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Tokamak Poloidal Field Systems

January 1—December 31, 1980

University of California

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ABSTRACT

Work is reported on the development of superconducting tokamak poloidal field system (TPFS) program. Progress is discussed on the design of the 20 MJ, 50 kA, 7.5 T superconducting pulsed energy storage coil to be operated in a bipolar mode from +7.5 T to -7.5 T in an energy transfer period of 1.5 to 5 s in 1982 followed by extensive cyclic testing. The facility to conduct the tests uses a traction motor energy transfer system and a nonconducting dewar. Status of the hardware development for the TPFS program is presented. Current interrupter development and testing for protection and energy transfer circuits are also presented. The 400 kJ METS coil test results are given.

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, 7.5 T superconducting pulsed energy storage coil operated in a 1 to 2 s bipolar mode from +7.5 T to -7.5 T by late 1982. Major accomplishments are briefly summarized here and certain specific accomplishments are listed even more briefly.

The 20 MJ superconducting coil design was completed with a successful design review. The contract for manufacturing the coil has been negotiated with Westinghouse Electric Corporation (W) and a subcontract, to be assigned to the Los Alamos National Laboratory (LA), has been set in place with Intermagnetics General Corporation (IGC) to make the 50 kA superconducting cable.

Prototype 50 kA superconducting cable was made by IGC. This was successfully tested at the Lawrence Livermore Laboratory and found to have a stability limit of 66 kA at 7.5 T. Loss measurements on the conductor meet design requirements.

Helium vapor cooled, 50 kA electrical leads to connect from the bus to the 20 MJ coil in the dewar have been designed.

A nonconducting, glass fiber reinforced epoxy dewar to hold the 20 MJ coil was designed for engineering specifications and an RFQ was issued. Bid responses are being evaluated.

A large effort was directed toward design of the energy transfer system to test the 20 MJ coil. Several circuit variations were considered and the performance of the traction motor array to act as an electromechanical capacitor was analyzed with the necessary switching elements in the circuit to predict transients.

Extensive testing of the traction motors has been undertaken to fix their pulsed performance limitations. Sixteen traction motors have been obtained. The method of mounting the traction motors has been devised, and the flywheels are

designed with the radius to be fixed by the exact number of motors finally chosen for the energy transfer system.

The control system for the 20 MJ coil test facility has been considered in detail, and the integrated operations of all major subsystems has been developed.

Technical assistance has been provided to the ETF Design Center and to the INTOR studies being conducted by the US. Computational efforts have been directed to study plasma startup and disruption in the presence of active and passive conducting structural components. For the Fusion Engineering Device (FED) resistive blip coils and magnetic field penetration were studied.

Specific accomplishments are as follows.

1. A power supply for the traction motors' field windings has been obtained and is being renovated. An additional supply will be needed if more than 16 traction motors are used.

2. The pulsed 50 kA bus to run from the traction motors to the main bus to the 20 MJ coil has been designed.

3. An RFQ has been issued for the main 50 kA circuit breaker and the switch elements to be used in the bypass switch assemblies.

4. A conceptual design and engineering cost study were completed for a wooden shed to house the 20 MJ coil.

5. The 3 MW, 100 kA/30 V, 50 kA/60 V power supply was installed. The 100 kA bus run into building SM 253 was also installed.

6. Some difficulties have been encountered with piston rod and shaft seal wear on the 700 W, 4.5 K helium refrigerator. An expanded gas recovery system is planned for installation in the refrigerator system. An RFQ has been issued to purchase vacuum jacketed transfer lines to run from the refrigerator cold box to the 20 MJ coil test area.

7. The LCP protective dump circuit for testing the CRNL 25 kA current interrupters in the LA 2 MJ switch test facility is nearly complete.

8. Vacuum interrupters with water cooled contacts designed by LA and made by W are to be tested to determine how much the steady state current can be enhanced.

9. A dissertation treating the theory of the arc discharge in air blast breakers was completed by Vogel.

10. A 7 T loss measurement apparatus to determine superconducting wire losses in a few second bipolar operation was completed.

11. The METS program was brought to a conclusion with both fast and slow mode energy transfers being run on the coil designed with mixed matrix conductor to operate up to 25 kA and 400 kJ of stored energy. The coil performance did not meet design specifications.

12. Analytical studies and experimental measurements indicate capacitive effects can generate high voltages for some transients.

13. A literature survey shows that data on electrical properties of irradiated dielectric materials in a radiation field in a cryogenic environment must be nonexistent.

B. 7.5 T, 20 MJ SUPERCONDUCTING TPFS COIL
1. 20 MJ Coil Design and Manufacture. A prototype energy storage coil is to be built and tested to demonstrate feasibility of using superconducting coils for induction of current in the plasma of tokamak fusion device. A 20 MJ coil to operate in a reversible manner from +7.5 T to -7.5 T in a bipolar energy transfer in 1 to 2 s was chosen as the smallest size that could be scaled to an intermediate size or large 1 to 2 GJ system. A current of 50 kA was chosen as the highest practical operating level for a pulsed superconducting coil and for the necessary attendant tokamak electrical power system. A design contract was issued to W for the superconducting coil and IGC was selected to make the 50 kA superconducting cable.

A final review of the design of the 20 MJ coil was held at the Westinghouse Research Laboratory in February. The design was accepted, and W was instructed to move into the manufacturing phase.

CTR-9 has begun detailed drawings which define the interfaces between the 20 MJ coil and the d'war, electrical lead, and refrigeration systems. Agreement has been reached on the locations of mounting pins and rings on the center post and bolt patterns for the electrical lead connections. W has been supplied with relevant drawings. The contract for manufacturing the coil has been negotiated with W with a subcontract for IGC to make the 50 kA superconducting cable. The IGC subcontract is to be assigned to LA to effect a substantial cost saving. The FY 81 schedule of work with the current level of funding will enable W to complete the verification tests and build all the coil assembly fixtures and will enable IGC to order the material, assemble 15 extrusion billets, and make the trial length of cable.

2. Prototype 50 kA Conductor Development. IGC completed fabrication of 1980 m of 0.204 cm diam prototype strand and the subsequent 7 m full scale prototype 50 kA cable shown in Fig. 1. Table I gives the parameters for the prototype strand of Fig. 2 and the 20 MJ coil strand design, which will have a lower loss. Table II gives the parameters for the prototype 50 kA cable. Energy loss measurements have been made on the prototype strand. Stability measurements were made on the strand, the first level subcable, and the full cable made with the prototype strand. Critical current measurements made on the prototype strand are given in Table III.

If self field is neglected, this measurement extrapolates to a full cable critical current at 7.5 T and 4.5 K of 70,000 A.

a. Energy Losses. Energy loss measurements were made on the prototype strand with various twist pitch lengths and etched configurations. The objective was to determine the distribution of

TABLE I
CONDUCTOR STRAND DESCRIPTION

	Prototype	20 MJ Coil
Metallic radius, r_s	1.020 mm (0.0402")	1.020 mm (0.0402")
With insulation, r_i	1.046 mm (0.0412")	1.046 mm (0.0412")
Core radius, r_c	0.664 mm (0.0261")	0.660 mm (0.0260")
Filament region, r_f	0.600 mm (0.0236")	0.600 mm (0.0236")
Fin thickness, t_f	0.066 mm (0.0026")	0.064 mm (0.0025")
Copper shell, Δr	0.098 mm (0.0038")	0.104 mm (0.0041")
Strand twist, L_s	8.1 mm (0.319")	7.72 mm (0.304")
Cu outer area	1.782 mm ² (54%)	1.825 mm ² (56%)
Cu core area	0.617 mm ² (19%)	0.633 mm ² (19%)
Cu total area	2.399 mm ² (73%)	2.458 mm ² (75%)
90 Cu-10 Ni area	0.356 mm ² (11%)	0.335 mm ² (10%)
Nb Ti area	0.514 mm ² (16%)	0.476 mm ² (15%)
Metal within r_s	3.269 mm ² (100%)	3.269 mm ² (100%)
Filament size, d	3.48 μ m	22.1 μ m
No. of filaments, N_f	540	1,356

Fig. 1. Prototype 50 kA cable.

Fig. 2. Prototype cable, individual wire strand cross section.

the losses as a function of the various components of the conductor and to verify the reduction in losses with reduced twist pitch length. To reduce the losses in the 20 MJ coil the twist pitch

length was reduced to four times the wire diameter. This pitch length produced no apparent degradation of the critical current or the electrical conduction in the stabilizer.

TABLE II
CABLE AND SUBCABLE DESCRIPTION

Overall Cable

Cable dimensions, cm	1.55 × 12.32
Number of subcables, N	36
Mandrel core material	Nitronic 40
Mandrel size with insulation, cm	0.229 × 10.21
Pitch length and sense, cm	65 (R. H.)

Subcable

Number of NbTi strands	6
Subcable diam, cm	0.635
Insulated core strand diam, cm	0.224
Pitch length and sense	4.95 (R.H.)
Core strand material	304 s. s.
Insulation	Polyester amide-imide (Omega ^a)
Core strand insulation thickness, cm	0.0025

^aWestinghouse trademark.

TABLE III
STRAND CRITICAL CURRENT

<u>Field, T</u>	<u>I_c, A</u>	<u>J_c, A/cm² (IG)⁵</u>
5	720	1.26
6	590	1.03
7	480	0.84

Measurements made on the basic strand, a strand etched to the copper nickel fins, and a strand etched to the copper nickel ring confirmed that the dominant dynamic loss was due to coupling currents within the core. The copper nickel ring effectively diminished the coupling current losses which occur in the outer copper sheath. The fins significantly reduced the eddy current losses in the outer copper sheath. Calculated losses were about 20% below measured losses. Extrapolation of the measured losses to the 20 MJ coil gives a predicted loss of 0.31% of the stored energy for a

1 s cosinusoidal bipolar swing from +7.5 T to -7.5 T.

b. Stability Measurements. Stability measurements to determine the cryostable limit of the conductor were made on the prototype strand, bare and insulated, a six around one subcable, and the full prototype cable. A significant enhancement in heat transfer occurred; and, consequently, recovery current for the insulated compared to the bare strand was higher. The respective heat transfer rates were approximately 0.5 W/cm² insulated and 0.3 W/cm² bare. Comparison of the results for the single strand and the six around one subcable shows a loss of about 40% of the available surface cooling area upon cabling. The single strand and subcable were measured in a totally open configuration.

The full 50 kA cable measurements were made in the Lawrence Livermore National Laboratory High Field Test Facility. The full cable was energized with the subcables connected in series in a

bifilar manner to avoid unwanted field contribution to the background coil. Several subcables were driven normal in the full cable stability test. Comparison of results for the isolated subcable and the subcable in a three turn configuration, shown in Fig. 3, indicated there was no degradation in the cryostable limit for the 50 kA cable. The results extrapolate to a recovery current of 66 kA at 7.5 T.

3. Tests to be Performed on the 20 MJ Coil to Simulate Tokamak Disruption and Startup Transients.

One question remaining from the 20 MJ coil design review was the possibility of using the ohmic heating central solenoid to create a plasma initiation pulse with about 250 V per turn. This capability for the coil had been abandoned over a year ago. Nevertheless, the question was raised again as a requirement. The ETF design center was contacted to resolve the question. The conclusion reached was that the plasma initiation is not a function for the ohmic heating coil set and that the designed 11 kV terminal to terminal insulation of the 20 MJ coil is adequate for all normal and fault mode operations.

Fig. 3. Three turn, 50 kA prototype cable coil.

Calculations of a plasma disruption and of various startup transients were done to estimate the effects on the ETF ohmic heating coil. Because there is uncertainty about how disruption time will scale from smaller tokamaks, disruption times of 1 ms and 25 ms were used. The 1 ms case is probably unrealistic because of the time constant of the discharge chamber and the stainless steel dewar wall. Although the ohmic heating coil is not now planned to be used for plasma initiation, such use was considered for the reason stated above. The intended method of plasma initiation is to use a separate set of coils close to the plasma. The effect of the plasma initiation coils on the ohmic heating coil was estimated for a normal plasma initiation and for a fault in which no plasma is formed. The values of current, field, and time rate of change of current calculated for the ETF ohmic heating coil can be simulated by tests on the 20 MJ coil. The required values of dB/dt on the 20 MJ coil can be produced by two switches and a resistor. One switch opens to insert the resistor into the circuit and the second closes to short out the resistor when the current has dropped the required amount.

C. 50 kA VAPOR COOLED CURRENT LEADS

Helium vapor cooled current leads were designed for the 20 MJ coil. These leads will carry a 50 kA continuous current from the ambient temperature bus to the superconducting coil at 4.5 K. They will vaporize liquid helium at the rate of 130 to 150 g/h with no current and will be operable without damage for about 15 minutes with full current and no helium vapor flow.

The leads are designed to withstand 15 kV for tests to simulate plasma disruptions. This necessitates a reasonably complex electrical insulation system and complicates the design of the mechanical restraints.

Each lead is built from a 5 in. nominal diameter copper pipe filled with roughly 1000, 1/4 in. diam copper refrigeration tubes. The gas flows through the bore of the refrigeration tubes which are soldered to each other and the pipe jacket at the ends. This section is 1 m long. The ends are finished with lugs to match coil and bus connections.

The leads are designed to avoid flashover along the insulation surface outside the dewar in air, flashover along the insulation surface inside the dewar in warm helium, and breakdown across warm helium inside the dewar. Each lead is wrapped with Mylar* film and surrounded by a G-10 CR glass fiber reinforced epoxy tube for electrical insulation. The top of the G-10 CR tube is finished in a G-10 plate and skirt, which act as a condensation collector and provide additional electrical insulation.

The leads are secured rigidly at the coil and braced against the magnet support post. They are sealed to the dewar lid by a flexible metal bellows and attached to the bus by flexible connections. Analysis indicates that they should successfully withstand 10^5 current cycles.

D. 20 MJ COIL NONCONDUCTING DEWAR

1. Dewar Design and Specifications. A nonconducting dewar to avoid magnetic coupling to the dewar and energy losses is to be used to test the 20 MJ coil. A preliminary design of the glass fiber reinforced plastic helium dewar for the 20 MJ coil was produced. This design served as the basis for subsequently issued specifications and preliminary facility designs.

The dewar consists of a double walled, vertical axis plastic vessel with super insulation in a high vacuum between the walls. The bottom end has ellipsoidal heads and the top has flanges and a flat bolted lid. The coil will be suspended from the lid, and the entire structure will be

supported on columns attached beneath the dewar flange. The height is 144 in. and the diameter at the lid is 91 in.

A request for quotation was issued, and three responses were received at costs which exceeded budget limitations. The first RFQ was canceled and the vessel design and specifications were modified to lower the cost. Responses to the revised RFQ have been received and are under review.

2. Use of a Metal Dewar with the 20 MJ Coil.

The energy losses in a large metal dewar for use with the 20 MJ coil and now at the Lawrence Laboratory were calculated. For a fast 1.4 s current reversal, the dewar losses in the inner vessel were two to three times the coil losses. Forces between the dewar and coil from radial misalignment of the axial position of the coil in the dewar were estimated. Because of the large losses and because the Livermore dewar is too small and would require extensive modification for use with the 20 MJ coil, a decision was made to delay active acquisition of the dewar until final quotations are received on the nonconducting dewar.

E. TPFS COIL TEST FACILITY

A facility is being devised to test the 20 MJ superconducting energy storage coil under realistic conditions to simulate operation in a tokamak fusion device. For ETF, the induction coil is discharged in about 6 s. Because a possibility still exists that neither radio frequency heating nor neutral beam injection will be adequate for heating the plasma, the 20 MJ coil is to be tested with a full bipolar energy transfer with field change from +7.5 T to -7.5 T in 1 to 2 s. In addition, fault mode operation has been considered. The most extreme condition for testing the coil is related to a plasma disruption that occurs just at the end of the full bipolar energy transfer. Tests will be conducted to simulate this condition to provide a rapid current change

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* duPont trademark

of about 5 kA in 20 to 30 ms with a 10 to 15 kV terminal to terminal coil voltage.

The test facility energy transfer circuit will use traction motors as electro mechanical capacitors to provide a resonant L-C circuit with the coil. Energy will be stored in the armatures of the motors, connected in parallel, and flywheels mounted on the armature shafts as needed. Traction motors were chosen for this purpose as economical pulsed energy storage devices and because of the flexibility in varying capacitance by changing the field current. Extensive studies of the circuit and all components to be used in the circuit have been undertaken. Tests of the traction motor performance are underway.

The test facility is shown in the artist's concept of Fig. 4. The picture shows the coil test area in a separate wood shed at the top of the figure with the nonconducting dewar to the left with busbar going to the dewar. The 20 MJ coil is to the right being assembled for testing. To the left, outside the long building, is the 3 MW, 50 kA power supply with connecting bus through the switching cabinet which depicts the entire complex switch and current interrupter functions. To the right is the array of traction motors with flywheels mounted. In the foreground is the refrigerator cold box and outside the building, the helium vapor surge tank dewar. These are connected to the dewar with cryogenic transfer lines. Not shown in the figure are the helium refrigerator compressor, gas recovery system, and gas storage tanks, all located in an adjoining building and outdoor area.

1. Circuit Design and Analysis. The TPFS circuit study focuses on the traction motors' interaction with the 20 MJ and a hypothetical 100 MJ superconducting coil during the oscillatory current reversal and on the switching problem posed by interrupting the main current. In the circuit chosen from several considered, the switching problem is the least significant. The superconducting coil's current is to be inter-

rupted to effect current transfer to the array of traction motors, which are initially essentially at rest. The second most important aspect of the study concerns the extrapolation of the traction motor performance from the conventional dc to the pulsed duty of interest. Consequently, the external parameters first used in the study were those measurements made by CTR-9 on the W model W362 motor in pulsed duty employing the 300 kJ, 10 kA superconducting coil of LA and the published continuous duty data of the three traction motor manufacturers. The motor characteristics are summarized in Table IV where the number in parallel is given by the maximum current, the number in series by the maximum voltage, and the energy transferred by the moment of inertia of the motor armatures and flywheels. Continuous variation of the transfer time is possible over the range 1 to 1.7 s by field control, whereas control in steps is achieved by the flywheel selection.

The optimum circuit for operation with the GE machines is shown in Fig. 5, with the sequence of operation indicated in Table V. Some voltages and currents typically occurring during the current reversal are plotted in Figs. 6 and 7, where the time scales in Fig. 6 are those of the initial part of the current reversal cycle. Figures 6 and 7 are based on LA measured characteristics of W traction motors. The pronounced voltage excursions in Fig. 6 are caused by the rate of current transfer and the armature inductance of the array of traction motors. The completion of the current transfer of Fig. 7 is for a traction motor field current of 100 A. The circuit breakers shown in Fig. 5 are air magnetic devices, because the current transfer should be no faster than indicated in Fig. 6. Hence, no capacitors are needed for counter pulsing, which would require 175 kJ at 2 kV. Most of the switching duty is performed by S1, intended to be an air breaker. Hence, only a minor counterpulse capacitor bank, not shown, is needed with S2, a vacuum breaker. The vacuum breaker in this combination offers the advantage

FIG. 4.
20-100 MJ TPFS
SUPERCONDUCTING
COIL TEST FACILITY

TABLE IV
TRACTION MOTOR CHARACTERISTICS

	Machine Type		
	GE ^a	EMD ^a	W ^a
Continuous current, kA	1.14	1.05	0.52
Starting current, kA	1.39	1.43	1.00
Total brush area, cm ²	65	48	51
Armature winding pattern	simplex lap	simplex lap	simplex wave
No. of poles	4	4	4
No. of parallel branches	4	4	2
No. of commutator segments	186	210	155
No. of series turns in each branch	46.5	52.5	78.5
Armature resistance, mΩ	10.0	12.3	19.4
Resistance per series turn, mΩ	0.215	0.234	0.247
Max. permissible pulse current, kA	3.4	3.2	3.0
No. of machines for 50 kA	16	16	18

^aGE = General Electric, EMD = General Motors Electromotive Division, W = Westinghouse

Fig. 5. TPFS coil test circuit.

TABLE V
SWITCHING SEQUENCE DURING OPERATION OF THE CIRCUIT IN FIG. 5

Time	Series Resistance	Operation	V_{max} , kV	I_{coil} , kA
	0.1 mΩ	close S1 - S2	0.040	0...50
0...3 ms	0.1...76 mΩ	open S1	1.8	50...38
6...7 ms	0.076...9.08 Ω	open S2	1.8	5...0

Fig. 6. Current, voltage, capacitance, and resistance as a function of time for the circuit of Fig. 5. Legend:

J1 = amperes through dc power supply and coil,
 J2 = amperes through coil and traction motors,
 $J = J_1 + J_2$,
 V = voltage across motor,
 C = farads of motors,
 RR = ohms of combined breakers,
 JCB = amperes through breakers.

Fig. 7. Current, voltage, capacitance, and resistance as a function of time for the circuit of Fig. 5. Legend same as for Fig. 6.

of providing the high voltage isolation needed when a high voltage test is performed on the superconducting coil at greater than a few kV. Not needed for the analytical study and not shown in the circuit is the 50 kA bypass switch in parallel with S2. Resistor, R_0 , would not be used if S2 is indeed a vacuum interrupter.

The study shows that not only parallel operation is stable in an array of traction motors, but series-parallel operation to obtain current reversal in a 100 MJ array is possible for obtaining a reversal time shorter than in parallel operation. This possibility can be considered because the region of asymptotically stable speed and acceleration was shown to exist within a boundary given by the armature tooth eddy current loss, armature Joule loss, and the field excitation. The equilibrium speeds are given by the ratio of armature resistances, field excitations, and brush friction of the machines in series.

The major uncertainty in analysis concerns the field penetration in the pulsed operation and the resulting interaction with the external field excitation. The magnetic fields of interest are the main field, commutating poles field, and armature field, the latter two being in quadrature with the main field. To satisfy commutation, the armature and commutating fields are desired to cancel approximately. Consequently, field penetration may affect commutation, hence, the region boundaries of permissible armature current and speed. Interaction between the pulsed fields and the external field circuit is a form of pulsed armature reaction and affects the equivalent capacitance of the machine.

The possibility of overspeed caused by the runaway condition created when the external field excitation is lost was considered in the study. Two discrete initial value sets were used to study the evolution of the armature's angular velocity in a defective machine with only remanent pole field. In Case 1, an initial armature current of 50 kA was assumed, with the armature at rest. In

Case 2, the armatures of 16 parallel connected machines were rotated initially at the maximum safe speed when the field of one machine was reduced to the remanent flux.

The set of equations consist of the differential equation of the external circuit with the defective machine, shown in Fig. 8, the emf of rotation in the defective machine with inclusion of the armature reaction and its saturation effect, and the energy balance equation in the defective machine including effects of the moment of inertia, brush and bearing loss, armature tooth current loss, and windage loss. For Case 1 the armature in the defective motor will accelerate to a speed well within the safe limit because of the losses. For Case 2 the speed of the defective machine decreases because the current and the associated losses increase to significant values.

A situation of concern arises when the pole flux is maintained while several of the parallel connected armatures become disconnected, the 20 MJ coil current of 50 kA then diverts to those armatures remaining connected to the coil. An interlock provision will be required to assure that all machines are connected into the circuit when the facility is used.

Fig. 8. Circuit of the defective machine.
 $R = 14.2 \text{ m}\Omega$, armature resistance
 $L = 2.25 \text{ mH}$, armature inductance
 $e = \text{emf of rotation}$
 $V = -L_{\text{coil}} di/dt$ in Case 1
 $V = \text{initial Voltage } V_0 \text{ reduced by the energy losses in Case 2}$
 $i = \text{armature current}$

2. Traction Motors for TPFS Power Supply.

a. Traction Motor Tests. Based on the system analysis, 16 type 752 GE traction motors were purchased for the 20 MJ TPFS coil pulsed power supply. The motors were tested upon receipt and three were found to be unsatisfactory. One had excessive bearing noise and two appeared to have excessive shaft runout of 0.005 in. These were sent to GE for repair, returned, checked and accepted.

A series of electrical and electromechanical tests were performed to confirm the analytical model used in the analysis and to determine operational limits not known by GE. In addition, a dialog was opened with GE to gain additional information the company has on the motors.

The open circuit saturation curve of one machine was measured and found to deviate considerably from the characteristic assumed in the preliminary analysis and to deviate slightly from a proprietary curve supplied by GE. Based on the measured curve, new values for machine capacitance were predicted. From these measurements the capacitances of 0.4 to 32 F may be obtained for a field current range of 50 to 1000 A for a single machine without flywheel.

A number of pulsed measurements were made to investigate the effects of armature reaction on capacitance and confirm values predicted from the experimental open circuit saturation curve for agreement with those observed during pulsed discharge. In this experiment the machines were spun up and discharged into salt water resistors. Capacitance values measured during the pulsed test exceeded the predicted saturation curve values by about 25%. The apparent increase in capacitance was the result of a decrease in field current during the test. This is the result of the armature current, by means of armature reaction, interacting with the regulated field power supply. On this basis, the saturation curve provides the best estimate of the capacitance if the field current is known. Further, there will be an inter-

action with the field supply that will make the field current difficult to determine.

Capacitance measurements indicate that armature reaction effects are much less in these machines than they were in the type W362 machines tested previously. The principal effects appear to be the result of current shift under the brushes. The decay time of the field current transient does not correspond to either the armature current decay time or the field time constant, as it should from classical theory.

Tests with the W362 machines and information from GE indicated the type 752 machines will not operate properly if the product of the armature current and rotational speed, $I\omega$, exceeds a value of 2×10^6 A-rpm. As originally designed, see Sec. E.1. above, the traction motor bank for the 20 MJ test facility would have operated at 3.1×10^6 A-rpm, which had a high probability for flashover of the machines. For this reason, one GE machine was operated at conditions which produced 2.65×10^6 A-rpm. Severe sparking was observed above 1.8×10^6 A-rpm but the machine did not flash. Tests will continue until a firm basis for determination of the number of machines for the system is established based upon a limiting value of $I\omega$. The most probable total number of machines is 24.

The armature inductance of one motor was measured at various frequencies with no current through the separately excited field winding. The armature inductance varied from 1.89 mH at 20 Hz to 1.129 mH at 1000 Hz. The armature inductance was also measured at 20 Hz with various field currents. The inductance varied from 1.89 mH at 100 A to 1.24 mH at 800 A.

The moment of inertia of one of the motors was measured. Knowledge of this parameter is required to design the flywheels. The motor was run at 1500 rpm for 5.5 hr before making any measurements. The armature voltage, V_a , and the armature current, I_a , were measured before interrupting the armature power. The speed versus

time during the deceleration was plotted on an X-Y plotter. The moment of inertia was calculated from the equation

$$J = (P/W) (dW/dt)^{-1}_{t=0}$$

where J = moment of inertia, kg-m²

P = armature power = $V_a I_a$, W

W = rotor speed, radians/s

dW/dt = rotor deceleration, radians/s²

The value of J varied from 23.30 to 28.48 kg-m². The design value of J is 23.26 kg-m².

b. Motor Mount. The traction motors will be mounted in pairs on steel A-frames supported on timbers. The frames will be bolted to the concrete floor. Two A-frames were fabricated, and a pair of motors was mounted. Two more A-frames with some modifications have been built. Mounting bolts, anchor bolts, and timbers have been received. A-frames are being fabricated for mounting the entire set of 16 motors already on hand.

c. Power Supply for Motor Field Winding. A surplus 50 V, 2 kA dc power supply is being renovated to supply power to the motor field windings. Because a number of power diodes were defective, all 12 are being replaced. A control chassis to operate the power supply has been built. The possibility of having to increase the number of traction motors in the bank to 24 or 26 not to exceed the I_w limit will require obtaining another power supply to excite the field windings.

d. Flywheels. Flywheels for the 20 MJ TPFS pulsed power supply have been designed with the exception of the specification of the outside diameter. The wheels will be made from 5 in. thick normalized 4140 steel. The wheels will be shrunk on the motor shafts with a radial shrink allowance of 0.001 in. This results in a maximum stress in the wheel of 13.3 ksi, and a left off speed of 4080 rpm, well in excess of the maximum allowable operating speed of the motors. If 24

motors and flywheels are used, the maximum steady torque rating of the motor shafts will not be exceeded during normal operation of the system. If 16 motors are used, this torque will be exceeded by a factor of two. For a coefficient of friction of one, the torque required to slip the flywheel on the shaft exceeds the rated shaft torque by a factor of six. The pull off force will be 1.80×10^5 lb under the same conditions. The loss of a flywheel, therefore, is not a credible fault.

A bore block gage was machined in a steel cylinder to test the accuracy of the drawings and specifications for the flywheel to armature shaft fit. Measurements with a transfer dye showed that a near 100% fit was achieved. The gage block will also be used to check the shrink and pumpoff procedures used to install and remove the flywheels. The diameter of the flywheels will be chosen when the number of motors is fixed.

3. Pulsed 50 kA Bus. Bus to connect 16 parallel connected traction motors to the 20 and 100 MJ coils during the discharge cycle was designed. Fifty kilo amperes of current were assumed to flow through the bus for 3 s during each discharge cycle for one discharge cycle per hour and eight such cycles per day. A bus consisting of two 0.5 in. x 9 in. type 1100 aluminum bars for each polarity was selected. The maximum temperature rise at the end of the eighth cycle will be about 71°C. The bus support and clamps have been designed; and several motor, bus layouts are under consideration including one for as many as 24 to 26 motors should the decision to expand the bank be made because of the I_w limitation.

4. Switches, Dump Resistors, and Steady State 50 kA Bus. Requests for quotations have been placed for the 50 kA circuit breakers and bypass switches for the test facility. Design of the 50 kA power supply reversing switch has been delayed. This is due to the shipment of a wrong switching element by Gould Brown Boveri. This element is to be modified by water cooling and then tested to

determine its current carrying capacity. A large number of these elements are necessary for the reversing switch. Preliminary design of the 20 MJ protective dump resistor has been completed. Preliminary design is underway on 50 kA flexible connections between the steady state 50 kA bus and the vapor cooled leads.

5. Shed to House 20 MJ Dewar. Preliminary design has been made of a wooden shed to house the 20 MJ coil dewar and to serve as an assembly area to mount the coil to the dewar lid. Wood is to be used to minimize magnetic coupling and force interactions. The shed, which is about 21 ft. wide, 37 ft. long, and 21 ft. high, will be located just south of building SM 253. One half of the building will hold the dewar and the other half will serve as an assembly area. The coil will be lifted into the assembly area and into the dewar with a crane through removable panels in the roof. Platforms will be erected as appropriate to give access to the dewar lid and coil during assembly and to the lid after the coil is installed in the dewar. An engineering cost study has been completed.

Presentations were made before the laboratory Facilities Planning Advisory Committee to request \$155,000 GPP funds for building. The request was denied for FY 81.

6. 3 MW Power Supply. A 100 kA/30 V, 50 kA/60 V dc power supply was purchased from Controlled Power Company. This supply was installed adjacent to SM 253 to provide power for switch testing and to charge the 20 MJ coil. A 100 kA busbar system was purchased from W. D. Whinery and installed with the full 100 kA connected into the 2 MJ switch test facility. This bus has stubs for a 50 kA connection to the 20 MJ coil.

7. 700 W, 4.5 K Helium Refrigerator. Last year a leak developed in a seal weld in a tank cluster holding impure helium. In normal operation of the refrigerator, gas contained in this cluster would be purified, sent to a cluster holding pure helium, and finally reliquefied. There are eight

tanks in a cluster and locating the defective seal required changing the tank manifold so that the tanks could be pressurized separately. Information was obtained from U. S. Steel documenting the tensile strength and results of Charpy impact tests at 40° F for the pressure vessel material. The results of these tests confirm the cause of the gas leak had to be a ductile failure. The leak is apparently in a seal weld on the plug in the tank neck. The bottom neck is inaccessible because the tanks are supported on a large steel plate with the neck protruding through holes in the plate. The LA Committee on Piping and Specialized Pressure Vessels approved a plan to repair the tanks. The new manifold has been installed, and the leaking tank can be valved out of the storage system.

A number of other changes to the liquid helium distribution system and helium gas recovery system will be required for the 20 MJ coil experiments. Some of these changes are installation of a 4500 cu ft gas bag in the pit under the cold box, installation of a 4 or 5 in. copper pipe from the gas bag to the 20 MJ experiment for recovery of warm helium gas, removal of the 1000 cu ft gas bag in the compressor building, installation of a 60 scfm Ingersoll Rand compressor, installation of a 1 in. i.d. vacuum insulated line to carry liquid helium to the 20 MJ coil, and installation of a 4 or 5 in. i.d. vacuum insulated line to return cold gas to the refrigerator surge tank. Installation of the new gas bag has been started, and specifications have been written and an RFQ issued for the vacuum jacket transfer lines.

The helium refrigerator was run for an hour after a 9 month shutdown but was turned off because of excessive leakage at the compressor rod seals. Inspection showed one 2 in. piston rod was badly corroded and a second had lost its chrome at several places. Water cups placed in the distance spaces to provide humidity for the seals are the source of the corrosion. Seals on the 1.5 in. rod

Fig. 9. Schematic of 20 MJ coil test system.

were changed only a few hundred hours ago and appeared to be badly worn. Inquiries have been initiated about the availability of graphite loaded Teflon seals to replace the graphite seals presently used.

The gas bearing turbines of the helium refrigerator have failed both at LA and other laboratories causing costly repairs and replacements. The refrigerator manufacturer held a users' workshop that identified the problem as possibly caused by unbalanced forces on the turbine shaft and by a leaking O-ring seal between the water cooling jacket and the helium gas passages. The unbalanced forces are thought to be caused by excessive dynamic load during rapid starting and stopping. Leak checks have been performed on the O-ring seals. One out of four LA turbines was found to leak. This turbine will be sent back for repair. The manufacturer plans to issue new operating instructions for starting and stopping that should relieve the unbalanced force problem. Regardless, the problem has not been fully resolved.

8. Controls and Instrumentation.

a. Introduction. Operation of the 20 MJ system involves the integration and control of various subsystems. A simplified schematic of the system is shown in Fig. 9. The subsystems are a

3 MW power supply, switches, traction motors, cryogenic equipment, data acquisition equipment, and the master control panel. The 3 MW dc power supply is used to charge or energize the 20 MJ superconducting storage coil to 50 kA. Bipolar operation of the coil is achieved by opening the charging switch to force the coil to oscillate with the traction motors, which act as capacitors. The reversing switches enable the dc power supply to charge the coil in either direction while the safety dump switch and resistor allow the system energy to be dissipated in about ten seconds. Each of these subsystems, except for the helium refrigerator, must be able to operate in a stand alone mode as well as by command from the master control panel. The safety dump resistor is shown in series but may be placed in parallel with the coil.

A block diagram of the control interface among the subsystems is shown in Fig. 10.

b. Master Control Panel. The operations required of the various subsystems during each coil test cycle are determined by the master control panel. To provide the proper event sequencing requires trigger delays ranging from milliseconds to seconds. Mechanical timers will be used to provide delays as short as 0.2 s while

Fig. 10. Block diagram of control interface among subsystems.

electronic digital delay generators will provide delays as short as 0.1 μ s. Independent triggering of the timers will allow the flexibility of control needed for various test configurations.

The master control panel will also include an interlock system to prevent or terminate testing if any subsystem or other interlocked device enters an alarm condition. Breaking the interlock chain or pushing the front panel SCRAM button results in a programmed shutdown of the coil test cycle by the master control panel. The interlock chassis and master controller chassis have been designed and will be built at LA. The digital delay generators are commercially available.

c. 3 MW Power Supply. The 3 MW dc power supply provides the power to charge the 20 MJ coil to 50 kA. A block diagram of the supply is shown in Fig. 11. Control of the power supply is accomplished by an existing remote control unit. The control interface requirements with this unit are shown in Table VI. After the power supply is energized and the manual controls adjusted, the output can be turned on and off by the master control panel. The alarm indicator is connected to one interlock channel while the voltage and current information is supplied to the data acquisition system.

d. Switches. Switches are key elements in the 20 MJ coil test circuit. The reversing switches connect the power supply to the coil during charging, short to protect the power supply from transients during the transfer period, and reverse to charge the coil in the opposite polarity. The charging switch interrupts the 50 kA current in the charging loop to initiate the transfer of energy from the coil to the traction motors. The safety protective dump switch opens to insert the dump resistor in the circuit to dissipate the system energy within 10 s under emergency condition. The operating sequence for the switches and the associated coil current waveforms during a bipolar test are shown in Fig. 12 and Table VII.

For life cycle testing, the coil would be cycled between 25 and 50 kA by turning the power supply on and off and not changing the switch positions. The scram sequence will be identical to the sequence for the bipolar tests with the traction motors remaining in the circuit. If the traction motors are removed, the safety dump switch in series with the protective dump resistor is placed in parallel across the coil, and the dump switch will remain open until triggered closed during the scram sequence.

e. Traction Motors. The GE traction motors will be connected with the armatures in parallel to serve as an electromechanical capacitor which can absorb the energy of the 20 MJ coil during a bipolar swing. A block diagram of the traction motor system is shown in Fig. 13. In the event the main supply fails, a battery powered backup supply may be used to provide the field current long enough to allow the coil energy to be dissipated in the safety dump resistor. Sixteen traction motors and a field supply have been procured while the design of the control chassis for the field supply is nearly complete. Additional traction motors and a supplemental field power supply may be needed as already indicated.

Fig. 11. Block diagram of 3 MW power supply.

TABLE VI
CONTROL INTERFACE REQUIREMENTS FOR 3 MW POWER SUPPLY

Control Function	FUNCTION	TYPE
START	Start cooling fans and module control electronics	PB switch
DC ON	Turns output power on	PB switch (DPDT)
STOP	Turns output power off	PB switch
EMERGENCY STOP	Trip main circuit breaker on all 6 modules	PB switch
<u>Status Functions</u>		
CONTROL POWER ON	Main control panel energized	Green light
SYSTEM ENERGIZED	Module fans and control power energized	Green light
ALARM ON	Fault detected by alarm circuit	Red light
DC VOLTS	Monitors output voltage, 0-100 V	Meter
DC KILOAMPS	Monitors output current, 0-100 kA	Meter
<u>Manual Controls</u>		
OUTPUT ADJUST	Adjust constant voltage (current) of output	Potentiometer
LIMIT ADJUST	Adjust peak current (voltage) of output	Potentiometer
TIMER SECONDS	Adjust period of timed output	Digital thumbwheels
TIMER BYPASS	Bypass timer for continuous output	Rotary switch
MASTER SELECTION CONTROL	Select master rectifier module	Rotary switch

Fig. 12. Coil current waveform and switch sequence during bipolar test.

TABLE VII
SWITCH AND POWER SUPPLY SEQUENCE DURING BIPOLAR TEST

Time	Event	SWITCHES				Power Supply
		Charging	Reversing	Safety Dump		
0	Ready	C	FWD	C		OFF
1	Charge (P.S. ON)	C	FWD	C		ON
2	Charge complete	C	FWD	C		ON
3	Turn P.S. OFF	C	FWD	C		OFF
4	Crowbar P.S.	C	SHORT	C		OFF
5	Transfer current	O	SHORT	C		OFF
6	Reverse P.S.	O	REV	C		OFF
7	Turn P.S. ON	O	REV	C		ON
8	Charge	C	REV	C		ON
9	Charge complete	C	REV	C		ON

SCRAM SEQUENCE (May occur anywhere in cycle)

	Initial conditions	?	?	C	?
A	Open safety dump	?	?	O	?
B	Turn P.S. OFF	?	?	O	OFF
C	Crowbar P.S.	?	SHORT	O	OFF
D	Dump energy	O	SHORT	O	OFF

f. Cryogenic Equipment. The cryogenic equipment for the test facility consists of the 700 W helium refrigerator and the dewar to hold the 20 MJ coil. A block diagram for the helium refrigerator is shown in Fig. 14. The refrigerator is operated manually and requires no control inputs from the coil test master control panel. However, the alarm panel of the refrigerator control station will be interlocked with the 20 MJ

controls so that any of the refrigerator alarm conditions can be used to scram the coil test sequence. These conditions are listed in Table VIII. Additional alarm conditions from the coil dewar and refrigerator will be added as required.

g. Data Acquisition System. Conditions in each of the subsystems to be monitored during tests of the 20 MJ coil will be recorded primarily

Fig. 13. Block diagram of traction motors.

with a PDP-11 computer and its associated data acquisition equipment. The computer will have the capability to monitor various conditions during a test, determine if they are normal, and scram the system if any fault has occurred. Conditions to be monitored and recorded by the data acquisition system are the test current and voltage of the coil, the coil losses, the internal coil voltages, coil quench detection, the traction motor speed and current in the armatures, and the alarm conditions in the various subsystems. The computer mainframe and some analog to digital conversion equipment are available and operating. The remaining A/D equipment and the required interfaces will be designed and procured after the subsystems are fully defined.

F. ENGINEERING TEST FACILITY (ETF) AND INTERNATIONAL TOKAMAK REACTOR (INTOR) CONTRIBUTION

1. ETF Study. Electric circuits for ETF during startup and plasma disruption were analyzed with active and passive conductors in some of the structural components of the ETF. The existence of a magnetic flux normal midplane and circular symmetry are assumed. The study examined the effects of insulating breaks in the ohmic heating coil dewar, vacuum shell, and armor. Because the passive conductors are 1 to 2.5 cm thick, which is thin when compared with the skin depth of 6.4 cm in stainless steel under a 20 ms plasma disruption, the eddy currents were computed by subdividing the passive conductors' long dimension

Fig. 14. Block diagram of helium refrigerator.

as shown in Fig. 15 and computing the resulting circulating currents.

The study was performed with two different distributions of the turns assumed within each of the coil sets ED, EO, IO, and OH. One of the turn distributions was suggested by the ETF Design Center for plasma startup from the internal coil sets IO and ID, the other one by LA for startup from the ohmic heating coil set.

The study* was compiled by J. Murray at the ETF Design Center, with additional contributions from G. Bronner, Princeton Plasma Physics Laboratory.

*J. G. Murray, G. Bronner, H. Vogel, "Electromagnetics in Structures of INTOR," USA Intor Report INTOR/ENG/80-11.

Fig. 15. Passive and active conductor configuration used for calculating the array of mutual inductances.

TABLE VIII

ALARM CONDITIONS FOR HELIUM REFRIGERATOR

Status Alarm Panel

Compressor oil failure
Flow failure first stage of north cyl. jacket
Flow failure first stage of south cyl. jacket
Flow failure first stage intercooler
Flow failure second stage cyl. jacket
Flow failure second stage intercooler
Flow failure third stage cyl. jacket
Flow failure third stage aftercooler
Flow failure Reavell compressor
Flow failure Joy compressor oil cooler
Flow failure Sulzer turbines
Flow failure Joy compressor
Pressure failure Joy compressor suction
Pressure failure Joy compressor discharge
Pressure failure air for instruments
Temperature failure first stage Joy compressor
Temperature failure second stage Joy compressor
Temperature failure third stage Joy compressor
Overspeed Sulzer turbine No. 1
Overspeed Sulzer turbine No. 2
Alarm on

a. Startup Energy. The total energy for the startup was found to be 3 to 4 MJ when supplied to the internal coils versus 180 to 400 MJ when supplied to the OH winding or a coil coupled closely to it. The latter number was obtained when a lossy blip coil was assumed to be coupled very closely with the OH winding.

b. Voltage Stresses. The voltage to be supplied for the startup was 60 to 70 V/turn to the internal coils versus 45 V/turn to the OH coil. In the former case, the voltage stress in the OH coil was 2 to 3 V/turn.

c. Current Change in the OH Coil. The current changed in the OH coil at the rate of 4.3 to 6.0 MA/s when the internal coils were used to supply the energy versus 7.7 MA/s when the OH winding or a coil very closely coupled to it was used. These numbers may be translated to 1.2 to 1.7 kA/s versus 2.2 kA/s in a 23 kA conductor or 2.7 to 3.7 kA/s versus 4.8 kA/s in a 50 kA conductor.

d. Effect of Breaks. When using the internal coils for supplying the startup energy, the effects of insulating breaks were calculated to be about 10% in magnitude. When using the OH coil, the startup energy was reduced by the presence of the breaks to less than 1/3 of its value without breaks.

e. Plasma Disruption. With no breaks and the internal and external coils shorted, the OH coil was stressed at 30 V/t and 65 MA/s for the assumed 20 ms disruption time, as shown in Figs. 16 and 17. These numbers correspond to

Fig. 16. Plasma disruption, external coils shorted, internal coils shorted, no breaks, voltage representation.

42 kA/s in the Los Alamos 50 kA, 20 MJ coil. If the external coils were considered to be short circuited and the internal coils nonexistent, then the corresponding numbers became 45 V/t, 80 MAT/s, and 50 kA/s. The voltage stress was approximately the same under the startup from the OH winding, a coil closely coupled to the OH winding, or for the 20 ms disruption. The 45 V/t stress, when integrated over the OH winding, amounted to 156 kV in the 23 kA winding or 72 kV in a corresponding 50 kA winding. The LA 20 MJ coil is being constructed in the form of 200, series connected turns, designed for an integrated stress of 11 kV. A high voltage test at 9 kV, that is, 45 V/t, is a possible addition to the test program.

2. FED/INTOR Study. A tokamak startup study is being completed, addressing some of the effects of insulating breaks in structural elements in the FED/INTOR baseline design. The study considers the design of resistive internal blip coils and magnetic field penetration. The emphasis is partly in response to Session IV of the INTOR Phase I workshop. Plasma startup considerations for ionization and plasma current initiation were found to favor strongly the use of an internal blip coil. The problem of field penetration with the need for conducting toroidal circuits for passive plasma control will require such coils. A credible configuration for normal conducting coils

Fig. 17. Plasma disruption, external coils shorted, internal coils shorted, no breaks, current representation.

in conjunction with the agreed common cryostat must be shown, following one of the workshop's recommendations.*

The calculations are approached similarly to those reported above. The 48 circuits of active and relatively thin passive conductors are shown in Fig. 18. The blip field penetration times are 90 to 50 ms and depend on the resistances of those passive components whose insulating break

resistance* is varied within a range judged to be reliable. The elements provided with the breaks are the inner wall, plasma shell, water pipe, breeder blanket, and outer shell. The total blip current is 4.8 MA and reduces to 3.4 MA for the greatest resistance.

G. TPFS SWITCH DEVELOPMENT AND HVDC SWITCH TESTS

1. LCP Dump Switch for ORNL. The Large Coil Project (LCP) requires an energy dump system to protect the superconducting LCP TF coils. Twenty five kilo ampere current interrupters to withstand 2.5 kV are being obtained by ORNL to divert the current into the dump resistors. These

*Sers. 2.1.2, 2.1.3 in T. E. Shannon, "ORNL Foreign Trip Report," ORNL/ENG/FTR-978, Nov. 14, 1980.

Fig. 18. FED/INTOR baseline design tokamak.

Legend:	1	startup plasma	25-26	TF dewar
	2, 3	bucking cylinder for the TF coils	27-30	breeder blanket
	4, 5	TF dewar	31-32	outer shell
	6, 7	spool	33	OH coil
	8, 9	inner wall	34	ED coil
	10-13	spool top, shell top	35-37	ED coils
	14-15	TF dewar	38-40	EC coils
	16-20	plasma shell	41-42	blip coils
	21-22	graphite	43-46	OH dewar
	23-24	water pipe	47-48	bucking cylinder

interrupters are to be tested by LA scheduled for January 15, 1981. The switches are comprised of a modified version of originally developed LA steady state bypass switch in parallel with a W type DMD dc circuit breaker. The hardware for the tests is being assembled in the 2 MJ switch test facility and is nearly complete.

2. Water Cooled Vacuum Interrupter. A 25 kA water cooled vacuum interrupter was designed by LA and built by W. Two versions were ordered, one with CuBi contacts and the other with CLR contacts. One of the interrupters has been delivered. A

special actuator to provide high interrupter contact pressure was designed and built. The actuator interrupter assembly is undergoing preliminary testing and will be fully tested at high currents in early 1981. The purpose of the development of water cooled contacts in vacuum interrupters is to increase their steady state current carrying capacity from a few kilo amperes to, hopefully, as much as 25 kA.

H. THEORY OF THE ARC DISCHARGE IN AIR BLAST BREAKERS

A study of the airblast breaker, noted for its large current interrupting capacity, was concluded by Vogel for his Ph.D. dissertation at the University of Texas at Austin. A closed set of differential equations for the arc discharge in airblast breakers was derived and compared with observation. The model is for the frequently used double jet configuration in which a cylindrical or conical arc develops during current interruption between the parting electrodes with the arc cooled by a jet of air expanding from a pressurized reservoir as shown in Fig. 19a. The arc's length increases with time and induces a voltage between the parting electrodes weakly defining the interaction between the arc and external circuit. The

Fig. 19. Contact configuration in airblast breakers.
a. Double jet configuration.
b. Double jet configuration, reduced for mathematical model.
c and d. Simple jet contacts.

circuit equations may be closed with an arc model that supplies the functions, derived from first principles, for the arc radius and length, the current density, and the axial voltage gradient. Several arc models, reported before, are heuristic formulations on the macroscopic level, or they do not represent closed sets of equations.

In the dissertation, a three component plasma is considered in the predominant species -- electrons, nitrogen atoms, and singly charged ions. The arc envelope, that is, the length and radius function is derived from the Euler-Lagrange equations in a Lorentz gas. A cylindrical arc envelope is predicted if the current density is radius independent. That condition is provided by MHD turbulence of the $m = 0$ mode caused by overcooling in the jet stream of the coolant gas. That same MHD turbulence can, in addition, explain the observed heat transport property within the arc by far exceeding the radial heat transport provided in other mechanisms such as radiation. Moreover, the characteristic time of the MHD turbulence is on the order of microseconds, consistent with the observed dynamic behavior of the arc, whereas the relaxation time is in a subnanosecond range.

Additional relationships for closure are provided by minima in the Helmholtz free energy. These yield the Saha equation at the quantum mechanical level and a temperature function of the arc radius, at the macroscopic external field, particle interaction level. The hydrodynamic equations were derived for the three component plasma by using the Enskog-Chapman formalism for evaluating the collision integral. The dissertation shows that all the conditions are satisfied for the Boltzmann equation to apply. The plasma is shown to be in thermodynamic equilibrium. A comparison of predictions with reported observation is shown in Fig. 20, where the opacity Γ is the external fitting parameter. The result is that $\Gamma \ll 1$, which is consistent with observation and indicates a degree of transparency that

Fig. 20. Computed and measured^a arc profiles versus the axial coordinate. The turbulent heat transfer coefficient, γ , is calculated from the measured pressure and cold gas velocity profiles; opacity, τ , is computed by fitting the temperature profile.

^aW. Hermann, U. Kogelschatz, K. Ragaller, E. Schade, "Investigation of a Cylindrical, Axially Blown High Pressure Arc," J. Phys. D: Appl. Phys. 7, 607,619 (1974).

excludes, as just mentioned, radiation as a mechanism to provide sufficient heat transport within the arc.

1. 7 TESLA LOSS MEASUREMENT APPARATUS

A 7 T loss measurement apparatus was built to measure losses in superconducting wire which is being considered for the 20 MJ coil. The facility contains a small solenoid coil whose magnetic field can swing from +7 T to -7 T in a time varying from 0.5 to 3 s. A pair of balanced pickup coils is inserted in the solenoid bore with

one of the coils containing the samples whose losses are being measured. The unbalance in the signal obtained from the coil can be related to the losses in the superconducting sample.

The entire circuit to drive and control current in the solenoid was completed. Traction motors are used as electromechanical capacitors to reverse the current in the solenoid. The motors can be run to a given speed before the current reversal by means of a rectifier and inductrol voltage regulator. Electrolytic resistors are used as dump and pulse shaping resistors. Circuit

breakers rated at 600 V dc and 1350 A are used for switching. A quench detector protects the coil while it is being charged by measuring the voltage at a center tap on the coil and comparing it with a resistive voltage divider connected across the coil. The control circuits and switchgear were first checked by using the facility to measure parameters of the traction motors.

The coil is wound with a Rutherford type conductor. This cable is manufactured from niobium-titanium alloy, copper stabilized wire with internal copper nickel barriers. The coil was wound with a specific conductor tension, predicted by analysis, to prevent separation of the coil layers during field reversal. The wire is uninsulated, so the turns and layers are separated by insulating spacers.

The solenoid dc performance was checked first and found to be excellent. The coil reached the design current of 1350 A in 100 A increments with only one quench at 1230 A. Current ramp rates for these tests were 10 to 20 A/s. Upon reaching maximum current for each test, the coil was discharged in 1 to 2 s either into the discharge resistor or the traction motors. Following these tests, the magnet was given a visual inspection. Some of the outside turns had slipped over the Teflon* interturn spacers as a result of axial Lorentz forces. No other damage was evident. The turns were moved to their original locations, and the number of outside braces was increased from 4 to 12 to prevent a recurrence of this problem. The complete system was then tested to evaluate coil and motor performance for a full bipolar swing. A typical trace of the magnet current versus time is shown in Fig. 21.

In Fig. 21 operation of many circuit elements shown in Fig. 22 can be detected from discontinuities in the current trace. A slow ramp charge to 1.1 kA is followed by a region of almost constant current. During this time, S_3 and S_4 are

Fig. 21. Current waveform from typical pulsed test of 7 T magnet.

open and all other switches are closed. The discharge cycle is initiated by opening S_1 and allowing the current to decay to a low value, in this instance about 80 A. During this time period, S_5 and S_6 are opened and the traction motors allowed to coast. When the current reaches a desired low value, switches S_3 and S_4 are closed, and the current is quickly brought to -1065 A. The recharge current waveform is a damped sinusoid, and the oscillations will continue until the energy is dissipated in R_1 and R_3 . In this experiment S_2 was opened before all of the energy was dissipated in the oscillatory circuit with a resistive decay at the end of the waveform.

A series of tests was run with increasing magnet currents to determine appropriate circuit parameters for full reversal. The maximum swing obtained so far was from 1280 A to -1220 A in 1.8 s, which corresponds to a maximum field of 6.6 T and an average field sweep rate of 7.2 T/s.

* duPont trademark

Fig. 22. Test circuit.

TABLE IX
PARAMETERS OF THE 400 KJ COIL

Inductance, mH	1.26
Design current, kA	25
Stored energy at design current, kJ	400
Winding length, cm	67.3
Mean radius, cm	27.9
Winding thickness, cm	10.3
Number of turns	64.75
Number of layers	3
Peak center line field at design current, T	2.31
Conductor support method	toothed form
Overall CuNi:C:NbTi	1:1.5:1
Strand diameter, mm	0.381
Filament diameter, μm	14.4
Filaments/strand	199
Wire twist pitch, cm^{-1}	3.15
Number of active wires in cable	504
Cable width, cm	2.48
Cable height, cm	1.91

J. ONE COMPONENT MODULE SUPERCONDUCTING PROTOTYPE METS SYSTEM

The fast pulsed superconducting inductive energy storage program was initiated to provide a system capable of delivering 488 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 one module or one component system was assembled. Table IX gives design parameters of the 400 kJ coil tested, and Fig. 23 shows the coil as it was being lowered into the dewar. Two sets of tests were performed. First, the coil was charged slowly and then discharged in 2 ms. Second, the coil was charged slowly and then discharged and recharged with opposite polarity in a few seconds.

The tests were delayed for a number of months, first because of problems with the epoxy fiberglass dewar used to test the coil and later by a shortage of liquid helium caused by a number of equipment failures at commercial producers. The dewar developed a leak at liquid nitrogen temperatures. Several attempts to repair it by applying epoxy resin to joints and a seal coat of resin to the inside of the dewar failed. Proper repair required wall scarfing and sequential multiple epoxy fiberglass cloth laminate applied to the inner shell over a thin inner tube joint originally used as a former to make the dewar. A seal coat of polyurethane was also applied over the wet layup. Three days were taken to cool the dewar to liquid nitrogen temperature to avoid thermal stresses.

Fig. 23. 400 kJ coil suspended above the dewar.

1. Fast Mode Test. Figure 24 shows the circuit used for the fast discharge tests. The circuit is basically an L-C-L resonant circuit in which current is transferred from the superconducting coil, L_p , to the load coil, L_L , and then crowbarred by ignitrons, I_{CB} . Hybrid switch, $O_1O_2V_1V_2$, served to disconnect the power supply and was made up of oil breakers, O_1O_2 , and vacuum breakers, V_1V_2 . Energy transfer was initiated by opening vacuum breakers, V_3 and V_4 , and then driving the current through these breakers to zero by discharging capacitor C. Components L_p and R_p are part of the apparatus for measuring losses in the superconducting coil. The maximum coil current achieved was about 19.5 kA, which is below the design operating current of 25 kA. No training effects were observed. Measurements of voltage drops at the joints between the coil and the leads

confirmed that the 19.5 kA current limitation was not due to heating at the joints, but was in the coil itself. Hysteresis losses associated with the maximum current attained were about 0.1% of the stored energy. Total losses should be twice that amount as scaled from short sample loss measurements.

2. Slow Mode Test. The slow discharge and recharge tests were performed by inserting a resistor into the circuit to discharge the coil and then recharging the coil with opposite polarity through a reversing switch to change power supply polarity. Air magnetic breakers were used to disconnect the power supply from the coil to initiate the discharge.

Data for the slow discharge and recharge tests have not been completely reduced. A cursory inspection shows that the total losses are very close to the hysteresis losses. Most of the data were taken for currents of 15 kA and below, although there are some data near 20 kA. Fastest time for discharge and recharge of the coil was about 7 s.

K. MISCELLANEOUS

1. Study of Oscillations in Coils. Resonant oscillations within a coil can be excited by externally applied transient voltages. These internal voltage oscillations may attain such high values under certain conditions that breakdown

Fig. 24. Circuit used for the fast discharge tests.

across part of the coil may be possible. An analytical study was performed to determine the severity of oscillations in a large energy storage coil. An experimental approach was also pursued on two 300 kJ superconducting coils at room temperature. One is a single layer coil, and the other is a four layer coil.

The resonant and antiresonant frequencies were determined with an rf vector impedance meter and a signal generator. For tests with the signal generator, a 10 Ω carbon resistor at the ground end of the coil was used to measure the current. The voltage and the current were observed on a dual beam cathode ray oscilloscope. A capacitive probe was used to measure the voltage distribution along the single layer coil.

Both coils exhibited internal oscillations. Table X compares the calculated values with those measured for the single layer coil. Calculations were made by neglecting the conductor resistance. For more accurate calculated values, the transient resistance of the conductor should be considered. The first harmonic for the single layer coil was measured at 0.577 MHz, and its peak amplitude was 11.76 times the input signal. The method of calculating the oscillations will be extended to the 20 MJ TPFS and 30 MJ SMES coils.

2. Radiation Effects on Dielectric Materials at Cryogenic Temperatures. Long term effects of radiation on dielectric materials at cryogenic temperatures are of concern to designers of superconducting coils for fusion applications. This is of particular concern for the poloidal field coil set under pulsed operating conditions and for the

toroidal field coils during emergency discharge when high voltages are developed. A literature search showed that data on electrical properties of irradiated dielectric materials in a radiation field in a cryogenic environment must be non-existent. Although some data are available at ambient temperature, extrapolation to cryogenic temperatures is not possible.

3. Capacitive Voltage Divider. The oil immersed resistive voltage dividers of the 900 kJ test facility were found to distort the recorded voltage across the opening breakers. Therefore, a 60 kV, 2000:1 voltage divider was built with a high voltage arm consisting of three 30 kV, 500 pF capacitors and two noninductive 10 k Ω resistors, all connected in series. The low voltage arm is a network consisting of three variable resistors, one 0.247 μ F capacitor and a variable capacitor. The step function rise time and the voltage divider ratio can be adjusted by the variable resistors and the variable capacitor. The rise time is less than 15 ns.

4. Power and Cooling Water Availability at LA. The CTR Division Office requested that CTR-9 determine the amount of electrical power and cooling water available at the laboratory to allow the division office to consider a proposal for location of the Fusion Engineering Device (FED) at LA. There are modest limitations on electrical power and severe limitations on cooling water. In addition, the maximum weight object ever shipped to LA is 125,000 lbs, and the maximum allowable as limited by roads and bridges is 200,000 lbs.

5. Applied Superconductivity Conference, September 29-October 2, 1980, Santa Fe, NM.

a. Conference Committee Members.

P. Thullen, Secretary
R. I. Schermer
J. J. Wollan

b. Papers Presented.

John D. Rogers, "Magnetic Energy Storage," invited paper.

TABLE X

300 kJ SINGLE LAYER COIL: RESONANT FREQUENCIES

Measured MHz	Calculated MHz	Deviation from Measured Values, %
0.577	0.530	- 8.15
0.970	1.134	+16.90
1.292	1.725	+33.50

M. S. Walker, J. G. Declercq, B. A. Zeitlin, J. D. Scudiero, and M. J. Ross, Intermagnetics General Corporation; M. A. Janock, S. K. Singh, E. Ibrahim, and P. W. Eckels, Westinghouse Electric Corporation; and J. D. Rogers and J. J. Wollan, LASL, "Superconductor Design and Loss Analysis for a 20 MJ Induction Heating Coil."

P. Thullen, D. Weldon, and J. Wollan, "A High-Field Bipolar Loss Measurement Apparatus."

S. K. Singh, E. A. Ibrahim, P. C. Gaberson, P. W. Eckels and A. J. Jarabak, Westinghouse; J. D. Rogers and P. Thullen, LASL; and M. S. Walker, Intermagnetics General Corporation, "Design of a Superconducting 20 MJ Induction Heating Coil."

J. J. Wollan, LASL; M. S. Walker, B. A. Zeitlin, D. A. Pollack, IGC; S. S. Shen, ORNL, "Evaluation of a Cryostable Low-Loss Conductor for Pulsed Field Applications."

W. M. Parsons, "Vacuum Switchgear for Fusion Experiments," 9th Int. Symp. on Discharges and Elec. Insulation in Vacuum, September 16-19, 1980, The Netherlands; Los Alamos Scientific Laboratory report, LA-UR-80-2072.

W. M. Parsons, LASL and R. J. Wood, ORNL, "Protection Circuits for Superconducting Magnets," 4th ANS Topical Mtg. on Tech. of Controlled Nuclear Fusion, King of Prussia, PA, Oct. 14-17, 1980; Los Alamos Scientific Laboratory report LA-UR-80-2884.

H. F. Vogel, "Design of a 28 MW Pulse Facility for Testing Superconducting Coils to Several Hundred Megajoule Capacity," 4th ANS Topical Mtg. on Tech. of Controlled Nuclear Fusion, King of Prussia, Oct. 14-17, 1980; Los Alamos Scientific Laboratory report LA-UR-80-2903.

J. G. Murray, G. Bronner, H. Vogel, "Electromagnetics in Structures of Inter," INTOR/ENG/80-13, (1980).

... Dissertation. H. F. Vogel, "Theory of Arc Discharge in Air Blast Breakers," dissertation for the Electrical Engineering Department of the University of Texas at Austin; Los Alamos Scientific Laboratory report LA-8488-1, August 1980.

... Other Papers. P. Chowdhuri, "Behavior of Thyristors under Transient Voltages," IEEE PES Winter Meeting in New York, February 3-8, 1980, Paper No. A80 114-9; IEEE Publication No. 80CH1523-0-PWR, 1980.

P. Chowdhuri and M. A. Mahaffy, "Wave Propagation in a dc Superconducting Cable Part I: Analysis," Paper No. of SM 617-1, and "Wave Propagation in a dc Superconducting Cable Part II: Parametric Effects," Paper No. 80 SM 618-9; Summer Meeting, Minneapolis, MN, July 13-18, 1980.

R. W. Warren, "Limits and Life of Vacuum Interrupters for Repeated Interruption of High DC Currents," IEEE Int. Conf. on Plasma Sci., May 19, 1980, Madison, WI; Los Alamos Scientific Laboratory report LA-UR-80-1009.

P. Chowdhuri, "Some Characteristics of Dielectric Materials at Cryogenic Temperatures for HVDC Systems," IEEE Trans. Elec. Insulation, presented for publication; Los Alamos Scientific Laboratory report LA-UR-80-1568.