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Tokamak Poloidal-Field Systems

January 1—December 31, 1981

Compiled by
John D. Rogers

Contributors

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ABSTRACT

Work on the superconducting tokamak poloidal field system (TPFS) program is being redirected. The development of the 20 MJ, 50 kA, 7.5 T superconducting programmed energy storage coil is being terminated. The superconductor for the 20 MJ coil is being processed only to an intermediate state, and manufacture of the epoxy fiberglass dewar is being stopped. Further, development of the TPFS test facility is in abeyance. Change in program emphasis arises from prospective rf plasma current driven or beam heated tokamaks with programmed coil characteristics for the poloidal field being different from those to have been simulated by the 20 MJ coil and from budgetary constraints. Work is reported on the development of the coil, conductor, nonconducting dewar, and test facility to the recent time when the program change was instigated. Work in support of the Large Coil Test Facility (LCTF) and the Fusion Engineering Design (FED) Center is given. Analysis of the experiments on the 400 kJ METS coil test was completed.

A. SUMMARY

The Tokamak Poloidal Field System (TPFS) goals have been to design, build, and test a scaled prototype superconducting energy storage coil and to develop testing facilities to demonstrate programmed operation of the coil for engineering feasibility in tokamak devices. A 20 MJ solenoid was chosen, because of early funding constraints, as the smallest meaningful size coil of practical application. The technology development for the solenoid is of direct applicability to both ohmic heating (OH) and equilibrium field (EF) coils for tokamaks. The high field, 7.5 T solenoid geometry was chosen with the guidance of the tokamak and magnetics community as being most relevant and of general usefulness. Subsequent to these guiding decisions, currents of a few hundred kiloamperes have been sustained in low density plasma in the PLT with rf heating in the absence of sustained OH inductive drives. The implication is that OH coils may not be needed in steady state tokamaks.

Because of the growing belief that steady state tokamaks with rf plasma current drives and/or beam heating will use superconducting EF coils and only copper OH coils, if indeed OH coils are needed at all, and because of funding limitations, work on the 20 MJ coil is being terminated. The superconducting strands intended for the 50 kA cable for the 20 MJ coil are being held in the manufacturing process at 0.090 in. diam without twisting. This permits the maximum possible variation in use of the wire in another coil, most likely a prototype EF coil. The design of the epoxy fiberglass dewar for the 20 MJ coil is nearly complete and the contract will be terminated at that point. Further work on the TPFS test facility is in abeyance until such time as the program redirection is established.

The work summarized and reported in detail should be considered in view of the fact that program directives to change emphasis are only very recent and the progress described relates to the goals stated at the beginning of this section. Also, because of the program change, this summary contains a status and accomplishment documentation and identifies costs for some components designed but not obtained, expenditures for the 20 MJ coil

and the 50 kA conductor, and values of some major TPFS test facility subsystems.

The TPFS program has been brought to a high level of technology. The following list presents the program status and accomplishments.

1. 20 MJ superconducting coil design complete. Manufacturing drawings 100% complete. Manufacturing contract in place with Westinghouse (W) being terminated.

2. Manufacturing plan 100% complete. Manufacturing process specifications 90% complete.

3. Verification tests 90% complete.

4. Coil winding tools and equipment obtained by Westinghouse and installed.

5. Contract in place with Intermagnetics General Corporation (IGC) to manufacture 50 kA superconducting cable being terminated.

6. Prototype 50 kA cable, 113 m (365 ft), completed by IGC.

7. Superconductor processing 75% complete and was on schedule for delivery of 50 kA cable by 4/82.

8. Contract in place for design and manufacture of epoxy fiberglass dewar being terminated. Dewar design being completed except for superinsulation specification and final material selection.

9. TPFS test facility and circuit defined in detail.

10. TPFS test facility components.

- a. Reversing switch designed and cost determined at \$60,000.

- b. 50 kA dc circuit breaker ordered from General Electric (GE).

- c. Bypass and isolation switches designed and 95% complete.

- d. Protective dump resistor designed and completed.

- e. Switch room bus bar detailed design complete and cost determined at \$40,000.

- f. Traction motors fully tested and characterized.

- g. Traction motor(s) (28) bank installed.

- h. 50 kA, pulse rated traction motor bus bar installed.

- i. Field winding power supply for traction motors installed and fully operable.

- j. 100 kA, 3 MW power supply installed and fully operable.
- k. 50 kA, vapor cooled leads designed and cost determined at \$85,000.
- l. Control hardware, commercial, 95% ordered and delivered.
- m. Control hardware, Los Alamos fabricated, 40% complete.
- n. 700 W, 4.5 K helium refrigerator installed and operated, upgrade 70% complete.
- o. Helium gas recovery system upgrade 70% complete.
- p. Helium transfer lines between refrigerator and test facility delivered.

Expenditures to date on the 20 MJ coil and the 50 kA conductor for the coil are

- 1. 20 MJ coil design; \$319,886.
- 2. 20 MJ coil verification tests and manufacture; \$453,308.
- 3. Superconductor for 50 kA cable; \$720,000.

Costs to have the 20 MJ coil and 50 kA cable completed are, respectively, \$1,231,000 and \$326,700.

Installed values of three of the major TPFS test facility subsystems are

- 1. 700 W, 4.5 K helium refrigerator; \$1,500,000.
- 2. 100 kA, 3 MW power supply and bus bar; \$800,000.
- 3. Traction motor bank; 50 kA, pulse rated bus bar; and field power supply; \$475,000.

Cost to complete the TPFS test facility is about \$400,000.

Progress and major accomplishments for the year are now summarized. Some of these are listed as accomplishments above but represent progress within the last year.

All interface details between the 20 MJ coil and the TPFS test facility were developed. We completed all manufacturing drawings and the manufacturing plan for the 20 MJ coil. Process specifications were nearly completed, and verification tests were 90% completed. The coil winding equipment was installed at W.

One hundred and thirteen meters (113 m) of prototype 50 kA cable was successfully made by IGC. Processing of the superconducting wire for the 50 kA cable is 70% complete.

Costs for the 50 kA vapor cooled leads were established and some lead support parts obtained.

Transient voltage effects from switching in the TPFS test facility for the 20 MJ coil were calculated for worst case conditions and found to be acceptable.

The TPFS test facility circuit was simplified and conceptual operational logic reduced to a definite control sequence permitting bipolar energy transfer and plasma disruption transient voltage simulation.

Traction motor characteristics were experimentally determined and the traction motor bank expanded from 16 to 28 motors, with 30 eventually required, to avoid flashover. The traction motor bank, its 50 kA, pulse rated bus, and the field power supply have all been installed. Design was completed for all of the TPFS test facility switches and the silicone oil immersed, 50 kA switches and the main 50 kA, air magnetic breaker are ordered. Costs for all switches and the steady state, 50 kA connecting bus were determined. Upgrading of the 700 W, 4.5 K helium refrigerator includes installation of improved piston rod seals, installation of a higher capacity gas recovery system, and correction of some as built by the manufacturer control logic defects. The main helium transfer lines from the refrigerator to the 20 MJ coil dewar were received.

The control system to operate the TPFS test facility was engineered and essentially all commercial control hardware was obtained. Considerable inhouse control hardware has been built and installed.

Calculations were performed in support of the Fusion Engineering Design (FED) Center and the International Tokamak Reactor (INTOR). Eddy current losses, induced voltages, and the effects of resistive joints and insulating sections in structures, dewars, plasma vacuum vessel, etc., were determined during plasma initiation.

The current bypass switch, crowbar switch, and d.c. interrupter for the Large Coil Test Facility (LCTF) were all successfully tested under simulated protective dump circuit operation.

The 7 T bipolar loss apparatus was operated in varying modes and the results analyzed to better interpret loss measurements made with the system.

An apparatus was built for making dielectric and surface tracking tests in a helium atmosphere. Some measurements have been made.

Measured losses in the 400 kJ coil were about twice those expected from calculations with details given in a Los Alamos National Laboratory (LA) report.

B. 7.5 T, 20 MJ SUPERCONDUCTING TPFS COIL

1. 20 MJ Coil Design and Manufacture. The scaled prototype energy storage coil to have been built and tested to demonstrate feasibility of energy storage in superconducting coils, to demonstrate programmed energy transfer out of and into such coils for induction of current in the plasmas of tokamak fusion devices, and for establishing a magnetic field to hold the plasmas in place, was designed to operate at maximum field of 7.5 T with a 50 kA current. The early selection of a possible bipolar mode of operation of the 20 MJ coil from + 7.5 T to - 7.5 T in 1 to 2 s was specified after consultation with and guidance from the tokamak and fusion magnetics community as being most relevant and of general usefulness. Even with the very early evolution of tokamak concepts requiring extended energy transfer periods of 6 to 15 s and re-evaluation of the relevance of the 20 MJ coil and the method of testing, guidance from the Engineering Test Facility design team and its advisory committee was to continue with the prototype coil as planned. On this basis contractual commitments were made to have the coil manufactured by W and to have IGC manufacture the 50 kA superconducting cable. The coil and conductor designs were continually monitored and found to retain a high level of meaningful technology development for both OH and EF coils of the evolving Fusion Engineering Device (FED) and steady state STARFIRE tokamak concepts. Energy transfer times as long as 15 s for testing the 20 MJ coil were incorporated into the design of the TPFS test facility with maximum flexibility of meeting possible FED requirements ranging from plasma disruption effects through programmed energy transfer.

All interface details between the 20 MJ coil and the refrigerator, dewar, 50 kA vapor cooled leads, and coil support tube were developed by LA and provided to W. The subcontract held by W to

have IGC manufacture the 50 kA superconducting cable was assigned to LA to reduce overhead costs. W completed all manufacturing drawings and the manufacturing plan for the 20 MJ coil. Process specifications were nearly completed, and verification tests were 90% completed. Coil assembly fixtures and winding tools and equipment were obtained by W and the winding train was completely installed. Some materials were ordered by W to start machining of coil structural parts. Work on the 20 MJ coil at W has been terminated and contract cancellation is in process in keeping with the DOE OFE program directive to stop work on the 20 MJ coil. All deliverable items are being inventoried for W to send to LA.

2. 50 kA Superconducting Cable. The IGC contract, assigned by W to LA, for the 50 kA superconducting cable requires delivery of 61 m of copper wire, prototype cable and 740 m of final 50 kA superconducting cable. One hundred and thirteen meters (113 m) of prototype cable, to have been used by W for trial winding and for measurement to determine any final manufacturing drawing changes, was successfully fabricated by IGC. The final cabling of 36 subcables made by IGC on an insulated austenitic steel strap was done on a cabling machine at Okonite Wire and Cable Co., Patterson, NJ.

The goals of the prototype cable program and the outcome were as follows.

a. To evaluate reverse twist direction between subcables and final cable. This produced a superior cable as compared to a shorter length of prototype cable with the same twist direction made earlier.

b. To establish the mandrel taping operation. This operation was successful.

c. To establish the cable overwrap taping operation. The overwrap protects the cable for shipping. Several correctable problems existed, but the basic operation was successful.

d. To determine the proper positioning for the tooling. The forming operation was successful. Occasional subcable crossovers occurred. Improvements were decided to assure the complete elimination of crossovers.

e. To evaluate various pitch angles and compactions. A 23.0° angle gave the best cable lay. Compaction was sufficient to form the cable and not damage the mandrel insulation.

f. To verify operational arrangement, procedures, and cleanliness. A number of needed improvements were identified.

The fabrication of the superconducting strand for the final cable is in process. Some minor fabrication problems were resolved with delays sufficient that the wire at the twisted final diameter would have been completed late in January 1982. IGC has tested several and LA one sample of superconducting strand. All samples exceeded the specified critical current of 418 A at 7.5 T. Many minor changes to the specification were made. These changes included adding material for a sixteenth billet for reserve stock, changing the subcable core strand from stainless steel to copper-nickel alloy, and changing the mandrel insulation material.

In keeping with the DOE OFE program directive to stop work on the 20 MJ coil, IGC has been directed to process all conductor to 0.090 in. diam without twisting the wire. Wire in this state and the cabling tools are to be stored or shipped to LA. One billet of conductor had already been processed to the final twisted 0.080 in. (2.040 mm) diam.

C. 50 kA VAPOR COOLED CURRENT LEADS

Helium vapor cooled leads had been designed for the 20 MJ coil. These leads were intended to carry 50 kA continuous current from the ambient temperature bus to the superconducting coil at 4.5 K and to be operable for about 15 min with full current and no helium vapor flow. The leads were designed to withstand 15 kV for tests to simulate plasma disruption. Lead braces to the 20 MJ coil center support tube were built to withstand the Lorentz force arising from the coil fringe field and the 50 kA current. Techniques were developed for soldering the over 1000, 1/8 in. diam phosphorus deoxidized tubes in the lead sleeve housing. Costs to make the leads were obtained but fabrication has been held in abeyance.

D. 20 MJ COIL NONCONDUCTING DEWAR

Quotations received at the end of 1980 for manufacture of the glass fiber reinforced epoxy plastic dewar for the 20 MJ coil were evaluated and an order was placed with Swedlow, Inc. to have the dewar manufactured. The contract required Swedlow to design the dewar based on plastics engineering experience and technology for LA approval prior to manufacture. The design is 90% complete and some materials screening tests were conducted. Because of program redirection, the contract is to be terminated at the end of the design phase. The superinsulation specification and final material selection will not be made.

The possible availability of a Lawrence Livermore National Laboratory metal dewar had been considered for use to test the 20 MJ coil, but the idea was discarded because of coupling losses to the dewar and because the dewar was too short. Because of the high expense associated with the glass fiber reinforced epoxy dewar, methods of measuring coil losses in the presence of high background coupling losses to a metal dewar of a factor of two to four times those for the coil were re-examined. Coil loss measurements can be made by measuring gas evolution and would permit use of a metal dewar. To reduce costs, metal dewar specifications were devised and an RFQ issued, although program redirection now negates the intent to purchase the metal dewar.

E. TRANSIENT VOLTAGE EFFECTS FOR 20 MJ COIL

The sources of transient voltages are most likely faults and switching. Transient voltages generated by switching within the test system are of particular significance for reliable operation. Because the analysis of transient voltages in superconducting coils seems heretofore to have been neglected, a rather extensive presentation is given here.

The dielectric components of a coil can be electrically stressed in two ways if a transient voltage is impressed across its terminals. First, the voltage distribution along the coil would be highly nonlinear if the transient voltage has a steep front and would concentrate the electrical stresses at the end turns, causing a dielectric failure between adjacent turns at these locations.

Second, the coil may resonate at one of its space harmonics if the applied transient voltage contains such a frequency component. Under this condition, an internal point of the coil may attain a voltage peak much higher than the applied voltage, and dielectric failure between parts of the coil may occur.

For transient analysis, a coil cannot be simply represented by its self inductance. The mutual inductances between parts of the coil, the capacitances between turns and between coil sections, and the capacitances between various parts of the coil to ground and return circuit must also be considered. Figure 1 shows the schematic representation of an N-section coil.

For transient analysis of a coil, a step function voltage is applied across the coil terminals. The solution for any other type of applied voltage can be obtained by the application of Duhamel's theorem. When a step function voltage is applied across a coil, it is initially represented as a capacitive network, the inductances giving infinite impedances.

This initial voltage distribution is nonuniform, being higher at the high voltage end. The nonuniformity of the initial voltage distribution is augmented by the capacitances of the coil elements to ground. The transition from the initial nonuniform voltage distribution to the final uniform distribution takes place through intermediate voltage oscillations. The initial voltage distribution along a uniform single layer coil under a unit step function voltage is given by

Fig. 1. Schematic representation of a coil as a lumped circuit.

$$V = \sinh \{ \alpha (1 - x/l) \} / \sinh \alpha, \quad (1)$$

where V = voltage to ground of a coil element at an axial distance x from the high voltage end,

l = length of a coil,

$$\alpha = l \sqrt{c_g/c_s},$$

c_s = series capacitance per unit length, and

c_g = ground capacitance per unit length.

The final uniform voltage distribution is a straight line drawn from unity on the voltage ordinate to $x/l=1$ on the axial distance of the coil. The intermediate oscillations may be assumed to oscillate around the final voltage distribution as the axis and with an amplitude equal to the difference between the final and initial voltage distributions. Therefore, the envelope of the maximum voltages along the coil can be drawn by adding the difference between the final and initial voltage distributions at each point along the coil to the final voltage distribution.

The schematic of a double disk or pancake coil is shown in Fig. 2. The entire coil is made of pancake shaped coils, each pancake being wound in a flat spiral. In a simple double pancake coil, the innermost turn of one pancake is connected to the innermost turn of the next pancake. In a pancake coil, subdivided into pairs of such double pancakes, the pairs are connected at the outermost turns. The simple standing wave theory cannot be

Fig. 2. A multiple pancake coil.

applied when the winding structure is as complex as the multiple pancake coil assembly.

The initial voltage distribution was determined in two steps. First, the major voltage distribution from each pancake to ground was determined from the total ground and series capacitances of the entire coil. Thus, the voltage across the first pancake at the high voltage end was determined. Second, by knowing the voltage across the first pancake, the voltage across the high voltage end turns was determined from the turn to turn and pancake to pancake capacitances.

The initial voltage of each pancake to ground was determined from Eq. 1. The voltage across the first two pancakes at the high voltage end, as per unit of the voltage across coil, is given by

$$V_1 = 1 - \exp(-2\beta) - (2 \sinh 2\beta) / [1 - \exp(2\alpha)], \quad (2)$$

where $\alpha = \sqrt{C_g/C_s}$,

$$\beta = \alpha/N_p,$$

C_g = total ground capacitances of coil,

C_s = total series capacitance of coil, and

N_p = number of pancakes.

Similarly, the initial voltage between the first two turns of a pancake, as per unit of the pancake voltage, is given by

$$v_1 = \gamma \cosh(\gamma/2n) / n \sinh \gamma, \quad (3)$$

where $\gamma = \sqrt{2C_p/C_t}$,

C_p = total capacitance between pancakes,

C_t = total capacitance between turns in a pancake, and

$n+1$ = total number of turns in a pancake.

The natural frequencies of a multiple pancake coil can be determined by considering the coil as a lumped network as shown in Fig. 1. Once the coil has been divided into an N-section ladder network, a convenient way of solving the network is by the state variable method. Thus,

$$dX/dt = AX + BV, \quad (4)$$

$$U = SX + DV, \quad (5)$$

where $X(t)$ = state vector,

$U(t)$ = output vector of node voltages,

$V(t)$ = applied voltage, and

A, B, D , and S = matrices of constant coefficients.

The eigenvalues of the matrix, A , are the natural frequencies of the coil. This analysis has the advantage that the output voltage at each node of the network can also be obtained for any type of applied voltage.

The various capacitances, such as turn to turn, pancake to pancake, coil to return lead, and coil to metallic dewar of the 20 MJ TPFS coil, were calculated. Cylindrical symmetry or parallel plate configuration were assumed. The different dielectric constants were included for the various materials used for the coil structure.

The total series capacitance, C_s , of the coil had to be determined to evaluate Eqs. 2 to 5. The total series capacitance of a pancake coil includes the turn to turn capacitance in each pancake and the capacitance between the pancakes. As existing analyses were not suitable, the following equation was derived.

$$C_s = 2C_e C'_e / [4C_e + (N_p - 2) C'_e], \quad (6)$$

where $C_e, C'_e = c_p [1 + (\coth(n+1)\theta) (\coth(\theta/2))]$,

$$\theta = \cosh^{-1}(1 + k/c_t),$$

$$k = 2 c_p \text{ for } C_e,$$

$$k = c_p \text{ for } C'_e,$$

c_p = capacitance between two corresponding turns on neighboring pancakes, and

c_t = capacitance between two neighboring turns within a pancake.

Figures 3 and 4 show the calculated initial values of voltages along the 20 MJ coil with unit step function excitation for both metal and nonconducting dewars. These figures also show the

Fig. 3. Step response of 20 MJ coil with metal dewar.
solid line = initial voltage distribution
dotted line = final voltage distribution
dashed line = envelope of oscillations.

Fig. 4. Step response of 20 MJ coil with nonconducting dewar.
solid line = initial voltage distribution
dotted line = final voltage distribution
dashed line = envelope of oscillations.

envelopes of possible maximum voltage oscillations along the 20 MJ coil. Table I shows the calculated values of the first two space harmonics of the 20 MJ coil.

The difference between the metal and nonconducting dewars is clearly shown in Figs. 1 and 2 and Table I. The nonuniformity of the initial voltage distribution is augmented by the capacitances of the coil elements to the walls of the metal dewar. Although the degree of nonlinear voltage distribution for the insulating dewar is less, the danger of overvoltages caused by resonances still remains. The only difference in this case will be a shift in the resonant frequencies. In a metal dewar, the amplitudes of voltage oscillations would be damped to some extent by eddy currents induced in the dewar walls.

Although the effects of the coil resistance were neglected, the importance of the damping caused by this resistance is emphasized.

TABLE I

CALCULATED RESONANT FREQUENCIES OF 20 MJ COIL

	First Harmonic kHz	Second Harmonic kHz
Nonconducting Dewar	97.1	131.2
Metal Dewar	85.6	127.5

Hysteresis losses in the superconductor and eddy current losses in the cryostabilizer will cause much needed damping. The possibility of damping by proper design of the cryostabilizer should be explored.

F. TPFS COIL TEST FACILITY

A facility had been under development for two years to test the 20 MJ superconducting coil under realistic conditions to simulate operation in a tokamak fusion device. The test facility was to be capable of energy transfer in times from ~ 1.5 to 15 s and to simulate high voltage transients of 10 to 15 kV, which might result from plasma disruptions. The test facility energy transfer circuit is designed to use traction motors as electromechanical capacitors to provide a resonant L-C circuit with the coil. Energy would store in the armatures of the motors, connected in parallel, as needed. Traction motors were chosen for this purpose because of the flexibility to vary capacitance by changing the field current and their low cost as programmed energy storage devices. Despite the results of thorough analysis and performance tests on the motors with the requisite number of motors increasing from 16 to 30 to avoid flashover, the economic advantage remains quite high. All 50 kA current interrupters, switches, and bus for the test facility were designed, some were ordered, and cost quotations were received on all items not already placed on order.

1. Circuit Design and Analyses. The evolution of the FED tokamak design and the improved versions of 50 kA bypass switches caused some TPFS test facility circuit changes and simplifications from the conceptual version reported for the previous year. The circuit, as finally designed and for which switch and bus quotations were obtained and some components ordered, is shown in Fig. 5. Switch and breaker operations reference this figure to provide the energy transfer profile of Fig. 6, which shows a coil charge and bipolar energy transfer with a superimposed fast current change between t_6 and t_7 to impose a high voltage across the 20 MJ coil to simulate a plasma disruption.

The initial condition is with S1--a 50 kA steady state, silicone oil immersed, water cooled bypass switch--closed; S2--a 50 kA, pulse operated

Fig. 5. TPFS test circuit.

Fig. 6. Energy transfer with plasma disruption.

silicone oil immersed isolation switch--closed; S3--a 50 kA, pulse operated, magnetic breaker--closed; S4--a 50 kA, pulse operated, silicone oil immersed isolation switch--opened; S5--a 50 kA, pulse operated, silicone oil immersed bypass switch--closed; VI--a 50 kA, pulse operated vacuum interrupter--opened; S6--a pulse operated make switch--opened; and RS--a no load, steady state, reversing switch--closed. The traction motor set, TM, is hard connected across the superconducting coil, SC. SH1, 2, and 3 are current shunts. R1 is an 18 m Ω protective dump resistor used when the traction motors are not in the circuit. The coil is otherwise protected by dumping the energy into the traction motors, which will go through a few damped oscillations. R2 is the plasma disruption,

0.2 to 0.3 Ω blip resistor. SR is a saturable reactor, and C is a counter pulse capacitor.

Operation for an energy transfer without plasma disruption simulation omits operations at t_5 , t_6 , and t_7 and is started by turning on the power supply until time t_1 , see Fig. 6. At time t_2 , S1 is opened; at t_3 , after all the current transfers into the S2-S3 leg, S3 opens; and at t_4 , S2 opens. The resonant energy transfer starts. RS can be placed in a crowbar position to short the power supply before the switching sequence is started and is reversed between t_4 and t_8 . At t_8 , switches S1, S3, and S2 are closed in sequence. The reversed polarity power supply then recharges the coil from about 43 to 50 kA, and the cycle can be repeated.

For plasma disruption simulation, the initial conditions and switching sequence are the same through t_4 . At time t_5 , VI closes. At time t_6 , S5 opens; then, after the current is transferred into the VI leg, VI opens and S6 is closed to counterpulse the 50 kA in VI to zero. SR comes out of saturation to hold the current through VI at zero with low dV/dt to allow for deionization in VI to open the circuit. The fast discharge, $L/R = 80$ ms time constant, occurs for 3 to 5 ms when VI and S5 are closed at t_7 to complete simulation of the plasma disruption. The balance of the operation follows the normal energy transfer. The plasma disruption simulation can be introduced at any time during the cycle.

Figure 7 shows the cyclic testing operation, which is accomplished merely by turning on and off the charging power supply. Cyclic testing in this

Fig. 7. Cyclic fatigue energy transfer.

manner does not require operation of the many switches for 100,000 cycles, and the time required to cycle to half current and one fourth energy is characteristic of the test system and coil time constants and is limited by the refrigerator capacity to accommodate the heat loads and coil energy losses. Cyclic testing would be checked at regular intervals with full bipolar energy transfers.

Detailed hardware design of the entire bus and switch array of Fig. 5 is complete and all component costs are firmly established.

Fault mode analysis of the circuit was extended. The perturbation of the traction motors with the potentially most damaging consequences is an external armature line to line flashover. This kind of flashover is also very unlikely to occur because the machines are designed to have internal flashover protection. When the motor speed is near its peak value and because the rate of current change is limited by the armature inductance, the current reaches a maximum of 1 to 2 kA per machine within 20 ms. Although this current is well within the machine capacity, the resulting product of current and angular velocity, $I\omega$, theoretically may become 2 MA/s (20 MA-rpm), which exceeds the commutator flashover limit by a factor of about eight. Thus, internal flashover will occur before this value is reached and the effect will be diminished.

Insertion of a resistor between the 20 MJ coil and the traction motor bank is proposed for obtaining ~ 10 kV test voltage on the coil. The 0.2 to 0.3 Ω resistance, R_2 of Fig. 5, needed for this test is inserted when a bypass breaker is opened. The coil voltage attains -5 kV during the switching operation and then reverses to reach its intended ~ 10 kV value. No unusual voltage pulses are expected.

2. Traction Motors for TPFS Power Supply.

a. Traction Motor Tests. A review of the design of the 20 MJ TPFS test facility electromechanical capacitor was begun following the observation of commutator flashing in a similar installation in the laboratory. A review of the literature and discussions with O. C. Coho of GE confirmed that flashing of the machines would take place if a specific value of the product of terminal current and rotational speed, $I\omega$, were

exceeded. Coho indicated that the critical value of $I\omega$ for GE-752 machines is above 2 MA-rpm and that the machines should not be operated above this level. The original design would have operated the machines at 3.1 MA-rpm and would have resulted in a commutator flash. On this basis the design of the system was reassessed by tests and analysis. The rotor moment of inertia of each motor was determined by measuring the time period of oscillation when the rotor was attached to a pendulum. Although the inertia variation among rotors was within $\pm 1\%$, the calculated moment of inertia was significantly higher, about 11%, than the design value, 23.56 kg-m², given by GE. The armature inductance of each motor with a field current of 800 A was measured to check the variation of armature inductance from motor to motor.

Careful measurements of the open circuit characteristics of the motors were used to determine that field trimming resistors cannot be used to match the capacitances of the 28 machines. The maximum deviation of the open circuit curves among the machines is $\pm 4.5\%$, which was considered for further analysis.

Each motor was tested to determine if it would commute successfully at an $I\omega$ of roughly 2.8 MA-rpm. The tests were performed by discharging a spinning motor into a resistor. Each motor was tested in steps to 2.8 MA-rpm with both clockwise and counterclockwise rotation. Of 57 tests performed, seven resulted in a commutator flash. The lowest flash value was 2.28 MA-rpm.

Peak values of voltage, speed, and current were held near 1182 V, 1538 rpm, and 1179 A, respectively, which represent the rms values anticipated in the 20 MJ coil test circuit. In that resonant L-C circuit, the current and speed are 90° out of phase; and the peak value of $I\omega$ occurs when I and ω reach their rms values.

The highest $I\omega$ value reached in each test is plotted on Fig. 8. Dots represent successful tests and crosses represent tests in which a flashover occurred. Observed values of $I\omega$ are plotted as a function of the terminal voltage, speed, and reciprocal resistance product at the time of maximum $I\omega$. Test points should lie on a 45° straight line and for the most part are clustered about such a line. When a motor flashes, current

Fig. 8. Maximum values of $I\omega$ achieved during tests of 28, GE-752-E8 traction motors.

may not all flow through the meter shunt, and the horizontal axis becomes a more reasonable estimate of $I\omega$.

With the coil characteristics, motor characteristics, and circuit configuration established, the only remaining free parameter is the number of motors. Table II lists equations which relate the number of motors and coil characteristics to the motor operating parameters which should not exceed

TABLE II
PARAMETER RELATIONSHIPS

Parameter	Relation to Number of Motors	Value for $N = 30$	Rated Value
V (V)	$LI\omega'$	1672	1270
$I\omega$ (MA rpm)	$\frac{I^2}{2} \left(\frac{L}{N^3 J}\right)^{1/2}$	1.81	
T (ft lb)	$I\omega' \left(\frac{LJ}{N}\right)^{1/2}$	9020	6700
I_m (A)	$\frac{I}{N}$	1667	1000
ϕ (V/rpm)	$\omega' (LJN)^{1/2}$	0.769	
I_f (A)	$f(\phi)$	1040	1000
ω (rpm)	$I \left(\frac{L}{JN}\right)^{1/2}$	2175	2440

ω = rotational speed, rpm
 ω' = natural frequency of L-C circuit

previously presented limits. For parallel connected motors, the terminal voltage is independent of the number of motors. All other parameters decrease as the number of motors increases with the exception of the flux linkages, ϕ , of the motor poles, characterized by the open circuit. As the number of motors is increased, the pole flux linkages and, hence, the field current also increase. When 30 motors are assumed, the field current reaches 1040 A, near the steady current limit of these motors. All other parameters are also near their operating limits, and this appears to be a reasonable operating point.

Additional support for the choice of 30 traction motors is given by consideration of the sensitivity of the peak value of $I\omega$ to variations of several parameters.

When attempting to build the most economical power supply, equipment should be operated at or near established operating limits. All equipment will exhibit some variation in parameters, and sufficient margin must be left in all parameters to allow safe operation under anticipated conditions. This is done by establishing the levels of deviation in the various parameters and performing an analysis which accounts for the anticipated or measured deviation.

The specification for the 20 MJ coil allows a $\pm 3\%$ variation in the inductance. With the exception of the terminal voltage, which is linearly dependent upon the coil inductance, all parameters which show a dependence vary as the square root of L . This means, for example, that the average value of $I\omega$ of the motor set may deviate by $\pm 1.5\%$ from the value of Table II as a result of coil inductance deviation.

The current in the coil should be set to within $\pm 1\%$. The greatest current dependence of all parameters appears in the value of $I\omega$, which has a current squared dependence. This will introduce a $\pm 2\%$ additional deviation.

The moment of inertia is also known to within $\pm 1\%$ and has a square root dependence in the $I\omega$ relationship yielding a $\pm 0.5\%$ error in that parameter.

The combined uncertainty in the value of I_w for the motor set, if it consists of 30 identical machines, is of the order of $\pm 4\%$. This by itself is not a serious consideration. When machine to machine deviations are included in the analysis, the uncertainty in knowledge of the operating point becomes much greater. If 29 out of 30 machines are identical and the thirtieth machine, called "x", deviates in both J and ϕ , then the relationship between $(I_w)_x$ and the value of the average machine, called "o", is

$$(I_w)_x = (I_w)_o \left(\frac{\phi_o}{\phi_x} \right)^3 \frac{J_x}{J_o} \quad (1)$$

or for small deviations,

$$(I_w)_x = (I_w)_o (1 - 3 \delta_\phi + \delta_J). \quad (2)$$

The deviations δ_ϕ and δ_J are known to be $\pm 4.5\%$ and $\pm 1\%$, respectively. With all uncertainties combined, the range of I_w becomes $\pm 18.5\%$. If the design value of I_w is 1.81 MA-rpm, machines in the set may operate at values from 1.48 to 2.14 MA-rpm for a set of 30 machines. The lowest measured flash point was 2.28 MA-rpm with most flash points around 2.6 MA-rpm on Fig. 8. When 2.14 MA-rpm represents the maximum operating point and the resistance in the circuit, which has been neglected, will reduce the value of I_w achieved, the choice of 30 machines appears reasonable. The choice to increase the traction motor bank to 30 machines was the most cost effective of several alternatives examined. An RFQ was issued and a quotation for two additional traction motors was received. Because of program redirection the motors are not to be purchased.

b. Motor Mount. All 28 traction motors were mounted on timbers and fastened together in pairs with steel A-frames. Figure 9 shows the traction motor installation and the 50 kA pulse rated bus prior to having the armature current shunts and motor tachometer installed.

c. Power Supply for Motor Field Windings.

The 1200 A, 200 V dc power supply from the Controlled Power Company was installed and energized. The output was connected to the 28 motor field windings in series. The supply was successfully operated at its full voltage and current ratings by both local and remote controls. A defective ammeter in the supply was replaced by the manufacturer.

Fig. 9. Traction motors and 50 kA, pulse rated bus.

3. Pulsed 50 kA Bus. A pulse rated 50 kA bus, Fig. 9, will connect the traction motors to the 20 MJ superconducting coil. Two GO and two RETURN, type 1350, 0-grade aluminum 1/2 in. by 9 in. bars are used. The bus system was installed, held every five feet on supports. Aluminum bus tabs, to connect motor armature terminals and current measuring shunts, and the current shunts, were installed.

4. Switches, Dump Resistor, Shunts, and Steady State 50 kA Bus. The bypass switch, S1 of Fig. 5, was redesigned, based upon an experiment for the reversing switch and reported below, for water cooling that allows the steady state current to double from 25 to 50 kA. Thus, the size of the switch was reduced by one half. Switches S1, S2, S4, and S5 were ordered and are 95% complete. These switches, for the TPFS test facility application, are all improved and modified versions of Large Coil Project (LCP) protective dump circuit, silicone oil immersed switches, which in turn are modified versions of an original LA switch development.

A Gould-Brown Boveri switching element for a 25 kA component in the power supply reversing switch was delivered and altered to provide water cooling of the terminals by flow in 10 ft (9-10 turns) of 5/16 in. o.d. by 0.032 in. wall copper refrigeration tubing wrapped and soldered on each terminal. The coil turns on each terminal

were connected hydraulically in series, and the coils for the terminals were connected hydraulically in parallel.

The switch was locked closed in new clean condition and carried 25 kA until the contact and terminal temperature reached equilibrium. The rocker temperature increased with respect to the cooling water exit temperature as

$$T = 0.0739 (q/2),$$

where T = rocker temperature excess over cooling water exit temperature in $^{\circ}\text{C}$ and q = ohmic dissipation in contact region in watts. A 2 in. long conduction path from the contact to the first turn of the cooling coil contributed 60% of the thermal resistance. The remainder was in the contact region.

The switch resistance was 2.2 to 2.8 $\mu\Omega$. The dissipation at 25 kA was 1.6 kW giving a contact temperature rise of 40°C . The cooling water exit temperature ranged from 8 to 12°C as determined by flow rate and bus temperature. The overall rocker temperature was 65 to 71°C .

Total cooling water flow rate for the two terminals in parallel was changed from 1.5 to 3.5 gpm. The effect was a change in cooling water exit temperature which was reflected in all other temperatures. The time for the rocker temperature to reach equilibrium was about 8 min. Bus and connection heating effects introduced a spurious time constant of about 30 min.

The steady state 50 kA, no load reversing switch, RS of Fig. 5, design was completed with the results of this test incorporated. The cost to fabricate the switch is \$60,000. This reversing switch can be used in actual poloidal field coil power supply systems to reverse current and eliminate the need for reverse polarity power supplies, thus saving substantial expenditure.

The 50 kA, pulse operated current interrupter, S3 of Fig. 5, is a steady state 12 kA rated a.c., GE air magnetic breaker known to have interrupted over 100 kA in experimental operation. The breaker is scheduled for 2/82 delivery.

The 18 m Ω , 20 MJ dump resistor, R1 of Fig. 5, was designed, fabricated, and is awaiting assembly. The resistor relies on the heat capacity of massive stainless steel as the resistive element and will

take two consecutive full energy dumps without harm with a 100°C temperature rise per dump.

The blip resistor, R2 of Fig. 5, was designed to be made of carborundum resistors. Assembly drawings remain to be detailed. Estimated cost for this resistor is \$25,000.

The steady state 50 kA bus system design to connect the power supply, switches, and 20 MJ coil is complete. Cost of the bus is \$32,000. Design of the bus support stanchions is complete and cost quotations are being obtained.

A section of a 50 kA flexible connector to go between the steady state bus and the 20 MJ coil was made and will be tested. The 50 kA connector will consist of 32 copper wire braided sections, each 42 in. long with a current density of 997 A/in.²

A 60 kA shunt, SH2 of Fig. 5, was designed to use two parallel 30 kA shunts, which have been obtained.

The conduit system design, which includes chilled water, air, electrical power, electrical instrumentation, and fiber optics, was started. This system likely would be assembled in the field from a layout. The busbar support stanchions would be used for support.

5. Shed to House 20 MJ Dewar. The need for a wooden shed, TPFS coil test bay, was re-evaluated. The wooden building, at a cost of \$175,000, would have provided weather protection without coupling to the magnetic field of the 20 MJ coil. As an alternative, a minimally sheltered concrete pad to cost \$25,000 was proposed. Testing of superconducting coils would be restricted under some adverse weather conditions.

6. 3 MW Power Supply. The 100 kA/30 V, 50 kA/60 V d.c. power supply installed in 1980 was accepted after field testing and deficiency corrections were made by a manufacturer's representative.

7. 700 W, 4.5 K Helium Refrigerator. Rod seals and piston rods were replaced on all four cylinders of the Joy compressor. Graphite seals in three of the four cylinders showed excessive wear, and all seals were replaced by carbon filled Teflon* seals.

* duPont trademark.

The 2 in. diam piston rods showed some corrosion and flaking of the chrome plating. This corrosion is attributed to water trays placed in the distance spaces to increase the humidity for the graphite seals. This practice was terminated.

Intermittent leaks were found between the gas side of the blower circuit and the water side of the refrigerator turbine cartridge cooling circuit. All four turbine cartridges were sent back to Sulzer for no-cost repairs.

Five turbine failures during past operations were traced to thrust bearing failures. Repairs take about four months and minimum of \$12,000 when there is a charge. Consequently, a second source of gas bearing turbines is being sought. Turbine cartridge drawings were made, specifications written for a user repairable turbine, and an RFQ issued. The low bid response from CREARE was examined for possible turbine development; however, the initial cost was too high to offset the \$12,000 repair.

Tests were performed on the refrigerator control system without running the plant. An air surge tank was added to the pneumatic circuit to the turbine inlet valve to slow its operation to avoid turbine damage. Two faults in the logic of the control system existed. One logic error turned off the turbine bearing gas while the turbines were at speed during an emergency shutdown and was the cause of the damage that was repaired. The other logic error did not allow helium gas to be introduced into the refrigerator unless the helium liquid level sensor power was turned on. These logic faults were corrected.

A surplus Ingersoll-Rand compressor rated at 60 scfm and 2000 psig is being installed to increase gas recovery capacity. The compressor foundation was poured, and the compressor was mounted. Motor controls were installed, and the intercooler-aftercooler was reconditioned. Quotations for gas purification equipment for the compressor were received.

The 1000 ft³ gas bag, formerly located in the compressor building, was removed and a 4500 ft³ bag was installed beneath the compressor cold box. A control unit was built to protect the gas bag from over inflation and give appropriate start and stop signals to the gas recovery compressor.

The manufacturer supplied liquid helium level sensor for measuring the helium level in the 100 liter dewar inside the cold box can only sense the level in the top third of the dewar. Automatic control of the helium level would be safer if the level could be sensed for the entire height. Accordingly, a level sensor based on a helium filled stainless steel capillary was inserted into the dewar through an access port that carries power to a heater inside the internal dewar.

A number of minor changes were made in preparation for placing the refrigerator into reliable service. The plastic compressed air lines to valve actuators on the 1000 gallon dewar became brittle from sunlight exposure and were replaced with copper tubing. Pressure transducers and necessary fittings were obtained to increase the amount of instrumentation on the refrigerator. The new manifold system on the tank cluster formerly used for impure helium storage was installed and the leaking tank was identified and isolated. The vacuum jacketed, liquid helium supply and cold helium gas return transfer lines to go between the refrigerator and the dewar for the 20 MJ coil were received. The vacuum on the lines was checked and found to be acceptable.

8. Controls and Instrumentation. A survey of all of the instrumentation requirements of the 20 MJ coil test facility was completed, and an engineering design made for the overall control system. The data collection system will contain a number of stations which amplify low level signals and provide electrical isolation between the transducers and two multichannel analog to digital converters. Sequencing of switches and monitoring of the coil for quenches will be performed by a microprocessor. There are also several closed loop servo systems used to control the refrigerator and coil vapor cooled leads, which will be monitored by the central computer. These systems can be converted to full computer control.

A computer automated monitoring and controls (CAMAC) system was selected to interface the overall experiment to an existing DEC PDP 11/34 computer. The data collection and control requirements are slow and spread over several buildings, so a fiber optic serial highway crate controller was chosen. Figure 10 shows the basic block

Fig. 10. TPFS control system block diagram.

diagram of the system. The computer is connected to two RK05 hard disks, a 7 in. magnetic tape unit, a DEC writer terminal, a Tektronix 4010 graphic terminal, two VT100 video terminals, and a Kinetic System 2050 CAMAC controller. The computer uses an RT11V4 operating system with a MACRO-11 device driver. All the computer hardware of Fig. 9 is on hand.

The CAMAC system consists of a Kinetic 2050 intelligent controller to fiber optic serial highway and two CAMAC crate standard modules located at the refrigerator and the main experimental control console. Within the crates are individual modules that will interface to the various subsystems. The data acquisition system will be capable of 300 analog inputs, 64 analog outputs, 192 digital inputs, and 192 digital outputs. Also within the crates is a provision for an LSI/2 minicomputer for control of the switches and quench detection system.

The software for data acquisition has been received. The 2050 intelligent CAMAC controller uses a device driver which is DEC software compatible and allows the CAMAC modules to be FORTRAN callable. This arrangement allows the software to be mostly application software rather than device drivers. The two VT100 DEC video terminals are to display the collected data and control status of the components.

The main control for the experiment is from a master control console which is controlled directly by an operator or remotely through the PDP 11/34

computer. This unit controls the switch yard (TPFS switches of Fig. 5), the 3 MW power supply, and the traction motor field supply. Interlocks from the coil instrumentation, refrigerator, switch yard, traction motors, and 3 MW power supply are monitored by the master control. The master control system will have full control of the experiment and will be able to terminate the test through an appropriate safe energy discharge at any time if a problem arises.

Signal conditioning stations were built and installed at the liquid nitrogen trailer and the gaseous helium supply trailers. These stations measure the amount of helium gas and liquid nitrogen present and will send a signal to the computer analog to digital converter. The vacuum and tank pressures of the liquid nitrogen trailer are also monitored. An interface was built to bring the water flow, temperature, and gas turbine overspeed alarms from the refrigerator control console to the computer. Helium flow switches, sensitive to 1 scfh, were developed and built to monitor gas flow in the helium purity monitors. The signal conditioning station to monitor the equipment in the refrigerator compressor building was built but not checked because the transducers are not installed.

The control unit to protect the gas bag from over inflation and give start and stop signals to the warm gas recovery compressor was installed and checked. Control cables were run from the control unit to the compressor motor starter. Some modification of the interlock chain for the compressor is required before the entire system, including the compressor, is checked.

A signal conditioning station was designed for bringing data from the control console of the helium refrigerator to the PDP-11/34 computer. Pressure transducers for monitoring critical parts of the refrigeration cycle were delivered, and installation procedures for the transducers were prepared.

A device to control the helium level in the 100 liter dewar inside the refrigerator cold box was designed and some of the hardware was built.

The valves, valve actuators, motor controller, and flow meters, needed to control helium flow in the vapor cooled current leads, were delivered.

Adapters were made to connect the valves and valve actuators. A prototype electronic controller to operate the valves is being fabricated.

A controller was designed to monitor in sequence the carbon-glass thermometers to be used during cooldown of the 20 MJ coil. The controller has provision for automatic calibration of the amplifiers and subtraction of thermoelectric voltages.

Instrumentation for the traction motor bank was designed in detail for 30 motors. The traction motors are connected with their field windings in series and their armatures in parallel. Each motor field voltage, armature current, and field current are measured with isolation amplifiers. A d.c. tachometer is attached to the shaft of each traction motor with an electrical insulating mechanical coupling. All of the traction motor signals are to be taken to the main control console for computer input. The circuitry for integrating the traction motor signals into the control system was tested in "bread board" configuration and is being built for permanent installation.

G. FUSION ENGINEERING DESIGN (FED) CENTER AND INTERNATIONAL TOKAMAK REACTOR (INTOR) CONTRIBUTION

The study, started in 1980, to determine some of the electric requirements for plasma current initiation from internal and normal conducting coils in the presence of cryostats and other major structures was completed. The eddy current losses, induced voltages, and the effect of bellows or highly insulating sections were determined.

The induced currents in the FED/INTOR structures, due to disruptions, will play a dominant role in the design of the vacuum vessel. This is beginning to be the case for machines now being constructed and will be more a problem for FED/INTOR because of the thicker vacuum vessel, large areas for neutron shield material, added cooling piping, the great amount of stored energy associated with the plasma current, and increased requirements for maintainability. A vacuum vessel shell with high conductivity in proximity to the plasma may provide a path for the image currents stabilizing the plasma. Conversely, the startup and control power requirements are rendered more

severe in the presence of a high conductivity shell.

The voltage of 100 V for 0.10 s required for plasma startup can be obtained by induction from the poloidal circuit or a special blip coil.

The FED/INTOR baseline design whose dimensions are shown in Fig. 11 is the basis of this study. All of the passive conductors in that structure are effectively thin, when compared with the skin depth in a plasma startup pulse. Hence, for the purpose of pulse analysis, the passive conductors were subdivided only in their long radial or axial dimensions.

The thickness and some additional characteristics of the structural elements are listed in Table III, and those elements are marked whose resistances are varied to determine the effect of including bellows or insulating sections. Circular symmetry and the existence of a magnetic flux normal midplane were assumed.

The current in all active coils and the plasma current in Data Case I, that is, for no added resistance or no high resistance section, are shown in Fig. 12, for which the voltage $V_{42} = V_{42} = 115 \text{ V/t}$ was applied as a step function. The plasma current rise was delayed to

Fig. 11. Configuration and plasma field.
The labels are defined in Table III.

TABLE III
ACTIVE AND PASSIVE CONDUCTORS

Subelements as Labeled in Figure 11	Element Number	Element Designation	Material	Thickness cm	Resistance above or below the midplane $2 R_1$ m Ω
1	1	plasma (20 cm rad.)			$R_1(t)$
2,3,47,48	2	bucking cyl. for TF coils	S.S.	1.0	0.0101
4,5,14,15,25,26	3	TF dewar	S.S.	1.0	0.124 ^b
6,7	4	spool	S.S.	1.5	0.250
8,9	5 ^a	inner wall	S.S.	1.5	0.255
10-13	6	spool top, shell top	S.S.	1.5,1.0	0.402
16-20	7 ^a	plasma shell	S.S.	1.0	0.328
21,22	8	graphite	graphite	2.0	0.685
23,24	9 ^a	water pipe	S.S.	1.0	0.936
27-30	10 ^a	breeder blanket	S.S.	1.0,0.5	0.879
31,32	11 ^a	outer shell	S.S.	1.0	0.940
33	12	OH coil	S.C.	---	0
34	13	EI coil	S.C.	---	0
35-37	14	ED coils	S.C.	---	0
38-40	15	E0 coils	S.C.	---	0
41,42	16	blip coils	copper	---	0.00955
43-46	17	OH dewar	S.S.	1.0	0.0286 ^b

^a To each of the pertinent subelements is added the resistance, R_{break} , that is, 0, 1.70, 8.50, 17.0, or 34.0 m Ω in the Data Case I, II, III, IV, or V, respectively, above the midplane, and the same R_{break} to the image element below the midplane.

^b Room temperature value.

approximately $\tau_d = 90$ ms. The observed delay was caused by slow field penetration, and those operations in the startup scenario that were not coupled to the electromagnetic field, such as the gas injection, could just be delayed by τ_d . The values of τ_d are listed in Table IV for five data cases. The conclusion of the study is that a blip coil should be provided in the case of rf nonassisted startup to provide for the delay caused by the vacuum vessel without insulating break. Whether or not the limiter impurity control will allow startup with only 100 V with no rf assist is not known. Before the design is started in detail, the possibility of rf assisted startup should be deter-

mined, and the high voltage blip eliminated if possible.

The vacuum vessel should be designed so that (a) arcing is not likely and if arcing occurs, the selected material will withstand the arcs; (b) a good toroidal current path is provided close to the plasma, and the vacuum vessel is designed to cope better with the disruption currents; (c) the vacuum vessel components such as coolant pipes and the divertor heat conducting sections, if made of low resistive materials, require special attention; (d) the induced currents in the structures at right angles to the toroidal fields are avoided where the structures cannot easily support these forces; and (e) if rf startup without the high voltage blip is

Fig. 12. Currents in Data Cast I, 115 V applied external voltage step, zero delay. The tangent on the plasma current defines the delay time, τ_d .

TABLE IV

ELECTROMAGNETIC DELAY TIME

Data Case	Added Resistance, m Ω , in Each Half Space w.r.t. the Midplane	Delay τ_d s
I	0	0.090
II	1.70	0.083
III	8.50	0.072
IV	17.5	0.056
V	34.0	0.050

utilitized, care is taken to assure that arcing, erosion, and forces will not be prohibitively high. Designing a well conducting liner or a uniform current path between each segment of the vacuum vessel is desirable. Startup with such a vacuum vessel is shown to be practical, and the power and energy to drive the plasma startup pulse are less than the corresponding requirements for the plasma control circuit.

For the Data Case I, four single blip coils, each built with 62 turns of a 20 kA copper conductor, with 50 A/mm² current density, would have dimensions of approximately 10 cm in the axial and 60 cm in the radial direction. Two coils would be mounted above the midplane, approximately as shown for the coils 41 and 42 in Fig. 11. The other two coils would be used for the image below the midplane. If constant current is assumed for 0.2 s, the temperature rise from converting the Joule loss to residual heat would be 3 K in the coils. The voltage per coil would be 8.5 kV with

required peak power of 700 MW for 0.19 s. At the end of the blip, the blip coils would be shorted. For this condition, some of the computations were extended to 4 s with the ohmic heating and external field coils as the drivers. These computations verified that the blip coil current would reverse and keep increasing in the negative direction. Opening the blip circuits at the current zero would thus provide a useful operating procedure. The time from the start of the blip pulse to current zero is approximately 0.55 s. The Joule loss over the 0.55 s equals approximately that for the 4.83 Mat over 0.2 s used for estimating the coil temperature rise.

The coil design just discussed is not optimized and is given only to convey an idea of the general size of the blip circuit.

The computer program FED has been revised to take into account the proper plasma characteristics and the various functions of the EF coils during the blip coil operation and the OH current reversal.

The revised program provides for

1. Current instead of voltage driving to force consistency with the EF and OH coil plots from the FED Center,
2. Determining and using the control coil current such that the vertical field null is maintained when all poloidal field coil currents are taken into account,
3. Plasma resistance as a function of plasma current, and
4. Blip pulse applied by the control coils.

In preparing for the rf assisted startup study in the revised FED, a code with a minimum demand on computer resources was developed for the computation of the inductance matrix with many elements, such as 100 x 100. Other existing codes execute too slowly or are not suitable for the large arrays of elements required in the revised FED geometry, which has no midplane symmetry. The new code uses spherical harmonics and a fast recursion method for computing the Legendre functions.

H. SWITCH DEVELOPMENT AND TESTING

The LCTF requires switches and current interrupters in the protective energy dump circuit for the LCP TF coils. Performance tests of these switches were performed for the Oak Ridge National Laboratory (ORNL). A formal report was written and the results are summarized here.

1. Interrupter Bypass Switch. The interrupter bypass switch in LCTF is required to carry 22.5 kA continuously and to interrupt this current and divert it into a parallel connected d.c. interrupter. It must then withstand a 5 kV arc voltage generated by the d.c. interrupter followed by a 2.5 kV dump resistor voltage. More than 200 synthetic tests were performed at 25 kA and 10 kV. Almost 40 additional tests involving full current transfers and circuit breaker interruptions were successfully conducted. Both sets of tests were done with and without oil in the switch.

2. Power Supply Crowbar Switch. The power supply crowbar switch in LCTF is required to close on 25 kA at a low voltage and to carry this current on a continuous basis. An oil cooled, high current bypass switch was successfully tested for over 200 make operations at 25 kA and run continuously for eight hours without excessive temperature rise.

3. DC Interrupter. The d.c. interrupter in the LCTF is required to divert 25 kA into a 0.1 ohm, 20 μ H resistor. This commercially available switch was subjected to over 120 interruptions ranging from 5 to 28 kA. Although every interruption was successful, the breaker had considerable trouble interrupting currents with recovery voltages in excess of about 1.5 kV. Two interrupters connected in series improved performance at these higher voltages. The possible use of a Swiss made, 4 kV, d.c. interrupter is being investigated. Some testing may be performed on this switch in 1982.

I. SUPERCONDUCTOR LOSS AND SHORT SAMPLE CRITICAL CURRENT MEASUREMENTS

The 7 T bipolar loss apparatus was used to measure losses in 20 MJ coil prototype conductor. A special series of runs was made to determine the operating parameters for the traction motors for various maximum field levels and field reversal times. Fifteen different operating points were set for five maximum field values ranging from 2 to 6 T

for three bipolar reversal times ranging from 0.7 to about 2.0 s. The data could be analyzed for an equivalent bipolar reversal which varied from 0.7 to 5.8 s. Loss measurements on the 20 MJ coil prototype conductor indicate the losses in the 20 MJ coil may be somewhat higher than calculated. A precise determination awaits measurements on the actual wire to be available in early 1982.

A new probe was built for measuring critical current in superconducting strands at currents up to 5 kA in fields up to 5 T. This combined range of current and field was heretofore unavailable at LA. Measurements were made on eight wire samples up to currents of 5 kA and fields of 6 T for the Lawrence Berkeley National Laboratory.

J. DIELECTRIC TESTS

Superconducting coils are connected to the room temperature electrical system with leads penetrating through the upper lid of the dewar. The helium at the upper end of the dewar is near ambient temperature. Helium at this temperature has the lowest dielectric strength of the known gases and the dielectric system must be designed with extreme care. Critical to the design of a gas dielectric system is the dielectric strength of the gas itself as well as the dielectric strength along the creepage path of a solid dielectric immersed in the gas. Data on ambient temperature helium are sparse because of lack of commercial applications.

The objective of the dielectric test program is to generate design data of flashover voltage stress along dielectric surfaces in a helium atmosphere. Two types of dielectric materials of cylindrical shape of various lengths are tested in helium gas at ambient temperature at various pressures. Dielectric samples are tested under both d.c. and transient voltages.

Because of the importance of these data to the design of superconducting coils, statistically designed experiments under carefully controlled environments are planned. The Statistics Group, S-1, has done a statistical design based on Latin square and split plot analysis of variances. Preliminary tests performed with this design will tell if previous history has any significance in the test results. If insignificant, then a considerable amount of time could be saved by

performing many tests with several variables for the same experimental arrangement and sample.

The preliminary tests were performed on 1 in. diam G-10 cylindrical rods under d.c. voltage. Surface flashover tests were performed by holding the test piece between the two 6 in. diam flat stainless steel electrodes housed in a 10 in. i.d. by 12 in. long acrylic chamber. The objectives were to determine the variation of flashover voltage from sample to sample, to determine the effect of previous tests on the same sample, and to observe the surface flashover characteristics in helium.

In addition, breakdown voltage tests in helium gaps were also performed with the 6 in. diam flat electrodes and 2 in. diam steel spherical electrodes to observe the breakdown patterns in helium as well as to check the results with published data.

The variation of flashover voltage from sample to sample was very small. Table V shows the results of part of a test program, in which each of the five samples was tested under four selected pressures of 25, 50, 75, and 100 psia. The objective was to detect any previous test history on the flashover voltage level. No history effect was detected. Multiple arcs, sometimes moving, were formed during breakdown. Sometimes a faint arc along the sample surface would precipitate a bright arc elsewhere. Similar tests in air produced only one arc along the sample surface. The multiple arcs appear to be a characteristic phenomenon of helium.

Breakdown tests in helium gaps, without the solid test sample between the electrodes, also showed the multiple arc phenomenon. Data on helium gap breakdown, with data from two other sources, are shown in Table VI.

TABLE V

DC SURFACE FLASHOVER VOLTAGE OF G-10 ROD IN HELIUM
ROD DIAMETER = 1 IN. ROD LENGTH = 1.5 IN.
HELIUM PRESSURE = 100 PSIA AT ROOM TEMPERATURE

Sample Number	1	2	3	4	5
Flashover Voltage, kV	25.83	25.83	25.50	24.83	25.17

TABLE VI

BREAKDOWN VOLTAGE IN HELIUM PRESSURE = 100 PSIA

Gap Length inches	Breakdown Voltage, kV			
	2 in. steel sphere electrode ^a	6 in. diam stainless steel plate electrode ^b	Dakin ^c	Olivier ^d
0.5	17.67	11.50	15.0	14.1
1.0	24.83	22.00	30.0	26.3
1.5	29.75	26.17	42.0	37.9
2.0	35.33	30.17	60.0	49.14

^a Average of five tests.

^b Average of three tests.

^c Compiled by Dakin et al. as an average Paschen curve from data taken by many experimenters with various types of electrodes.

^d Each value derived from theoretical equations suggested by Olivier et al.

The data with 6 in. plate electrodes, as expected, are lower than those with 2 in. spherical electrodes. Because of the larger area of the 6 in. plate electrodes, compared with the points of minimum distance of the 2 in. spherical electrodes, the probability of breakdown of the 6 in. plate electrodes is high; hence, the breakdown voltage level is comparatively low.

Results from these tests are generally lower than those from Dakin¹ and Olivier². Dakin's Paschen curve was drawn as an average of data published by many experimenters, based on the assumption the breakdown depends only on gas density. However, gas breakdown depends on many other factors, such as electrode shape and material. Moreover, the points at the higher voltages on Dakin's curve were taken from experiments performed at pressures up to 85 bars and/or temperatures down to 4.2 K. The validity of the Paschen curve is questionable under these extreme conditions.

The data with 2 in. spherical electrodes with gap spacing up to 1 in. are comparable with Olivier's theoretical data. At larger gaps, the data show lower breakdown voltages. This may be caused by the nonuniform electric field in the gap created by the large ratio of gap length to sphere diameter. For near uniform fields this ratio should not exceed 0.5, such as a gap length of 1 in. for a 2 in. diam sphere.

A six stage Marx generator was built to get surface flashover data under transient voltage conditions. Each stage has a 0.25 μ F capacitor, capable of storing 28 J. The maximum output voltage is about 80 kV.

K. ONE COMPONENT MODULE SUPERCONDUCTING PROTOTYPE METS SYSTEM

Data from the tests of the so called 400 kJ coil were analyzed, and a report was written summarizing the results. The coil quenched consistently at 19 to 20 kA and fell short of the 25 kA design current required to store 400 kJ. Two sets of tests were performed in the prior year. In the first set, the coil was charged over a period of about a minute and then discharged in 1 ms. In the second set the coil was charged over a period of about a minute and then the current was reversed in 7 to 20 s. Table VII gives parameters of the 400 kJ coil with those of a similarly built and previously tested 300 kJ coil for comparison. The 300 kJ coil had been tested to 540 kJ.

TABLE VII
PARAMETERS OF ENERGY STORAGE COILS

Parameter	400 kJ	300 kJ
Inductance, mH	1.26	6.05
Resistance at 20° C, Ω	0.087	0.165
Design current, kA	25	10
Stored energy at design current, kJ	400	300
Winding length, cm	67.3	79.1
Mean radius, cm	27.0	25.5
Winding thickness, cm	10.3	4.74
Number of turns	64.75	159.5
Number of layers	3	4
Peak center line field at design current, T	2.31	2.13
Conductor support method	toothed form	toothed form
Overall CuNi:Cu:NbTi	1:1.5:1	0:2.5:1
Strand diameter, mm	0.381	0.813
Filament diameter, μ m	14.4	18
Filaments/strand	198	529
Wire twist pitch, cm^{-1}	3.15	1.42
Number of active wires in cable	504	72 ^a
Cable width, cm	2.48	1.68
Cable height, cm	1.91	0.84

^aTotal number including inactive strands is 84.

For the slow, 7 to 20 s tests, electronically measured losses, shown in Fig. 13, were about twice those expected from calculations.

The superconducting wire used in the coil contained some flaws in that radial cracks occurred in three of the five billets during drawing. Because of fiscal and scheduling constraints and a requirement to bring the program to a conclusion, the wire with the cracks was used to make the cable for the coil. In some wires the radial cracks extended from the surface to near the center of the wire and ran for extended lengths along the wire. The cracks appeared to follow the Cu-Ni matrix hexagonal interface. A number of short sample critical current measurements had been made on the superconducting wire with the result that the critical current was not affected by the crack. This result weighed heavily in the decision to proceed with the wire to fabricate the coil in view of schedules and costs to complete the METS work.

Fig. 13. Energy losses in the 400 kJ coil for current reversal tests as a function of the maximum field on the winding. The open circles refer to hysteresis losses. The solid circles refer to a 12 to 20 s current reversal time and a 7 s discharge. The crosses correspond to a slightly faster, 4.8 s discharge time. The triangles refer to a 6 to 7 s reversal time with a 3.6 s discharge time.

L. MISCELLANEOUS

1. Eddy and Circulating Current Code Development.

The computer program DIFDIRA (DIFFusion Equation DIRect Algorithm) has been developed to integrate with Winslow's finite difference method the diffusion equation in an open $(x,y;t)$ and $(r,z;t)$ domain. Computing composite structures of air, nonferric metals, and coils of small conductors connected to an external circuit is the immediate objective. Eventually, the computations of iron dominated problems is to be included.

The code was primarily developed to consider the transient and not the stationary problem with step currents or ramp currents, such as the trapezoidal pulse, with front and tail times input adjustable in the open interval $t > 0$. Stationary results such as the a.c. case are obtained at the asymptotic time limit.

Results compare with analytic solutions for short times within a fraction of a percent. For long times, analytical results imply a 10% faster progression of the field diffusion than DIFDIRA predicts. The difference may be caused by an unusually coarse lattice structure. The integrating time step is chosen to be consistent with the (x,y) lattice; hence, a finer lattice implies smaller time increments. The accuracy is approximately that obtained with other codes. The code is capable of solving the B_x , B_y , I_z problem and not the B_z , I_x , I_y problem.

2. Magnetic Field Gradient in a Three-Dimensional Lattice of Scalar Potentials.

Work in support of the ZT-40 physics program was undertaken to obtain more satisfactory accuracy when the magnetic field gradient is computed from a set of scalar potentials. The proposed formalism uses a potential function fitted to the mesh point and its first and second order neighbors in a three dimensional lattice. The Legendre and associated polynomials are shown to be best as regards accuracy and provide by far the greatest economy in computing resonances. The algorithms and relationships were developed in detail to obtain the fitting coefficients and to compute the components of the gradient.

3. Oil Immersed Bypass Switch Safety Study. In the coil protection circuit of the LCTF and in the 20 MJ coil charging circuit of the TPFS, d.c.

current interruptors are used. These switches consist of a bypass switch for continuous duty and a parallel connected fast operating circuit breaker. The contactor is a mechanical device in which contact is maintained by a copper wedge inserted between two bus sections; the fast circuit breaker is an air magnetic breaker. To increase the dielectric strength of the open contacts, the bypass switch contacts are submerged in a container filled with approximately 24 kg of silicone fluid. Because of the significant amount of fluid coils and the energy in the circuits, 100 to 200 MJ for the LCTF coils and 20 MJ for the TPFS, the hazard potential was studied. Previously, the flash point was assumed to be sufficient at 320° C to be safe. This is not necessarily the case. Some tests conducted by GE indicate that large volumes of silicone oil can be hazardous. With the silicone fluids exposed to an arc in a confined transformer tank, an explosion occurred; but no fire hazard seems evident.

The thermochemical dissociation of silicone oil was considered under potential arc conditions. The flammable decomposition products, in order of abundance, are hydrogen, methane, and other light hydrocarbons, all of which can form explosive mixtures with air in confined space.

The volume of evolving gases is small under normal operating conditions when the current is transferred from the opening contacts to the fast circuit breaker. Under an accidental condition when the breaker is open while the bypass switch opens, a large part of the coil energy may be deposited in the arc. Under this condition, the rate of energy transfer could be high and the shock wave under oil may cause significant damage. To avoid damage the silicone oil immersed LA switches are to be covered with inert gas and the G 10 containing boxes are equipped with low pressure rupture disks.

A thermal runaway condition is known to occur under certain conditions when closed contacts under oil carry current for a long time as may be the case at the LCTF. An oil film grows slowly between microcontacts, which are the microscopic regions of actual contact and through which the contact current is actually conducted. The film growth rate is a function of temperature and thermal

runaway may occur after weeks, months, or years of continuous operation.

Typical data indicate low temperatures are important to avoid oil film growth between contacts and thermal runaway. Oil immersed switches should have the contacts monitored for long time temperature trends. The wiping action of opening and reclosing switches will destroy the film.

4. 900 kJ Switch Test Facility. The 900 kJ switch test facility was placed in standby early in the year and partially dismantled because it had been superseded by the 2 MJ facility. Some of the capacitors were removed from the 900 kJ facility to replace leaking capacitors in the 2 MJ facility. The electronics group E-11 requested use of the facility for development of high repetition rate opening switches and restored the facility to operating condition.

5. HVDC Interrupter Proposal. Two meetings were held with Brown Boveri Electric, Inc. to design a 3 kA, 150 kV d.c. circuit breaker in response to a DOE-Electrical Energy Systems request for proposals. The program managers at ORNL commented that the LA approach seemed the most feasible. Unfortunately, funds for the project were cancelled, but the LA approach will be included in the ORNL final review. The LA-Brown Boveri proposal is to use a commutated SF₆ arc spinner interrupter with a parallel metal oxide varistor stack for energy absorption. This interrupter, if successful, would then be extrapolated to a 3 kA, 500 kV unit.

6. Work for National Security Programs. Two programs were suggested and preliminary performance estimates prepared. One is based on an idea in the generalized field of guided wave propagation of the electromagnetic and sound types. The result is a broad range of practical applications. A description of the concept was sent to the Defense Sciences Office at DARPA.

The second suggestion concerns rail guns and is based on an idea relating to the electric arc. The idea was presented to Group M-6 for evaluation. Both ideas were filed for patent consideration.

7. Professional Committee Work. P. Chowdhuri participated in the first revision of IEEE Standard 518-77, particularly in the writing of the radio frequency interferences, and attended the ANSI Committee 63 meeting in Boulder, CO, as an IEEE delegate.

8. Geological Superconducting Survey Device.

P. Thullen and P. Chowdhuri participated in a review of the geological superconducting survey device at the Richmond Field Station of the University of California to provide consultation on high voltage problems and on design of the superconducting magnet system. This was done on a reimbursable basis from Exxon, the project sponsor.

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