuclear Society Topical Meeting on the Technology of Controlled Thermonuclear Fusion, Richland, Washington, September 20-23, 1976. A related paper by J. E. Akin and A. R. Moazed on the thermoelastic dissipation portion of the losses was also presented at the Applied Superconductivity Conference.

A workshop in Tucson, Arizona on the computer code GIFTS, a graphics-oriented finite element computer code for structural analysis, was attended. GIFTS-II was in use at ORNL previously, and the meeting was to familiarize users with the GIFTS-IV release. GIFTS-IV was obtained and, after conversion from the PDP-15 to the PDP-10, put in service; however, some of the calculational modules remain to be fully checked out at this time.

The computer code GFUN-3D was acquired from Rutherford High Energy Laboratory in England. C. W. Trowbridge and J. Simkin consulted with ORNL to familiarize local users in the theory and operation of the program as well as to help incorporate recent modifications into the ORNL copy. The program is generally checked out at ORNL; however, the interactive and graphics features remain to be implemented. GFUN is designed to analyze magnetic field in the presence of saturable materials, i.e., iron. It has been used to analyze problems ranging from small solenoids for conductor tests to large vacuum vessels for the LCP.

A meeting on the Structural Analysis Needs in Superconducting Magnets was attended at Brookhaven National Laboratory, where informal talks and discussions were held over three days. Generally, it appears that definitive hardware experiments need to be performed to substantiate

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[*] Author

the many approaches to analysis. The area of accident conditions received much discussion, with the recognition that this will be a highly important area for magnets in fusion reactors. It was felt that the topical area of structural analysis needs a means for technical interchange on a regular basis and a mechanism for accomplishing this was set up.

The structural analysis of electromechanical systems using the finite element method was discussed in a paper presented at the First SAP User's Conference, UCLA, June 8-11, 1976. The paper represents the experience of local analysts of magnets and structures including FBX, SCORE, ORMAK-Upgrade, and EPR. Information exchanged at the meeting indicated that the local analysis capabilities are at least state-of-the-art in this area. The paper was written by W. D. Cain and W.C.T. Stoddart.

In the structural analysis of magnets, consideration must be given to the nonhomogeneous nature of the physical properties, i.e., modulus of elasticity, Poisson's ratio, and thermal expansion coefficient. A study was made of the interaction of these variables in a solenoid magnet to gain insight about the poloidal and toroidal magnets of a tokamak. The study presents a solution for displacement, stress, and strain in a transversely isotropic axisymmetric solenoid. The solution characteristics show that for thick solenoids with widely differing moduli in the hoop versus radial direction, peak hoop stresses may occur in the interior of the winding. The study also produced several graphs which are convenient for performing simplified analysis such as field factors and hoop stress factor as functions of coil geometry, using the elastic modulus as a parameter. More detail is included in ORNL/TM-5528, *Electromechanical Stress Analysis of Transversely Isotropic Solenoids*, by W. H. Gray and J. K. Ballou.

The materials evaluation program continued in the experimental area during this quarter. Some new work was proposed and some experiments reached the point of documentation. A proposal to study the effect of neutron irradiation on electrical insulators for use in a fusion reactor was submitted in cooperation with both the Metals and Ceramics Division and the Solid State Division. The proposal defines an experimental plan to use the Bulk Shielding Reactor at ORNL to simulate the neutron environment of a fusion reactor in a test of electrical insulator concepts at liquid helium temperatures. A stress-related post irradiation test plan is also defined. We are awaiting response on this proposal.

The results of a series of experiments on the lap shear strengths of selected adhesives in a room temperature and liquid nitrogen environment was reported by K. J. Froelich and C. M. Fitzpatrick in ORNL/TM-5658. This report presents the results of experiments with several epoxies, a varnish, and B-stage cloth adhesives, using a common adherend of copper and intermediate materials such as Kapton, Micarta, Nomex paper, and G-10 epoxy fiberglass board. Shear strengths up to 25 MPa (3700 psi) were obtained under the best of conditions. For further details see the subject report.

## 3.5 PROJECTS BY SUBCONTRACTORS

### 3.5.1 Force-Cooled Magnets

FED Personnel: C. G. Lawson[*]
Massachusetts Institute of Technology: A. Bejan,
M. Hoenig, Y. Iwasa, D. B. Montgomery

The Francis Bitter National Magnet Laboratory subcontract to develop forced-flow, supercritical-helium-cooled, cabled superconductor was extended through FY 1977. The work to be performed will include:

- the design and fabrication of an approximately 1 m × 1/2 m oval or racetrack coil which will be subjected to a 7.5-T field furnished by a pair of iron-core split field coils for determining the effect of wire motion under magnetic stress,

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[*] Author

- continued tests in 6-in. coils to determine the effect of wire motion on recovery currents with triplex cable,
- the effect of transposition and twist length on recovery current, and
- further development of cabled conductor concepts in NbTi and $Nb_3Sn$.

Extensive calculations were performed to predict the recovery currents and pressure drop requirements of triplex and fluted wire-cabled conductors subjected to energy inputs equivalent to heating the conductor to 15 K. Tests have also been performed on 0.10-m diam coils subjected to such energy pulses. The test recovery currents agree well with the calculated results. However, in some cases the actual recovery time is slower than the calculated recovery time.[1]

The fluted wire cable was found to have a lower self-critical current than short sample tests of the wire before fluting. However, the short sample tests of wire after fluting agreed closely with the cable of fluted wire results. The wires were examined by etching and it was found that extensive superconducting filament breakage had occurred.[2]

The self-critical current of the triplex wire was found to be about 60% of the short sample tests. The reasons for this are being explored; the fault is believed to be in the connection of the superconducting cable wires to the current bus.

An analysis of pumping requirements was made for larger superconducting cables.[3,4] The analysis shows that a cold liquid helium piston pump is much more efficient than a centrifugal pump or a gas compressor working at a higher temperature.

A small pulse pump with a capacity of 0.004 kg/sec has been developed for magnet experimentation.

References

1. Y. Iwasa, M. J. Lupold, M. O. Hoenig, J.E.C. Williams, and D. B. Montgomery, "Stabilization of Large Superconducting Magnets: Experimental Models," paper presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976.
2. M. O. Hoenig, Y. Iwasa, and D. B. Montgomery, "Cryostability of Four Inch Diameter Force Cooled Superconducting Coils Made from Cabled Hollow Conductor and its Effect on Large Scale Coil Designs," paper presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976.
3. A. Bejan and M. Hoenig, "Method for Estimating Refrigeration Costs of Supercritical Helium Cooled Cable Conductors," paper presented at the 1976 Applied Superconductivity Conference, Palo Alto, California, August 17-20, 1976.
4. A. Bejan, "Refrigeration for Force Cooled Large Superconducting Magnets," Paper 76WA/P/D-4, to be presented at the ASME Meeting, New York, December 6, 1976.

### 3.5.2 Refrigerator and Liquid Helium System

FED Personnel: C. G. Lawson*
Engineering: W. C. Anderson, J. P. Kois

The purchase and procurement of the 3.5-K Liquid Helium Compressor is proceeding according to schedule with Cryogenic Technology, Inc.

The heat exchangers, turbine expander, and helium gas compressor were ordered and are on schedule. The long-delivery-time spare parts necessary to assure continuous operation of the refrigerator were ordered.

The compressor for the refrigerator is a two-stage, oil-lubricated screw compressor being supplied by Sulair Company. The second stage has a 1000-hp motor and the first (low pressure) stage has a 400-hp motor. The low pressure stage will be sealed against vacuum by pressurizing the oil at the rotary screw suction above atmospheric pressure.

Detailed flow sheets of the liquid helium coolant system for the Large Coil Program are being prepared. A liquid helium pump will be

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*Author

procured and tested to assure adequate flow and pressure drop for the force-cooled supercritical flow magnets of the LCP test facility.

## 4. VISITORS*

June 1 to September 30, 1976

| | |
|---|---|
| June 3 | Ed Laich (Kawecki Berylco) |
| June 9 | Eugene J. Rapperport (Magnetics Engineering Associates, Cambridge) |
| June 10 | William V. Hassenzahl, Robert I. Schermer (Los Alamos Scientific Laboratory) |
| June 14 | Fred Fickett (National Bureau of Standards, Boulder) |
| June 14-15 | Mitchell O. Hoenig (MIT-National Magnet Laboratory, Cambridge) |
| June 15 | Jack Ekin (National Bureau of Standards, Boulder) |
| June 16 | Herbert H. Woodson (University of Texas, Austin<br>Robert W. Johnson, James L. Perry (Cryogenic Technological Company, Waltham, Massachusetts)<br>Lloyd van Horn, D. Wyman Tidwell (Biles Associates) |
| June 17 | Fletcher Brown Quillan (Craft Associates, Atlanta) |
| June 21 | B. Aldefeld (Phillips Forschungslaboratorium, Hamburg, W. Germany) |
| June 28 | Larry V. Clements, Jack L. Christian, Edward H. Johnson, Jon Raat, C. E. Roye, Robert E. Tatro, John P. Waszczyak (Convair, San Diego) |
| June 29 | Joey N. Kemp, Nathan E. Welch (Aero, Inc.) |
| July 8 | A. G. Koury, R. J. Senn (Air Products, Inc.) |
| July 15 | John Mayhall (Lockheed, Huntsville) |
| July 16 | Anthony J. Marolda (Arthur D. Little, Inc., Cambridge) |
| July 27 | Henry Smith Trentman (Airco-Tennescal) |
| July 27-30 | H. Jack Fivel (McDonnell Douglas Corporation, St. Louis) |
| July 28 | Robert Avrill, W. G. Langton, E. J. Rapperport (Magnetics Engineering Associates, Cambridge)<br>Larry T. Talley (Veeco Instruments) |
| August 5 | Michael E. Clarke, Garry R. Morrow (Intermagnetics General Corporation, Guilderland, New York) |
| August 9-10 | E. T. Henson (American Magnetics, Oak Ridge) |
| August 26-27 | Pierre Genevey, Jacques Parain (CEN/Saclay, France) |
| August 27 | John Mayhall (Lockheed, Huntsville) |
| August 27 | Prof. Wei-ho Chen (National Cheng-Kung University, Republic of China) |
| September 2 | Klaus-Peter Jungst (Institut für Experimental Kernphysik, Karlsruhe, W. Germany) |
| September 7 | Hans-Gunter Riés (Institut für Experimental Kernphysik, Karlsruhe, W. Germany) |
| September 10 | H. Ishimoto (Fermi National Accelerator Laboratory) |
| September 13 | Akihiko Miura (Heavy Apparatus Engineering Laboratory, Tokyo Shibaura Electric Company, Ltd.) |
| September 21 | Charles Laverick (Chicago) |
| September 20-24 | C. W. Trowbridge, John Simkin (Rutherford High Energy Laboratory) |
| September 23 | Reinhart L. Willig, Jr. (University of Wisconsin, Madison) |

### Visitors
### Large Coil Project Workshop
June 22-24, 1976

Robert A. Ackermann (Intermagnetics General Corporation, Guilderland, New York)

Gaston Bronca (CEN/Saclay, France)

James Dickson (Airco, Murray Hill, New York)

Kenneth R. Efferson (American Magnetics Inc., Oak Ridge)

John J. Ferrante (General Electric Company, Schenectady)

---

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

Carl D. Henning (ERDA-DMFE, Washington, D.C.)

Mitchell O. Hoenig (MIT-National Magnet Laboratory, Cambridge)

S. Y. Hsieh (Brookhaven National Laboratory, Upton, New York)

Clifford K. Jones (Westinghouse Research & Development Center, Pittsburgh)

Albert Koch (Brown Boveri, Switzerland)

Peter Komarek (Institut für Experimental Kernphysik, Karlsruhe, W. Germany)

A. Knobloch (Max Planck Institut für Plasmaphysik, Munich, W. Germany)

Charles Laverick (543 Hampshire Lane, Boling Brook, Illinois)

A. Martinelli (CEN/Saclay, France)

Jack J. Nolan (Magnetics Engineering Associates, Cambridge)

James R. Powell (Brookhaven National Laboratory, Upton, New York)

John R. Purcell (General Atomic Company, San Diego)

Robert N. Randall (Supercon Inc., Natick, Massachusetts)

Richard L. Rhodenzer (Intermagnetics General Corporation, Guilderland, New York)

William Sampson (Brookhaven National Laboratory, Upton, New York)

Robert I. Schermer (Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

Z.J.J. Stekly (Magnetics Corporation of America, Waltham, Massachusetts)

Moss Suenaga (Brookhaven National Laboratory, Upton, New York)

Claude Swanson (Cornell University, Ithaca, New York)

John Tarrh (Magnetics Engineering Associates, Cambridge)

Richard Thome (Magnetics Corporation of America, Waltham, Massachusetts)

Carl H. von Keszycki (Grumman Aerospace Corporation, Bethpage, New York)

Kenneth D. Williamson, Jr. (Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

Martin N. Wilson (Rutherford High Energy Laboratory, England)

Eugene J. Ziurys (ERDA-DMFE, Washington, D.C.)

## Visitors
## Large Coil Program Meeting
## August 30-31, 1976

**Airco, Murray Hill**

Eric Adam
E. Gregory
William Marancik

**Alcoa Technical Center, Alcoa Center**

Douglas A. Koop

**American Magnetics, Oak Ridge**

David Coffey
Howard Coffey
Kenneth R. Efferson

**Argonne National Laboratory, Argonne**

Robert L. Kustom
Sou Tien Wang

**Brookhaven National Laboratory, Upton, New York**

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Alfred Koch

**CEN/Saclay, France**

A. Martinelli

**Centro Gas Ionizzati, Frascati, Italy**

M. Spadoni

**General Atomic Company, San Diego**

John Alcorn
John R. Purcell

General Dynamics, Convair, San Diego

Ray F. Beuligmann
R. D. Bradshaw
T. E. Johnson
John P. Waszczak
Wally W. Withee

General Electric, Schenectady

Donald J. Anthony
Michael A. Broder
Robert W. Bryant
Charles R. Carder
John J. Ferrante
Robert Quay

Grumman Aerospace, Bethpage, New York

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Jack Campbell
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Robert A. Ackermann
John P. Heinrich
Richard L. Rhodenizer
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Carl H. Rosner
Bruce Zeitlin

Institut für Experimentelle Kernphysik
Karlsruhe, W. Germany

Professor Klose
Peter Komarek

R. B. Jacobs Assoc., Boulder

Robert B. Jacobs

Japan Atomic Energy Research Institute
Tokai Research Establishment, Tokai, Japan

Susumu Shimamoto

Consultant to DMFE

Charles Laverick

Lawrence Livermore Laboratory, Livermore

Donald N. Cornish
Dan Deis

Los Alamos Scientific Laboratory, Los Alamos

Robert Schermer

MIT-National Magnet Laboratory, Cambridge

Mitchell O. Hoenig

Magnetics Corporation of America, Waltham, Massachusetts

Theo deWinter
Edward J. Lucas
William Punchard
Z.J.J. Stekly

Max Planck Institut für Plasmaphysik
Munich, W. Germany

A. Knobloch

Office of R&D & Technology Application
IEA, Paris, France

Niels de Terra

Reactor Centrum Nederland
Petten, The Netherlands

J. D. Elen

Supercon, Natick, Massachusetts

Robert Randall
James Wong

Westinghouse R&D, Pittsburgh

John Wen Hua Chi
Donald Thomas Hackworth
Carl John Heyne
Clifford Kenneth Jones
John Herbert Murphy
Russell David Setzko
Robert Arthur Smith
Josiah Lynn Young

## 5. STAFF TRIPS*

June 1 to September 30, 1976

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| August 17-20 | Applied Superconductivity Conference, Palo Alto |

R. L. Brown

| | |
|---|---|
| June 29 | Argonne National Laboratory and Fermi National Accelerator Laboratory |
| June 30 | Phelps Dodge, Ft Wayne |
| August 17-20 | Applied Superconductivity Conference, Palo Alto |
| September 14 | Grumman Aerospace, Bethpage |
| September 15 | Westinghouse, Pittsburgh |

L. Dresner

| | |
|---|---|
| August 17-20 | Applied Superconductivity Conference, Palo Alto |

W. A. Fietz

| | |
|---|---|
| June 29 | Argonne National Laboratory and Fermi National Accelerator Laboratory |
| June 30 | Phelps Dodge, Ft. Wayne |

| | |
|---|---|
| August 10 | Lawrence Livermore Laboratory |
| August 11 | Lawrence Berkeley Laboratory |
| August 17-20 | Applied Superconductivity Conference, Palo Alto |
| September 1-2 | University of Wisconsin, Madison |
| September 28 | Cornell University, Ithaca |

W. H. Gray

| | |
|---|---|
| June 14-28 | GIFTS User's Workshop, Tucson |
| September 8-10 | Brookhaven National Laboratory |
| September 20-23 | ANS Meeting, Richland, Washington |

C. G. Lawson

| | |
|---|---|
| August 12-13 | CTI, Waltham, and MIT |
| August 17-20 | Applied Superconductivity Conference, Palo Alto |

C. J. Long

| | |
|---|---|
| September 14 | Grumman Aerospace, Bethpage |
| September 15-16 | Washington, D.C. |

M. S. Lubell

| | |
|---|---|
| June 3 | DCTR-ERDA |
| August 16 | Lawrence Livermore Laboratory |
| August 17-20 | Applied Superconductivity Conference, Palo Alto |
| September 26-October 7 | Moscow, Leningrad, France, and W. Germany |

J. W. Lue

| | |
|---|---|
| August 17-20 | Applied Superconductivity Conference, Palo Alto |
| September 21-23 | ANS Meeting, Richland, Washington |

J. N. Luton

| | |
|---|---|
| June 14-18 | Nuclear Energy & Society Joint Meeting of the ANS/Canadian Nuclear Association, Toronto |
| June 29 | Argonne National Laboratory and Fermi National Accelerator Laboratory |
| June 30 | Phelps Dodge, Ft Wayne |

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

| | |
|---|---|
| September 14 | Grumman Aerospace, Bethpage |
| September 15 | Westinghouse, Pittsburgh |
| September 16 | Varian, Palo Alto |

J. R. Miller

| | |
|---|---|
| August 17-20 | Applied Superconductivity Conference, Palo Alto |

R. E. Schwall

| | |
|---|---|
| August 9 | University of Texas, Austin |
| August 11 | Lawrence Berkeley Laboratory |
| August 16 | Stanford University |
| August 17-20 | Applied Superconductivity Conference, Palo Alto |

S. S. Shen

| | |
|---|---|
| August 17-20 | Applied Superconductivity Conference, Palo Alto |

W.C.T. Stoddart

| | |
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| September 7 | Office of Naval Research, Washington, D.C., and Princeton Plasma Physics Laboratory |
| September 8-10 | Brookhaven National Laboratory |

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