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Tokamak Poloidal Field Systems

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TOKAMAK POLOIDAL FIELD SYSTEMS

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Compiled by

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ABSTRACT

Work is reported on the development of superconducting tokamak poloidal field systems (TPFS). Progress is discussed on the design of a 20 MJ, 50 kA, 7.5 T superconducting pulsed energy storage coil operated in a 1 to 2 s bipolar mode from +7.5 T to -7.5 T in 1982. Conductor development for the coil is presented. A facility that uses a traction motor energy transfer system to test coils in the 20 to 100 MJ energy range is discussed. Current interrupter development and testing for protection and energy transfer circuits are also presented. The 400 kJ METS coil test preparation is under way.

A. SUMMARY

The principal goal of the group continues to be the development of superconducting tokamak poloidal field systems (TPFS). The major object of the program is to provide a feasibility demonstration of 50 kA, 20 MJ, 7 T superconducting pulsed energy storage coil operated in a 1 to 2 s bipolar mode from +7.5 T to -7.5 T by 1982. Major accomplishments are briefly summarized here and certain specific accomplishments are listed even more briefly.

A contract was placed with the Westinghouse Electric Corp. (W) for design of the 20 MJ coil. The coil is to have a spiral pancake configuration with a 7.5 T field with a liquid helium pool bath cooled 50 kA conductor. The fabrication design of the coil is very nearly complete.

A test was performed on a 50 kA conductor at the Lawrence Livermore Laboratory in the MFTF conductor solenoid at a background field of 6 T. The results indicated that laboratory tests on smaller components of the cable can be used to predict overall cable performance. The recovery current for the cable was predictably low.

The design of the traction motor energy transfer system for testing the 20 MJ coil has been advanced into a more detailed engineering state. The design is based upon data obtained from operating two traction motors as electromechanical capacitors with the 300 kJ coil. An RFQ has been issued to purchase the traction motors for the system.

Preliminary design considerations for upgrading the traction motor system for testing a 100 MJ coil instead of a 20 MJ coil indicate that for the ETF energy transfer times of 5 to 8 s that a mere flywheel change is all that will be required.

The 2 MJ switch test facility which is intended to operate at currents up to 150 kA and recovery voltages of 100 kV has been completed. This facility is probably the largest dc switch testing facility available in the U.S.

The LCP conducted by the Oak Ridge National Laboratory (ORNL) requires a facility for testing the superconducting toroidal field coils. The coils must be protected from damage by a fast energy dump system. Circuits for this purpose and the switches for the system have been developed in cooperation with ORNL. The switches will be tested by the Los Alamos Scientific Laboratory (LASL).

Pulsed induction coils for operation near 7 T require confirmation of the design characteristics of the superconductor. This can be done, in part, by measuring the conductor losses in a pulsed background field. A small 7 T pulsed superconducting solenoid has been made to perform the necessary loss measurements on superconductor for the 20 MJ coil 50 kA cable.

The 400 kJ coil, which evolved from the fast pulsed METS program for the theta pinch system, has been completed by W and delivered to LASL. The coil is being assembled into the test facility and will be operated at 25 kA under fast and slow pulsed conditions. The high current and the CuNi-Cu mixed matrix conductor of the coil are of interest to the TPFS program.

The cryogenic disconnect made to operate at 25 kA with a $40(10)^{-9} \Omega$ resistance tested unsuccessfully at $1.44(10)^{-6} \Omega$.

Specific accomplishments not covered above are as follows.

1. Quench calculations for the 20 MJ coil show that the coil can be adequately protected with reasonable switching delays to dump the energy.

2. An order was placed with Controlled Power Co. for a 3 MW power supply capable of delivering 50 and 100 kA at 60 and 30 V, respectively.

3. A 7 in. vacuum interrupter with water cooled electrodes was tested and found to be able to carry ten times the steady state current of an equivalent commercial vacuum interrupter with uncooled electrodes.

4. Early counterpulse operation of a vacuum interrupter indicated that considerably extended life can be obtained by this method of arc extinguishing.

5. Parallel operation of 7 in. vacuum interrupters was successful and pointed to necessary design modifications to eliminate potentially destructive faults.

6. A high closing force, fast actuator for vacuum interrupters was developed.

7. Critical current and preliminary loss measurements have been made on a prototype superconducting strand for the 20 MJ coil 50 kA cable. The critical current values are satisfactory, and the first loss measurements are high.

8. The external breaker for testing the 400 kJ coil was tested thoroughly under more realistic conditions and found to require a two by two series parallel array of vacuum interrupters and bypass switches for reliability.

9. The 25 kA vapor cooled leads for testing the 400 kJ coil were successfully operated at full current.

10. Pressure joints and soldered superconductor to bus contacts were tested at 25 kA and the resistances measured.

B. 7.5 T, 20 MJ SUPERCONDUCTING TPFS COIL

1. Coil Design. The contract for the fabrication design of the 7.5 T, 20 MJ superconducting coil for the tokamak poloidal field system (TPFS) program was placed with W. The design contract calls for drawings, specifications, standards, procedures, and detailed information such that a package results which can be used without further work to proceed with the fabrication of the 20 MJ coil. The design phase has been closely monitored by monthly meetings to review the work status. Whenever necessary, complementary analytical work has been undertaken by group CTR-9 of LASL to assure the correctness of the work by W. Some of this analytical work is discussed below. The coil design is nearly complete.

The coil will be wound of cabled NbTi superconductor and will be cooled with pool boiling liquid helium. General characteristics are listed in Table I. Figure 1 is a cross

TABLE I

20 MJ TOKAMAK POLOIDAL FIELD SYSTEM PROTOTYPE COIL

Peak field, T	7.5
Type of conductor	flat cable
Cooling	pool boil at 4.5 K
Winding	pancake
Current, kA	50
Conductor thickness, cm	1.573
Conductor width, cm	12.48
Conductor current density, A/cm ²	2546
Coil length, cm	135.5
Coil i.d., cm	60
Coil o.d., cm	146
Turns/pancake	25
Number of pancakes	8
Overall current density, A/cm ²	1716
Inductance (Grover's method), mH	16.18
Stored energy at 50 kA, MJ	20.23

Fig. 1.
Cross section through 20 MJ superconducting prototype TPFS coil.

section through the coil showing the principal components.

Following discussions between LASL and W on the merits of radial and axial helical coil windings a decision was made to design a radial-spiral pancake coil in conformance with the final contract specifications. This winding form

was considered to be more adaptable to the long solenoidal magnets found in tokamak designs and to be more consistent with the tokamak community conceptual engineering designs. Pancake windings are made in modules which can be replaced and repaired with relative ease.

Analyses indicated that they could be made to operate at higher average current densities than axial helical wound coils. Because high current density is a principal reason for employing superconducting coils, the winding form which best maintains this advantage was chosen for the prototype coil. Pancake coils suffer from the possible disadvantage of having two electrical connections per pancake pair; however, this is not considered to be an overwhelming problem. The design meets the specifications and has a reasonably high current density.

During the period following the proposal for this program, the operating modes for proposed tokamaks with superconducting poloidal field coils have changed. Suggested reversal times for currents in the induction coils have been lengthened from 1 s to about 6 to 8 s. This led to discussions with the ETF tokamak design teams about the goals of the 20 MJ TPFS coil program. A conclusion was reached that a reversal time of approximately 1 s should be maintained as a design specification because uncertainties still exist for r.f. and neutral beam plasma heating which would lead to the longer reversal times. If the 20 MJ prototype coil is operated successfully at a reversal time of 1 s, longer reversal times will be achievable with lower losses in the superconductor. The 20 MJ coil specifications are unchanged, and the experiment will serve as a benchmark for future designs of coils with any longer current reversal time.

A final design review will be held in February 1980 with DOE representatives and experts from the community of fusion magnet designers in attendance.

Verification tests to determine the stress and cyclic fatigue limits of the materials used for various components of the 20 MJ coil remain as points of discussion. Facilities to perform some tests are not readily available, and the expense of performing some is high. The verification

tests are still being evaluated to determine those absolutely necessary to assure acceptable coil performance.

2. Prototype 50 kA TPFS Superconducting Cable Development and Evaluation. The development and evaluation of a 50 kA cable for the 7.5 T, 20 MJ induction coil is underway. Two prototype cables have been considered. The first cable, with the major emphasis on proving manufacturing feasibility, was successfully fabricated by Magnetic Corporation of America (MCA) in conjunction with New England Electric Wire (NEEW). The critical current, stability current, and energy losses of the cable and its sub elements were evaluated. Extrapolation of the results showed that the cable would carry 55 kA at 7 T. The recovery current, however, was only about 33 kA, and the projected coil losses for such a cable were too high. These results were expected because the cable design was not optimized. Recovery current measurements as a function of applied field were made on the first level soldered subcable and on the full cable. The heat transfer at the maximum recovery current for the isolated first level subcable at zero field was only 0.15 W/cm^2 as a result of the known poor insulation. Without the insulation, this value increased to 0.32 W/cm^2 . For the full cable the value of the heat transfer coefficients are listed in Table II.

The perimeter used to calculate the heat transfer assumed that one-third of the first level cable surface area was occluded as a result of the second level cabling. The spacers and the central cable mandrel were assumed to have no effect on the amount of cooling surface. Extrapolation and comparison of the results to zero field data indicate these are reasonable assumptions. The decrease in the critical heat flux with field is not well understood but may be a result of

TABLE II
HEAT TRANSFER FOR 50 kA CABLE

Field, T	3	4	5	6
$\frac{I^2 \rho(B)}{AP}, \frac{\text{W}}{\text{cm}^2}$	0.13	0.13	0.10	0.08

distortions in the cooling curve caused by the insulation system.

A second, optimized prototype cable is being manufactured by Intermagnetics General Corp. (IGC). This cable will utilize a cryostable, low loss, advanced mixed matrix conductor. Early failures in the manufacture of this conductor have delayed the cable development. Critical current measurements on a sample of the basic strand have now been made and show that it meets specifications. The production of all the strand for the full prototype cable is almost complete.

3. Stress Analysis of Pancake Coils. A number of simplified analyses of stresses in pancake windings and related structural elements have been performed to gain a greater understanding of the behavior of this winding form and to serve as a check on analyses performed for the coil design. Three areas have received detailed attention. These are shear stress between the turns, winding pretension and the resulting pressure on the center bobbin surface, and buckling of the coil bobbin.

Many well founded analyses of stresses in solenoid magnets have been presented in the literature. The more sophisticated address the effect of anisotropy, winding tension, and differential thermal contraction. In all cases the coil is considered to be composed of concentric hoops. This, of course, is never the case since all windings are formed from a length of conductor with free ends. This is particularly evident in pancake coils which are wound in a fashion resembling a watch spring and can expand and contract much like a watch spring when placed under load. Gradients of tension exist in the turns of a pancake coil with high tension at or near the bore, low tension or compression at or near the outer surface of the coil, and no tension at some terminations. These gradients in tension require the presence of shearing forces on the conductor surface, which can be provided by either elastic deformation of a matrix or surface friction. The analysis undertakes a derivation of the normal, hoop, and shear stress in a pancake coil wound of membrane like turns incapable of bending. It shows that the shear equation becomes decoupled from the normal and hoop stress

equations for coils with a small pitch helical winding. This allows computation of normal and hoop stresses by conventional means and deduction of the shear stress from these results. Shear stresses, while small when averaged over the area of a turn in a potted coil can become large when concentrated on a few spacers in a pool boiling cooled superconducting coil. Motion of the turns with consequent heat generation can result if insufficient shear strength is provided by the structure. This can cause quenching of a superconducting coil and insulation failure in a conventional coil. This analysis is the first that includes shear stresses and provides a simple method for calculating their magnitude based on existing algorithms and codes.

An integral expression for the pressure exerted on the surface of the coil bobbin or former as a function of winding pretension for an isotropic winding was developed from the classical solutions to the Lamé thick cylinder stress equations. This expression was compared with a numerical solution generated by the computer code STANSOL2 for a particular coil design and found to be in agreement. The formulation provides a simple expression for determination of the pressure at the inside of a coil winding which aids in design of the bobbin, winding spacers, insulation and other components.

An expression to determine the external load which will result in buckling of a winding bobbin was devised using the energy method. The bobbin is subjected to an external pressure load resulting from winding pretension and is at the same time supported by the elasticity of the surrounding winding. The behavior is similar to that of a beam on an elastic foundation. The winding pretension induced pressure at which the bobbin will buckle exceeds the buckling pressure of an externally pressurized cylinder.

These various analyses have demonstrated the accuracy of the solenoid stress analysis code STANSOL2 used in common by IASL and others and have allowed an independent verification of the stress calculations.

4. Coil Quench Calculations. The computer program QUENCH was developed about ten years ago by Martin Wilson of the Rutherford High Energy

Laboratory and has been improved by several different users. The version from Saclay was further modified to include heat transfer to liquid and/or gaseous helium, variable time steps, and a propagation velocity that changes as the central region of the quench increases in temperature. This program is now operational on the LASL CCF and is being used to study quenches in the 20 MJ TPFS pulsed coil and the 7 T solenoid to be used to make loss measurements.

The results of the quench calculations for the 20 MJ coil are given in Table III. For all cases an instantaneous energy source is assumed to create a 15 K temperature in the center of the region allowed to go normal. The calculations are to be repeated with a 25 K initial temperature. The table lists the fraction of turns in the coil allowed to go normal, the time delay after normalcy occurs to initiate the protective dump, the L/R dump decay time constant, the maximum conductor temperature before recovery begins, and the time after normalcy occurs to reach the maximum temperature. The coil appears to be quite safe with any reasonable protection circuit.

C. TPFS COIL TEST FACILITIES

1. Facility Layout. A location has been selected for the 20 MJ coil. This location is about 150 ft from the helium liquefier and 50 ft from the 3 MW power supply used to charge the coil. The arrangement also places the traction motors close to the coil. The cost per foot for bus work is considerably more than the cost of liquid helium

transfer line, so it is desirable to minimize the length of bus work. The piping for recovery of helium vapor generated after a field reversal in the 20 MJ coil has been sized and the pressure drop between the dewar and gas recovery bag is small. A field map of the stray field shows there is no unusual problem for personnel exposure. The problem of forces on the coil from nearby steel buildings is being investigated.

2. Traction Motor Energy Transfer System. A power supply capable of handling a reactive pulsed power flow of 50 MVA is required to reverse the current in the 20 MJ coil. A review of available rotating machines indicated that reconditioned traction motors are capable of being integrated into an inexpensive pulsed high power supply. Eighteen traction motors are required for this supply at a probable cost of \$225 000 for rebuilt equipment. New machines have an anticipated cost of \$540 000, and an alternator, transformer, rectifier system has an anticipated cost of \$2 250 000. Obviously, traction motors have a strong economic justification for their use.

A series of tests, run over a period of a year, established the transient characteristics, defined the region of successful commutation, and confirmed the steady state operating characteristics of Westinghouse type 362 traction motors.

A detailed circuit analysis for the traction motor power supply to test 20 and 100 MJ coils was undertaken based on these tests. Present cost and availability of traction motors has forced the consideration of General Motors Electromotive type D-79 and General Electric Company type 752 motors in addition to the Westinghouse type 362, which is no longer in production. This will not alter the performance of the supply and will increase the number of vendors capable of responding to the request for quotation.

Information generated in these tests was supplied to Sandia Laboratories and the University of Texas at Austin for use in the design of a power supply for a lightning simulator.

The objectives of the test facility are to drive the current in the 20 MJ coil to 50 kA, to reverse the current to -50 kA in a time interval of 1.6 to 5.0 s, and to continue current driving

TABLE III
QUENCH CALCULATIONS FOR 20 MJ COIL

Normal Zone Turns	Dump Time Delay, s	L/R s	T _{max} K	Time to T _{max} , s
1	1	5	22	2.5
1	5	5	33	8
1/4	10	5	42	13
1	1	1	21	1.4
Full Coil	10	5	36	12

at -50 kA for an indefinite time. To accomplish programmed current drive which requires an energy transfer of 20 MJ with minimum capital investment a resistor and a set of traction motors are used to force the current reversal in a two step operation. During the initial step the resistor provides current attenuation. To complete the current reversal the traction motors serve the function of an electromechanical capacitor with the resistor being disconnected. A 3 MW power supply, which operates from the local power system, drives the current to 50 kA. After having been disconnected for the current reversal, the power supply is reconnected through a reversing switch for the final current driving at -50 kA. The low system cost results from the low market value per unit kinetic energy stored in traction motors equipped with flywheels. Because of the modest energy efficiency of this type of electromechanical energy storage device, the traction motor armatures are rotated to a predetermined speed while the 20 MJ coil is being charged to 50 kA. The kinetic energy of the traction motors is added in the circuit during current reversal to make up for the losses. An additional free parameter is needed and is provided by varying the length of the time interval for the resistive discharge. The circuit under design is shown in Fig. 2.

The operating sequence follows.

a. All switches are open, B and E discharged.

b. Close (1), wait until the 50 kA value has been reached; close (4) to precharge E; open (4).

c. Close (2) and open (1) to discharge partially B into D. Note that this step c may be used for time intervals extending for 0 to many seconds.

d. Close (3) and open (2) to reverse current by way of the precharged capacitor E.

e. Reverse polarity of A; close (1) and open (3) to maintain current in B.

f. Close (2) and open (1) to discharge B.

To select the circuit breakers the following aspects are studied. The breakers must open when a local quench in the coil has been detected. The closed state duty of switches (2) and (3) is limited to the duration of the current reversal,

Fig. 2:

Traction motor circuit for testing TPFs.

A = charging supply - slow charge 15 min, fast charge 30 s

B = 20 MJ coil

C = protective (L/R = 0.16 s) dump resistor

D = discharge resistor to initiate current reversal cycle (adjustable)

E = electromechanical capacitor to complete current reversal, internal inductance L and resistance R

F = charging supply to provide initial charge on E

l_{line} = line inductance of respective loop, $l_{line} \approx 35 \text{ mH}$

whereas switch (1) must be capable of continuous operation in the closed state. Breakers (2) and (3) must develop significant arc resistance so they may open the circuit. A vacuum interrupter with commutating circuit is expected to be used for switch (1). Air magnetic or vacuum interrupters are under consideration for switches (2) and (3).

The energy transfer system designed for testing the 20 MJ coil in 1.5 to 5 s bipolar times can be upgraded to test 100 MJ coils in 5 to 17 s transfer times merely by changing the flywheels. The flywheels, made of 1020 steel for the 20 MJ operation rotate at 1900 rpm, have a surface velocity of about 230 ft/s, and store approximately half the energy. The flywheels for the 100 MJ operation at the same rotational speed have a surface velocity of about 430 ft/s, store most of the energy, and will be made of 4340 steel. The cost to upgrade the system is nominal.

Preliminary design has been completed for the bus between the coil and the traction motors. It is assumed that the bus will consist of six parallel aluminum plates of 1/4 in. by 6-1/2 in. dimensions, with a 1/4 in. space between adjacent plates. The busses will be interleaved. The total length, which may be high, was estimated to

be 300 ft. The 50 kA direct current was assumed to be applied for 10 s. Under the assumed conditions, the temperature rise will be 7.4 °C; the force between adjacent plates will be about 21 lbs per ft length of the bus. The magnetic field at a distance of 1 m will be about 33 G if the busses are not interleaved and 0.8 G if interleaved.

3. 3 MW Power Supply. An order was placed with Controlled Power Co. for a 3 MW power supply to be used to charge TPFS coils and to run I²t heating tests for switches in conjunction with the operation of the 2 MJ switch test facility, which is reported upon below. The supply has a dual voltage-current output capability of 30 and 60 V with respective current ratings of 100 and 50 kA. The power supply is to be delivered in early 1980.

D. TPFS SWITCH DEVELOPMENT AND HVDC TESTS

The storage of energy in superconducting coils for fusion applications requires the ability to interrupt high currents and to withstand relatively high voltages while the current or energy in the coils is being transferred. For the TPFS coils the energy transfer is fundamental to their function whereas for the tokamak toroidal field coils the energy transfer is merely to perform a protective function. In both cases switches and circuits are being developed and tested for these purposes.

1. 60 kA, 800 kJ Test Facility. Several electronic circuits in the control system were malfunctioning because of damage to some of the components. The damaged components have been replaced, and the control system is functioning properly. Two resistive voltage dividers were found to distort the recovery voltage across the opening contacts of the vacuum interrupter under test. A damped capacitive voltage divider has been designed which faithfully reproduces the recovery voltage across the vacuum interrupters. Two 150 kV capacitive voltage dividers are now being developed. A number of tests and developments performed on the 60 kA, 800 kJ test facility are presented immediately below.

a. Water Cooled Vacuum Interrupters. A water cooled 7 in. vacuum interrupter, normally capable of 1.2 kA steady state operation, carried

13 kA for 10 minutes with no damage. A new interrupter, designed by LASL, is currently being fabricated at W. Combined with a high closing force actuator, this interrupter is intended to carry 25 kA on a continuous duty basis as well as interrupting the 25 kA.

b. Early Counterpulse Experiments. A 4 in. vacuum interrupter was made to interrupt four times its normal maximum limit of 6 kA with an early counterpulse to extinguish the arc. A 4 in. interrupter was run 1200 times at 10 kA with no failures. Upon disassembling this interrupter, it was discovered that electrode erosion was almost nonexistent.

c. Parallel Vacuum Interrupter Experiments. Two 7 in. vacuum interrupters have been operated in parallel to interrupt currents in excess of 50 kA. Modifications to the mounting of stainless steel bellows on the movable electrode are being made to eliminate destructive faults in the case of a single interrupter failure. Such modified vacuum interrupters are on order from W for further parallel interrupter testing.

d. Actuator Development. A fast pneumatic/electric cylinder was attached to a vacuum interrupter and tested to 600 psi. Total time from trip to 1/4 in. gap was 1.55 ms. Alterations will be made to reduce this to about 1.2 ms. This actuator will be useful in early counterpulse circuits as well as possible applications in an electric utility fault current limiter system.

A high closing force actuator has been developed for use in high current and water cooled vacuum interrupter experiments. The high closing force is desirable to overcome popping (Lorentz) forces in high current switches and to diminish contact resistance and heating in water cooled electrodes. The maximum force is 2400 lbs. Opening speed is about 10 ft/s.

e. Howe-Yin Test Circuit. A circuit has been devised to test a new dc breaker for industry. Interruption ratings are 15 kA and 2 kV. The continuous current rating is 2 kA. This circuit breaker will also be tested to its 90% reliability level. Testing is scheduled for the spring of 1980.

2. 2 MJ Switch Test Facility. The 2 MJ switch test facility was completed in 1979. Preparations are underway to test the GE rod array vacuum interrupter. This interrupter should be capable of interrupting 100 kA and to stand off 100 kV. As such it provides a good first test to check the facility. The 40 kA power supply has been installed for use with the 2 MJ test facility, and the 3 MW, 100 kA power supply will be installed in FY80.

3. LCP Dump Switch for Oak Ridge National Laboratory. A circuit and testing scheme has been developed for the LCP protective dump system at ORNL. This hybrid switch consists of a high current bypass switch based upon the LASL hybrid switch development in parallel with a dc circuit breaker. System requirements are 25 kA continuous current capacity, 25 kA interruption duty, 2.5 kV recovery voltage, and <100 ms total operation time. Testing of a prototype switch in the 2 MJ test facility at LASL is planned for late FY80.

E. CRITICAL CURRENT AND LOSS MEASUREMENTS OF SUPERCONDUCTORS

1. Critical Current Measurements. Critical current measurements were made on a sample of the IGC finned conductor for the 20 MJ prototype 50 kA cable. The results are given in Table IV. These results extrapolate to about 410 A at 7.5 T for the basic strand and 88 kA for the full 50 kA cable.

2. Loss Measurements in Superconductors.

Hysteretic and pulsed loss measurements have been made on a large variety of conductors for fields

up to 2.2 T and for exponential field decay times from 0.7 ms to 0.28 s.

Preliminary loss measurements on the first prototype superconducting strand for the 50 kA cable give values which are 50% above the 20 MJ coil specification. These losses are mostly due to coupling among filaments and hence depend upon the twist pitch length and transverse resistance. These parameters for the wire, as supplied, are being determined.

Measurements on in-situ produced filamentary Nb₃Sn wire manufactured by D. K. Finnemore of Iowa State University indicated that the filaments were coupled together either directly or because of the proximity effect. This caused the losses to be very large.

Measurements on the cable for the new 7 T loss magnet showed the losses increased by a factor of 2 if the cable was soldered. The cable for the 7 T coil was left unsoldered.

3. 7 T Loss Measurement Apparatus. A new apparatus for measuring losses in short samples of superconductor is being constructed. This apparatus works by measuring the magnetization of samples placed in one of two identical sensing coils connected to give opposite voltage as a surrounding magnetic field is changed. The magnetic field is provided by a solenoid designed to operate from +7 T to -7 T in about 1 s. This apparatus will be used on short samples of wire intended for the 20 MJ coil.

The magnet for the apparatus was wound of a mixed matrix NbTi superconductor and is cooled by pool boiling liquid helium.

Stresses in the superconductor winding under all conditions--warm with pretension, cold with pretension, and operating from +7 to -7 T--were calculated using STANSOL2. Based on this investigation G10 epoxy fiberglass in the coil form and spacers should have the glass laminate in the radial and axial or radial and tangential directions to reduce the relative thermal contraction between the conductor and the structure. With this design the winding pretension need not exceed 50 lb.

Accurate analysis of the coil required knowledge of the elastic constants of the superconducting cable. The cable is a compacted

Field, T	I _c , A	J _c , 10 ⁵ A/cm ²
0	2950	6.0
1	2100	4.3
2	1530	3.1
3	1270	2.6
3.5	1100	2.3
5	680	1.4
6	560	1.15
7	460	0.94

unsoldered Rutherford type. Because the cable is unsoldered the effective longitudinal modulus of elasticity of the unrestrained cable is much higher in tension than compression. In addition, the unsoldered cable will buckle, that is, it will revert to a cylindrical configuration from its normal rectangular shape when subjected to sufficient tension. A model test made with an Instron machine showed that sufficient lateral load will be applied to the conductor in the winding to lock the strands together by friction. The buckling load was found to equal the ultimate strength of the wire. Elastic properties determined by tests in the Instron tester were used for the stress analysis and design with the resulting 50 lb pretension requirement. The magnet has been installed in its dewar and the preliminary dc testing is complete. The superconducting cable and magnet details are given in Table V.

Quench calculations for the 7 T magnet show that under adiabatic conditions a normalcy which deposits 27 kJ of energy in the inner five layers of the magnet will raise the temperature to 84 K in 2.4 s. A similar quench with a 56 kJ energy deposit will raise the temperature to 110 K in 7 s. These effects are without a protective system.

The 7 T magnet will be charged from a conventional power supply and then rapidly discharged by switching the power supply out of

the circuit and allowing the current to decay through a resistor in parallel with the coil. The magnet will be recharged with opposite polarity by switching in a pair of traction motors used as electromechanical capacitors. The equivalent capacitance of each traction motor can be varied from 0.25 to 15 F by changing the field excitation. Electrolytic resistors will be used as dump resistors and conventional dc air gap breakers will be used for switching.

F. ONE COMPONENT MODULE SUPERCONDUCTING PROTOTYPE METS SYSTEM

The fast pulsed superconducting inductive-energy storage program was initiated to provide a system capable of delivering 480 MJ of energy to create a 5.5 T field on a theta pinch fusion plasma. To bring the program to a logical conclusion in view of the de-emphasis of theta pinch research and to obtain a maximum amount of information for ongoing inductive energy storage systems, a complete one module or one component system is being assembled for test provided the subcomponents can be developed on a timely basis without delaying the test of the coil.

1. METS Prototype Coil. The 400 kJ coil made by W was delivered. This coil will operate at a current of 25 kA and is made of Cu-CuNi mixed matrix superconductor to reduce coupling losses as the field is changed in the coil. Even higher current cables (50 kA) and low loss superconductor are both design features for TPFs. Operation of the 400 kJ coil will provide more information for the pulsed energy storage coil program. Assembly of the 400 kJ coil test system is underway.

The first tests of the coil will involve a very slow charge of the coil followed by a rapid discharge (~1 ms) with a capacitor bank and a normal conductor load coil in a resonant L-C-L circuit. Later tests will consist of a slow charge followed by a discharge on the time scale of a few seconds and a recharge, also on a time scale of a few seconds. This latter scale resembles that expected in a tokamak plasma current induction cycle.

2. Coil-Dewar Interface. The mounting for the coil in the dewar was modified to lower the coil

TABLE V

SUPERCONDUCTOR AND 7 T MAGNET DETAILS

<u>Cable</u>	
I_c	1700 A at 7 T
I_{op}	1350 A at 7 T
Dimensions	0.152 cm x 0.633 cm
Cable current density	14 kA/cm ²

<u>Coil</u>	
Inner radius	3.0 cm
Outer radius	11.73 cm
Length	24.4 cm
Total turns	1198
Inductance	0.062 H
Overall current density	7.6 kA/cm ²

location in the dewar to reduce the liquid helium inventory.

3. Cryogenic Disconnect. The cryogenic disconnect is a no-load switch that serves to separate series connected METS coils in a multiple coil system. It is placed in the helium bath adjacent to the superconducting coils and must have a resistance of less than $4(10)^{-8}$ ohms while carrying 25 kA and must open in 20 to 50 ms with no current load. Earlier tests were made on a model disconnect with three pins which carried 4500 A. A full scale 19 pin disconnect to carry the 25 kA in the test was assembled and tested.

A delay was encountered in testing the disconnect because the fast acting York actuator became defective and was returned to the factory for repairs. During the delay the disconnect was immersed in alcohol to protect the bright solder coated contact surfaces of the 19 pin assembly from contamination. Unfortunately the drum containing the disconnect was not sealed and moisture absorption into the alcohol bath occurred and most likely was the cause of the disconnect failure. The earlier tests conducted on the 3 pin model clearly indicated the need of a galling contact of bright solder surfaces. The disconnect surfaces had oxidized while stored in the methanol.

The disconnect was tested at the full 25 kA current. The resistance was measured to be $1.44(10)^{-6} \Omega$. This is a factor of 36 above the desired $4(10)^{-8}$ ohms. Because of the delay that would be involved in the 400 kJ coil test, any effort to make the disconnect operable at the necessary lower resistance was abandoned.

The disconnect opening time ranged from 34 to 55 ms and was dependent on the gas pressure to the actuator. Delay times for the actuator to release and start to open the disconnect ranged from 97 to 125 ms.

4. External Breaker and Transfer Interrupters. To remove the charging power supply from the 400 kJ coil, the current in the series charging loop will be interrupted by a circuit breaker placed external to the dewar. The external breaker must carry the 5 min charging ramp to 25 kA, interrupt it, and withstand up to 60 kV. To meet these requirements the breaker will consist of a

combination of vacuum interrupters and bypass switches connected in parallel to form a hybrid switch.

A full-scale prototype of the bypass switch has been built and was further tested this year. The results of the test clearly indicated the need for two bypass switches in series connected in parallel with two series connected vacuum interrupters for high operational reliability. This arrangement for reliability has been extended to the ORNL LCP protective dump switch circuit. Several modifications are being made to the bypass switch to give better performance. The two vacuum interrupters of the external breaker will be simultaneously operated by the Maxwell actuator. Modifications were necessary because the actuator originally operated only one interrupter.

The two transfer interrupters, type General Electric PV08, will be individually actuated by two Ross actuators which will be operated by a single Ross driver. The driver will be modified for operation with optical signals.

5. 25 kA Electrical Leads. The 25 kA vapor cooled electrical leads developed for testing the 400 kJ coil were used to test the disconnect and were found to operate properly; however, the amount of vapor discharged for cooling was excessive because of the high heat generation of the disconnect.

6. 25 kA Pressure and Solder Joints. The testing of the cryogenic disconnect at full current provided data on the highest known level of current conduction through indium pressure joints and soldered joints in a liquid helium environment. The indium pressure joint measured $1.1(10)^{-8} \Omega$ with a total contact area of 110 cm^2 , and the soldered joint measured $1.2(10)^{-9} \Omega$ with a contact area of 180 cm^2 . The pressure contact is between the 25 kA vapor cooled lead and a bus bar going into the helium bath. The bus bar was made of laminated copper with Nb_3Sn ribbon sandwiched between the copper bars. The contact area given is to two surfaces on either side of the lead; however, the superconducting lamination was adjacent to only one side and the effective contact area may more nearly be 90 cm^2 . The solder joint was to the lower end of the bus with approximately 30, 0.040 in. diam Cu matrix NbTi superconducting wires. The results of the tests

are being used for the design of the 50 kA, 20 MJ coil joints.

7. Rebuilding Dewar Pit. The plastic dewar used to test the 300 kJ coils has been removed from the dewar pit and replaced by the larger 400 kJ coil dewar. Both the steel grating covering the pit and the steel beams supporting the grating were removed to fit the new dewar into the pit. The new support structure and plywood cover made for the pit are designed to eliminate shorted electrical turns around the coil. A new vacuum system was installed in the pit to provide the dewar insulating vacuum. Repairs to the dewar vacuum gasket seal between the inner and outer vessel shells have been completed and the dewar has been evacuated.

8. Electronics. A zero-current detector has been designed to detect when current in the cryogenic disconnect is zero. A gate circuit was designed to prevent the cryogenic disconnect from opening unless the current in it is zero. New digital readout meters reading directly in kA have been built for the homopolar generator and the Rapid-Electric rectifier. Two meters in parallel give a quick check that the meter system is operating correctly. All circuits are essentially complete for operating the 400 kJ coil.

G. RFX CONCEPTUAL DESIGN

A set of operating conditions has been set for the RFX ohmic heating interrupter. These are maximum heating prior to interruption of $5(10)^9 \text{ A}^2 \text{ s}$, maximum interruption current of 50 kA, and maximum recovery voltage of 50 kV. The interrupter is tentatively designed as a vacuum interrupter array connected in series and parallel or an SF_6 puffer. Cost estimates for the interrupter are being made.

H. MISCELLANEOUS

1. Theory of the Arc Discharge in Air Blast Circuit Breakers. Based on the Boltzmann equation and the Enskog-Chapman resolving formalism, a consistent mathematical theory of the electric arc is developed, leading to a closed set of first order differential equations with four external parameters. The complete set of external parameters is composed of the circuit current, its

first time derivative, the gas kinetic pressure, and the heat conductivity in turbulent heat transport. Clarification of some conceptions existing in the current literature is obtained from the formalism developed, and good agreement with reported observation is demonstrated. The quantities compared between computation and observation are arc resistance as a function of current and arc diameter. The physics of the afterglow is not considered. This work has been done as part of the doctoral research of H. Vogel.

2. ADL Study of Superconductivity in the Electric Utility Industry. Arthur D. Little Inc. completed a LASL monitored contract on superconducting generators. A report entitled "Superconducting Generators: Current Technology and Future Benefits" has been issued in draft form. This was presented to DOE and industry representatives for comment. These comments have been integrated into a final document which was scheduled for publication in late 1979. The report is favorable and indicates an economic incentive for the development of superconducting alternators.

3. Helium Conservation and 700 W, 4.5 K Refrigerator. The helium liquefier was operated for a length of time sufficient to insure that the operating procedures did not contribute to turbine failure. An analysis of the economics of operation indicated that there was no justification for helium production under normal conditions and the helium conservation program was suspended. The steady production rate for the refrigerator was confirmed to be 256 l/hr.

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