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Proposal

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Proposed Tokamak Poloidal Field System Development Program

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PROPOSED TOKAMAK POLOIDAL FIELD
SYSTEM DEVELOPMENT PROGRAM

by

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ABSTRACT

A program is proposed to develop poloidal field components for TNS and EPR size tokamak devices and to test these components in realistic circuits. Emphasis is placed upon the development of the most difficult component, the superconducting ohmic-heating coil. Switches must also be developed for testing the coils, and this switching technology is to be extended to meet the requirements for the large scale tokamaks. Test facilities are discussed; power supplies, including a homopolar to drive the coils, are considered; and poloidal field systems studies are proposed.

I. INTRODUCTION

Large tokamak devices of the EPR class require considerable development of various technologies before they can be constructed. Among the new technologies to be developed are those required for the poloidal field coils and power systems. Present day technology is inadequate for the task, largely because of the large switching costs for the higher power level and the need for superconducting coils. Systems studies of the requirements for large tokamak poloidal field systems have been in progress at LASL for several years and have defined the needs rather generally.

This proposal presents a program for the development and testing of a superconducting coil system for creating the pulsed fields and ohmic-heating currents for large scale tokamak devices. The program will emphasize a systems approach and will account for constraints during start-up by weighing possible tradeoffs between physics and technology. Various circuit options will be developed to provide the necessary technology for adaption to an actual tokamak design. Collaboration will be maintained with other tokamak efforts in the country both to guide the experimental program and to conduct studies on poloidal field systems. Circuits will be analyzed to establish the requirements for the switches, coils, power supplies, and other circuit components. Ancillary components for the systems will be identified and developed as required for realistic systems type tests.

The principal functions of the poloidal field coil system in a TNS or EPR¹⁻⁵ tokamak are to build the plasma current to a level which provides stability for the plasma through interaction with the equilibrium field and supplies the base plasma heating of approximately 1 keV, to hold the plasma in proper position within the toroidal chamber, and to shield the toroidal field coils from the pulsed fields. The circuit needed to provide the proper

current waveform is complicated by the many requirements. The plasma discharge initiation calls for a rapid initial current rise of limited duration to be followed by a slow increase to raise the plasma temperature. Plasma current maintenance during the beam heating burn period requires an increasing primary current, and plasma current shutdown requires careful programming to control heat conduction to the wall. Recovery of the ohmic-heating drive coil to its initial conditions for starting the next cycle is a final requirement. The various design choices may make some of these functions unnecessary.⁴

Very demanding conditions will be imposed upon the superconducting ohmic-heating coils, particularly the central solenoid. These coils, like the rest, must be operated in the bipolar mode, undergoing a complete field and current reversal twice during each cycle, and are in the maximum field to be experienced by a superconducting winding. The current swing requirement is made difficult by the eddy current loss from the changing poloidal field, the radiation flux, frictional energy, and conduction heat leaks. Because of this set of complications the ohmic-heating coil development should also solve many of the lesser demands of the rest of the poloidal field coils.

Ohmic-heating systems have not been designed in detail for very large tokamaks. Probably the most complete design made to date is for the TFTR,⁶ but this does not involve superconducting coils. The study⁷ by the Los Alamos Scientific Laboratory, University of Texas at Austin, and Westinghouse Electric Corporation based on the ORNL design of an EPR is one of the most complete designs involving superconducting coils. A portion of the results of that study was reported by Vogel et al.⁸ Their calculated ohmic-heating energy and switching requirements are given in Table I. These are the results obtained for the typical circuits indicated in Figs. 1 and 2.

The cost analysis of the circuits is contained in a Westinghouse report⁹ contributing to the study.⁷ All switches in these circuits used SCR's, a very costly approach. With this inclusion the homopolar circuit component costs, exclusive of the ohmic-heating coil, total \$176 000 000 and the ac machine circuit component costs total \$167 000 000. Of this amount the homopolar bypass switches and commutating circuit components

TABLE I

OH ENERGY AND SWITCHING REQUIREMENTS FOR THE EPR

		<u>Homopolar circuit, Fig. 1</u>			<u>ac machine circuit, Fig. 2</u>		
				PMM ^d module assuming 120s burn			PMM module assuming 120s burn
	<u>UNITS</u>	<u>OH winding</u>	<u>Shieldg.- decouplg. winding</u>		<u>OH winding</u>	<u>Shieldg.- decouplg. winding</u>	
Energy converted to heat in blip resistor	MJ	440	(2.5) ^a		272	(0.9) ^a	
Energy transferred in shield-decoupling circuits	MJ	650	150	10 ^c	813	92	10 ^c
Energy into plasma	MJ		34			31	
Maximum stored energy in OH coil	MJ	1250			1250		
Maximum energy stored in "capacitor"	MJ	680			1200(817) ^b		
Total Vs/turn transferred to OH coil/shielding-decoupling	Wb	67	21		56	17	
Resistive Vs into plasma	Wb		9.6	16		9.4	16
Maximum voltage	kV	75	1	0.07	75	1	0.07
Maximum current	kA	143	470	175	143	470	175
Controlled power, blip interrupter	GVA	11			9		
Required di/dt, blip resistor	A/μs	>14	-		>14	-	
Required dV/dt, blip resistor	V/μs	> 7	-		> 6	-	
Minimum cycle time	s			100-200			100-200

^aEnergy supplied by shielding-decoupling supply during blip.

^bEnergy released.

^cEnergy supplied by PMM.

^dPMM denotes dual rectifier plasma maintenance module.

Typical, one of three circuits. Each pair of Homopolar Generators serves eight coils in parallel. Total number of generators is six, of coil segments is 24. Each resistor, R , has a resistance of $\sim 0.16\Omega$ to produce ~ 8 kV for a total initiating voltage of ~ 16 kV across 85 turns. Maximum voltage to ground is 8 kV.

Figure 1. DC generator OH circuit.

Typical, one of two independent circuits. Each generator feeds two parallel circuits with a total of eight coil segments. Each resistor, R , has a resistance of $\sim 0.37\Omega$ to produce 18.5 kV for a total initiating voltage including generator output of ~ 48 kV across 254 turns. Maximum voltage to ground is then 24 kV.

Figure 2. Round rotor ac generator OH circuit.

cost \$55 000 000; and the plasma discharge initiation resistor switches and commutating circuit components cost \$91 000 000. For the ac machine circuit the respective costs of these components are \$31 000 000 and \$55 300 000. The costs are dominated by the SCR switches. The use of very low cost switches would give a \$40 000 000 cost advantage to the homopolar circuit for a reduced total cost of \$35 000 000. The need for an SCR rectifier set in the ac circuit prevents costs for that system from being reduced to the same level. The costs with SCR switches are given in Tables II and III.

The significance of the study is that both low cost, high voltage, high current interrupters and homopolar machines should be developed for tokamak ohmic-heating systems. Also, further study is needed to optimize the circuit choices. Thus, besides the need to provide the superconducting coils, it is apparent that to test coils in a prototypical energy transfer cycle will require other parallel advances in technology.

The possibility of removing the plasma discharge initiation function from the ohmic-heating circuit and incorporating it into a separate coil system or into another existing set of poloidal field coils might eliminate some of the most costly switches. This concept warrants further study and requires consideration of the entire magnetics design of a large tokamak.

The EPR poloidal coil system, and particularly the ohmic-heating coils, lend themselves to parallel operation. Under these conditions the individual coil current can be established at a maximum value in the neighborhood of 25 to 50 kA. This is close to the near term METS coil program goal of 25-kA superconducting cable. Thus, from the maximum current of Table I, it is concluded that six or seven coils in parallel would meet the EPR requirement. Further, the 75-kV potential developed across each such coil is not significantly more than the 58 kV already reached in testing the METS 300-kJ coil.

TABLE II

EPR OH CIRCUIT — HOMOPOLAR ENERGY STORAGE COST 1

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
6	Homopolar Generators	850 MVA 200 kA, 4.25 kV	5100 MVA	3.06×10^6	18.4×10^6
6	Generator Switches 2 Comm. Circ/Sw	850 MVA 200 kA, 4.25 kV	5100 MVA	9.12×10^6	54.7×10^6
12	Line Rectifiers	4.25 MVA 50 kA, 85 V	102 MVA	0.840×10^6	10.1×10^6
24	Resistor Switches, 1/2 Diode, 1 Comm. Circ/Sw	400 MVA 50 kA, 8 kV	9600 MVA	3.78×10^6	90.8×10^6
24	Resistors	20 MJ/pulse 50 kA, 8 kV	480 MJ/pulse	0.0934×10^6	2.2×10^6
	TOTAL				176.2×10^6

TABLE III

EPR OH CIRCUIT — AC GENERATOR ENERGY STORAGE COST 2

Quantity	Item	Rating	Quantity x Rating	Unit Cost	Total Cost
4	AC Generators (Salient Pole)	919 MVA 13 kV, 40.8 kA	3675 MVA	4.85×10^6	19.4×10^6
4	Generator Rectifiers	875 MVA 50 kA, 17.5 kV	3500 MVA	13.71×10^6	54.8×10^6
8	Generator Rectifier Switches	437.5 MVA 50 kA, 8.75 kV	3500 MVA	3.88×10^6	31.0×10^6
4	Generator Drives	1.5 MVA 18.6 kV dc, 80 A	6 MVA	0.396×10^6	1.6×10^6
4	Line Rectifiers with Transformers	12.75 MVA 50 kA, 255 V	102 MVA	1.13×10^6	4.5×10^6
8	Resistor Switches, 1/2 Diode 1 Comm. Circ/Sw	850 MVA 50 kA, 17 kV	6800 MVA	6.91×10^6	55.3×10^6
8	Resistors	25.5 MJ/pulse 50 kA, 17 kV	204 MJ/pulse	0.12×10^6	0.9×10^6
	TOTAL				167.5×10^6

The switches for the ohmic-heating circuit have several functions. This is easily followed by considering Fig. 1. Assume the coils initially to be charged to the full current level with all the SCR diodes conducting, i.e., the switches are closed. Under these conditions they carry the full current and act as shunts to both the blip resistors and the homopolar generators. The sequence of opening the switches depends upon a decision, determined by the plasma physics, whether to delay the blip somewhat in time as the energy transfer from the ohmic-heating coil is under way. In any event, the blip initiation is early, and the switches across both the blip resistors and the homopolar generators can be considered to be opened simultaneously. This is done by counterpulsing, driving the current to zero with the commutation circuits. The current transfers to the blip resistors and a high voltage develops across them. This high potential is of short duration of several tens of milliseconds after which the resistor shunt switches are closed. See Fig. 5. On a slower time period of 1 to 2 s, also shown in Fig. 5, the energy in the ohmic-heating coils is transferred to the homopolar, which acts as a resonant capacitor, and then back into the coils with the current and fields reversed. The switches across the homopolar are then crowbarred shut. The energy transfer swing and the field reversal create the transformer action between the ohmic-heating coils and the one-turn plasma secondary. This is followed by the long time burn phase of tens to one hundred seconds. The cycle is then repeated. Thus the switches must both interrupt and carry the full current and withstand the maximum circuit voltage in the open state.

Besides the function of resonant energy transfer per se, the homopolars can be used in a start-up and shutdown mode. For start-up the machine can be brought to full speed and the energy transferred into the ohmic-heating coils by closing a switch in series between the two. For shutdown the energy reversal process of the coils can be stopped halfway by crowbarring the switches across the machine. The energy can then be dumped into a resistor. The extra circuitry for start-up and shutdown are not included in Fig. 5.

A 10-MJ, fast discharge, 30-ms homopolar is currently under development as a collaborative program involving EPRI, Westinghouse, and Los Alamos. The fast discharge homopolar will provide information on many technical facets common to both fast and slow machines, e.g., high rotor speed, high current density brushes and current collection systems, rotor-field misalignment effects, superconducting field systems, etc.

The program is to include coil and switch development for ohmic-heating systems. The early development involves low loss superconductor, superconducting cables to carry currents up to 50 kA, cryostable conductor and cable designs for both forced flow cooled and pool bath cooled coils, conductor and cable stability determinations including cryostability, small coil designs up to a few hundred kilojoules stored energy and their fabrication and testing to evaluate performance, steady state 50-kA leads to withstand 75 kV for carrying the current into the coil dewars, 50-kA conductor joints, large ohmic-heating coil design, and eventually 10-MJ and 50-MJ coil fabrication and testing.

Proposed switch work will evaluate and test series-parallel vacuum interrupters, air blast circuit breakers, and SF₆ circuit breakers for tokamak ohmic-heating circuits. Alternative approaches to switching which use combinations of different types of breakers will be explored. Existing testing facilities for this work will be expanded and new larger facilities will be built.

Ongoing tokamak poloidal field system studies are proposed.

Schedules are given for FY's 78 thru 86. Costs are given for FY's 78 thru 82.

II. TOKAMAK POLOIDAL FIELD SYSTEMS

The present Program Plan¹⁰ of the Division of Magnetic Fusion Energy assumes that a large tokamak which would achieve ignition of a thermonuclear plasma will be built in the mid 1980's. Typical EPR parameters for what was intended as the original experiment are given in Table IV. (The difference in the values of this table and those of Table I merely reflects the results of different studies performed at different times.)

This machine would have a large circulating power but could nevertheless have a net power output. Conceptual design studies of an EPR were done by ANL,³ GA,^{2,5} and ORNL^{1,4} over the two-year period from mid 1974 to late 1976. As a result of these studies, it became clear that the extrapolation in both technology and physics was so large that a machine intermediate in size between TFTR and EPR should be built before the construction of an EPR was attempted. Typical parameters of this machine, the TNS, are given in Table V. This machine will also achieve ignition, although it will have a smaller plasma and shorter burn time than EPR. A cross-sectional view of the EPR designed by General Atomic is shown in Fig. 3 as a graphic reminder of the size of an EPR.

The requirements of the poloidal field system are very difficult to meet, and for purposes of developing the appropriate technology we take the requirements to be these of TNS and EPR. Consequently the next two sections will consider in some detail the ohmic-heating systems of these two machines.

A. Experimental Power Reactor

Figure 4 shows the coil positions of the EPR designed by ORNL. Table VI gives the positions, approximate dimensions, and number of turns required for the coils which are pulsed during the start-up and plasma burn. The peak voltage and current applied to the ohmic-heating coils depend upon the method of connection as well as assumptions made in the computer codes which calculate response of the plasma to the applied voltages. The coils described in Table VI were designed to operate at 50 kA. One possible method of connection is to connect coils above and below the median plane in series and then to connect these two coil sets in parallel. With this method of connection, the ohmic-heating power supply would have to supply

TABLE IV

TYPICAL PARAMETERS OF AN EXPERIMENTAL POWER REACTOR

Plasma Parameters

Major radius, m	6.75
Minor radius, m	2.25
Maximum plasma current, MA	7.2
Ion density, m^{-3}	0.71×10^{20}
Ion temperature, keV	12
Burn time, s	100
Start-up time, s	2
Thermal energy, MJ	150
Magnetic energy, MJ	300

Toroidal Field Coils

Toroidal field on axis, T	4.8
Maximum field, T	11
Stored energy, GJ	29

Ohmic-Heating Coils

Peak field, T	6.5
Stored energy, GJ	1.9
Peak current, kA	175
Peak voltage, keV	55-95
Flux, Vs	130

Shield or Equilibrium Coils

Stored energy in plasma - equilibrium coil system, MJ	170
Peak current, kA	450

TABLE V

TYPICAL PARAMETERS OF TNS FUSION REACTOR

Plasma Parameters

Major radius, m	5
Horizontal minor radius, m	1.25
Maximum plasma current, MA	6.4
Ion density, m^{-3}	2×10^{20}
Ion temperature, keV	13.5
Burn time, s	20
Start-up time, s	1
Thermal energy, MJ	350

Toroidal Field Coils

Toroidal field on axis, T	4
Maximum field, T	8
Stored energy, GJ	6.4

Ohmic-Heating Coils

Peak field, T	3.1
Stored energy, MJ	700
Peak current, kA	200

Figure 3. Cross-sectional view of the EPR designed by General Atomic. (Courtesy GA.)

Figure 4. Coil positions of the ORNL EPR design.

TABLE VI

PULSED COIL DIMENSIONS IN THE LAST ORNL EPR DESIGN

<u>Ohmic-heating Coils</u>					
<u>Coil No.</u>	<u>Mean Radius (cm)</u>	<u>Z-Coordinate of Center (cm)</u>	<u>Turns</u>	<u>Thickness (cm)</u>	<u>Length (cm)</u>
1, 2	170	± 53.3	121.6	40	106.6
3, 4	170	± 160	121.6	40	106.6
5, 6	170	± 266.7	121.6	40	106.6
7, 8	216	± 348	60.8	41.8	45.6
9, 10	244	± 426	60.8	41.8	45.6
11, 12	302	± 526	60.8	41.8	45.6
13, 14	418	± 618	30.4	29.8	32.2
15, 16	577	± 643	15.2	21.0	22.8
17, 18	789	± 580	7.6	14.8	16.14
19, 20	1005	± 425	3.8	10.2	11.4
21, 22	1160	± 199	3.8	11.0	11.4

<u>Decoupling Coils</u>					
<u>Coil No.</u>	<u>Mean Radius (cm)</u>	<u>Z-Coordinate of Center (cm)</u>	<u>Turns</u>	<u>Thickness (cm)</u>	<u>Length (cm)</u>
1	203	160	-5	20	320
2	263	390	-1	25	17.5
3	312	493	-1	25	17.5
4	514	626	-1	25	17.5

<u>Shield Coils</u>					
<u>Coil No.</u>	<u>Mean Radius (cm)</u>	<u>Z-Coordinate of Center (cm)</u>	<u>Turns</u>	<u>Thickness (cm)</u>	<u>Length (cm)</u>
1	424	190	1	15	15
2	544	287	1	15	15
3	654	314	1	15	15
4	754	305	1	15	15
5	842	267	1	15	15
6	912	207	1	15	15
7	962	131	1	15	15
8	987	45	1	15	15

<u>Trim Coils</u>					
<u>Coil No.</u>	<u>Mean Radius (cm)</u>	<u>Z-Coordinate of Center (cm)</u>	<u>Turns</u>	<u>Thickness (cm)</u>	<u>Length (cm)</u>
1	170	350	-2	15	45.6
2	230	390	-2	45.6	15
3	450	630	1	20	20
4	665	628	1	20	20
5	954	472	1	20	20
6	1169	175	1	20	20

a peak current of 100 kA. The studies of reference 7 indicate that when the ohmic-heating coil turns are adjusted to require a peak current of 175 kA, the peak voltage required at the beginning of the start-up ranges from 55 to 95 kV. A lower voltage peak (~ 35 kV) occurs in the middle of the start-up phase as shown in Fig. 5. In the normal operating mode of the ohmic-heating coil, the current is maximum at the beginning of the start-up phase and is completely reversed during the start-up.

Since the total stored energy can amount to 2 GJ and the transfer time is about one second, the ohmic-heating power supply must remove energy from the ohmic-heating coil and charge it with the opposite direction current at an average power of 4 GW. During the burn, current in the ohmic-heating coils is gradually increased to make up for resistance losses in the plasma. At the end of the burn, current in these coils is reduced in a programmed shutdown sequence and reversed to prepare for the next cycle.

Figure 5. Ohmic-heating coil applied voltage waveforms.

B. TNS

Possible arrangements of the ohmic and equilibrium coils in TNS are shown in Fig. 6. Figure 7 shows a typical TNS cross-sectional view. The plasma cross section in TNS is about half of the cross section of EPR, and the major radius is also reduced by 25%. This smaller cross section, along with more peaked current distributions which appear in flux conserving tokamaks, could increase the required volt-seconds to maintain plasma current during the burn. In the EPR designs the volt-seconds required during the burn ranged from 3% to 30% of those required during start-up. For TNS the number may reach 100%. For the most part, however, the demands in peak power, voltage, and current will be less for TNS compared with EPR since TNS is a smaller machine.

C. Design Interactions

The areas in the ohmic-heating system design where major technical problems exist are closely interrelated, and one part of the design cannot be optimized in isolation from the other parts. Choosing the simplest design for one part of the system may put intolerable burdens on another. Some of the points which must be considered in the overall system design are presented in the following sections.

1. Coil Design

Most of the ohmic-heating coil designs using superconducting coils have half biased the current, i.e., the designs provide for the current swing during a complete cycle to move from its peak value in one direction to the same value in the other direction. Half biasing minimizes the stress levels on the coils but requires that the coils remain superconducting after a change of 6 to 12 T in 1 s, be cryostable so that they can recover their superconductivity, or both. The first option requires that hysteresis and dynamic losses be minimized by using a mixed matrix superconductor. The second option leads to complex heat transfer and hydraulic problems to remove a larger heat load from a conductor with a high copper matrix ratio. In both cases it is desirable to reduce eddy current losses in the coil internal support structure, and it is especially important if the coils are to remain superconducting.

Figure 6. Possible coil arrangement in TNS.

Figure 1. Typical TNS cross-sectional view.
(Courtesy ORNL)

The magnitude and direction of the forces on the coils is another area which has to be considered carefully. A tabulation of the forces on the ohmic-heating coils which was done by ANL showed some results which are revealing. Vertical forces on some of the coils could reverse in sign in event of a sudden quench of the plasma. Axial compression forces may turn out larger than expected and altered in sign at a given axial position within a winding because of interaction with other coils. Some of the hoop forces turn out to be compressional rather than tensional for the same reason. Finally the large radii of the coils can lead to large hoop stresses.

Current and voltage to the ohmic-heating coils can be varied over all practicable values as long as the power delivered to the plasma remains unchanged. Several considerations come into selecting an operating current. Technical judgment fixes the largest single superconducting cable to have a current carrying capability of about 50 kA. The largest cables built to date are those constructed for the METS program, and more development work in this area is clearly needed. If the power supplies to the ohmic-heating coils are best operated at currents much higher than 50 kA, it will be necessary to parallel cables or possibly even to transform the current. Some paralleling methods can lead to problems with circulating currents which degrade cable and coil performance.

2. Power Supplies and Switches

The principal problem in the power supply and switch system design is to minimize the cost while keeping reliability high and maintenance low. Systems which use conventional components are very expensive, and the cost estimate for EPR ran to \$170 M. Present cost estimates put homopolar based systems and ac generator systems at about the same price for systems operating at 175 kA. Development will be needed for the homopolar generator. The largest cost savings can be obtained by not using conventional solid state switch systems. If this can be done, the homopolar based system becomes significantly cheaper than the ac generator based system.

III. PROGRAM

A. Superconducting Energy Storage Coils

1. Design Criteria - Current, Voltage, Field

The ohmic-heating coil array of an EPR poses a number of practical problems. These coils range a factor of six in diameter and ten in axial dimension. The shorter axial lengths correspond to the larger diameter coils. The large aspect ratio of diameter to length for the outer coils creates some structural stability problems; however, these are a consequence of the size which by itself should not pose unusual problems on a superconducting coil.

The greater requirement imposed upon superconducting ohmic-heating coils is that of the high field and complete transfer of energy out of the coils with one field polarity and back into the coils with reverse field polarity in periods as short as 1 s. The LASL program will have as its early goal the design, fabrication, and testing of model ohmic-heating system coils capable of complete field reversal with energy transfer out and back in 1-to 2-s periods.

Typical central solenoidal ohmic-heating coils are represented by the ORNL^{1,4} and GA⁵ EPR designs. The ORNL design proposes using six segments of equal length with each segment having 6.08 MA-turns. The coils are to have 25.3-kA conductor wound in 10-turn pancake spirals. Twenty-four such pancakes will be combined to make a 240-turn coil segment with 2560 m of conductor. The outside dimensions of each of the six solenoidal segments are 150-cm i.d. by 190-cm o.d. by 107 cm long.

The ORNL calculations show that the peak field on the conductor is near 6.5 T and that two-thirds of the energy loss during transfer for the ohmic-heating coils occurs in the central coil solenoid. The energy dissipation per cycle for each of the six central coil sections is roughly 8.8 and 0.8 kJ, respectively, hysteresis and coupling losses. If a thin walled stainless steel forced flow confining conduit is used to sheath strands of the superconductor, then 5.5 kJ of eddy current losses occur during the transfer. The total ohmic-heating losses are 90 kJ hysteretic, 5.9 kJ coupling, and 40 kJ in the conduit.

The GA⁵ EPR poloidal field coil design proposes to use multiturn superconducting E-coils outside of the toroidal field coils and to provide a flux change of 75 Vs. This compares well with the Vs values for the ohmic-heating and shielding-decoupling system values of Table I.

The GA central solenoid E-coil design is a single long coil having 60 MA-turns. The coil is designed to have a 134-turn, single layer winding and proposes to use 450-kA conductor. This size conductor is a large extrapolation of superconducting technology; however, the peak voltage during energy transfer is only 10 kV. The solenoid dimensions which include the structure are 195-cm i.d. by 325-cm o.d. by 15.3 m long.

The GA calculations show that the peak field on the conductor is 5.65 T. Most of the energy loss of the E-coil system will be in the central solenoid where the field is high. The total system losses per pulse are 38.9 kJ hysteretic and 12.7 kJ coupling.

A superconducting test coil, to give meaningful data on the performance of a tokamak ohmic-heating system, must reach the 6-to 7-T field level, have an appropriate current density, be cryogenically stable, be capable of removing the heat generated, remain superconducting during the energy transfer, and undergo numerous energy transfer cycles.

Studies¹⁻⁵ for EPR tokamaks have established rather adequate but broad design criteria for superconducting ohmic-heating system coils. These are given in Table VII. The lower current, higher voltage combination of parameters appears to be the most practical or readily attainable advance in superconducting technology. AC rotating machinery as an energy store more readily matches the low current condition, whereas a homopolar machine more readily matches high current coils. For a practical low value current level system, it becomes necessary to parallel connect coils or to transform machine current output to match the coils.⁷

TABLE VII

PARAMETERS FOR EPR SUPERCONDUCTING OHMIC-HEATING SYSTEM COILS	
Current, kA	25-450
Voltage, kV	10-95
Field, T max	5.7-6.5

2. Cable Design

The basic approaches to superconducting cable design are twofold. They rely on the method of removing heat from the cable, namely, by forced flow or pool immersed heat transfer. The former uses cable in a sheath¹¹ and the latter follows the more conventionally designed coils which have been successfully used in pulsed METS operation.^{12,13} Cables for both types of heat transfer systems must otherwise be very nearly the same. They require many strands of wire, highly transposed and of small diameter. The small diameter gives a large heat transfer area to volume ratio and decreases the eddy current losses. This latter point may not be too important if an effective composite matrix superconductor which decouples each filament and its stabilizing copper sheath can be developed. The physics of the wire in the cable has been developed over the years and is discussed below.

The largest superconducting cables for use in coils have been those developed for the METS system.¹²⁻¹⁴ One such cable used 319 strands of 0.39-mm o.d., CuNi-Cu matrix, multifilament NbTi in an $11 \times (4 \times 7 + 1)$ array. Limiting transport current was measured in a test facility described by Miranda¹⁵ to be 17 kA at 3 T. Another cable also developed for a 300-kJ coil designed by Westinghouse Electric Corporation was made of a 72, 0.81-mm-o.d. active strand Cu matrix, multifilament NbTi superconducting wire in a Roebel transposition of twelve cabled sub-bundles. The coil was operated in an overrated condition carrying 13.3 kA with a peak field on the conductor of about 2.9 T.

Prototype cables for a full scale METS 400-kJ coil have been developed. These cables are intended to operate at 25 kA. The cable development program has obtained information on cable transposition, interstrand shorting, and properties of electrical insulation of wires in cables. Cable designs with a minimum of shorting, only a few interstrand shorts were found in moderately compacted cable lengths of 50 feet, have been made. Circulating currents may occur in badly shorted cables. Insulation comparisons indicate that both Formvar and GP200 (Isonel 200), a polyester/amide-imide, are promising for cables.

Cable development for superconducting ohmic-heating coils will depend to a great extent on the actual coil designs. It is the intention of this program that the coils and cables be designed simultaneously, even in the conceptual stages. Short lengths of cables, both prototypical nonsuperconducting and superconducting, will be developed early in the program on a collaborative basis with industry. These will be used to make small coils, conduct heat transfer tests, study effects of mechanical motion, observe losses, make cable joints, determine stability, and measure limiting transport current. Cables for both forced flow and pool immersed heat removal are to be evaluated.

3. Cryostability

The ohmic-heating coils of an EPR typically will store 1 to 2 GJ's of energy. (See Tables I, IV, and V.) Although energy transfer times are relatively fast, of the order of one to a few seconds, because of functional requirements, other system demands point to an absolute need for a cryostable ohmic-heating coil system. Because of the large amount of energy contained, any accidental or abnormal mode of operation could cause catastrophic damage to an expensive system. The mere act of charging the ohmic-heating coils for startup must be such that minor perturbations caused by mechanical motion and magnetic flux flow do not give rise to a superconducting to normal conducting transition. Such a transition would release large amounts of energy and prevent the reaching of full field and energy storage. The cyclic current and field swing in bipolar operation of the coils requires that the coil not go normal, except on a transient basis and in such small regions as not to cause excessive Joule heating. Large I^2R losses would create prohibitive refrigeration loads; hence, ohmic-heating coils must be cryostable with fast recovery times if localized normal transitions do occur.

The cryostable requirement is contrary to the low energy loss requirements for an optimum system. Pulsed operation of superconducting coils generate eddy currents which vary with the mass of conducting material in the wires. This poses a unique design compromise to be achieved for the superconducting coils.

Cryostability is a condition which is dependent not just on the superconducting wire but is a manifestation of the entire coil system and its cryogenic environment. Thus the program plan includes the design, fabrication, and testing of realistic cables and coils to assure cryostability. The cryostable characteristic most likely will depend upon the He dewar or coil enclosure, and experimentation will consider such limitations.

4. Losses

Energy losses in the coils will arise from electro-magnetic and mechanical effects. The former are associated with magnetic flux flow and are attributed principally to eddy currents in conducting structures and in matrix materials of the superconductors, hysteresis in the superconductor, and coupling and self field effects. The latter arise from strain energy changes with field, current, and Lorentz force changes as the stored energy is transferred in and out of the ohmic-heating coils. Frictional heat is also released from relative motion of coil parts during the energy transfer cycle.

Studies and assessments of poloidal field coil development generally advocate a program which models the large coils. Electro-magnetic heating effects are modeled rather well in such simulations. Mechanical heating effects, particularly those from friction, usually are not predictable with high accuracy in going from small to large coils. This becomes particularly troublesome when the frictional energy release arises from conductor motion.

As a part of the METS program, two methods of measuring energy losses were devised.¹⁶ One was an indirect calorimetric observation and the other was electrical. The calorimetric method collects helium gas in a shroud over the coil with a calibrated container. Liquid is vaporized by the heat released during the energy transfer from the coil. The electrical measurement was made by a method similar to one proposed by Wilson¹⁷ and reported by Lucas.¹⁸ This method plots the current in the coil against the time integrated voltage across the coil. For initial and final current of zero, the enclosed area of the curve represents the energy loss.

For the 300-kJ METS coils, energy losses ranged up to 2% of the stored energy. Measurements made by the calorimetric method were accurate to within a few percent for the larger losses and to within 10% for the lower ones. The electrical loss measurements were good to within about 1%. Uncertainties as to the origin of small extraneous effects contributed to the experiments.

The loss measurement techniques developed for the METS program are directly applicable to this work.

5. Heat Transfer and Stability

Experiments on forced flow He heat transfer have been conducted^{19,20} with emphasis on supercritical pressure conditions for cooling superconducting magnets. The forced flow data show improved heat transfer as compared with pool boiling conditions.^{21,22} The supercritical single phase, although subject to large fluid property changes in the low temperature and moderate over pressure ranges, has hydrodynamic advantages such as avoiding bubble formation. Although flow, pressure, and temperature instabilities²³ might be encountered under some conditions, these can be minimized by proper choice of the fluid state conditions and pressure drop. In general, flow stabilities should be minimal and choking flow nonexistent.

Disadvantages of forced flow cooled superconductors include the requirements for a pump, either ambient or low temperature. If a low temperature, high efficiency ($\geq 70\%$) pump can be developed, then a low temperature fluid loop looks promising. Further, the need to have flow channels in parallel and series imposes manifolding and flow distribution problems. These flow channels will most likely not coincide with the coil electrical paths which will cause further complications. The situation is even more complex for ohmic-heating coils in comparison with toroidal field coils since the voltages across the coils will be high. See Table VII.

In terms of coil design and construction there is no doubt but what those for pool immersion cooling are less complicated. The literature is replete with successfully operated pool immersed cooled coils. Almost all of these are for dc operation. The METS program coils^{12,13} are the largest pulsed energy storage coils made which operate in a pool immersed mode.

Their intrinsically stable design and purposefully quite low energy losses¹⁶ of 0.3 to 2% of the stored energy places them in a unique category.

In contrast, measurements in the last years on force flow cooled superconductors have been aimed at determining pressure drop⁴ and stability^{24,25} for dc tokamak toroidal field coils. The pressure drop data give friction factors for the sheathed superconductor of factors of three to five over those for smooth circular tubing. The very recent²⁴ stability data yield steady state recovery currents from imposed pulsed perturbations which are 10 to 20% above predicted values.

The experimental program of Hoenig and Montgomery is to extend their measurement on forced flow conductors to an 18-turn, 1-m-wide by 2-m-tall race-track coil to operate at 5 kA, 8 T, and 3.5 K steady state and to recover from pulsed heating cycles for a 10-K temperature rise.

The ohmic-heating coil development program will evaluate both forced flow and pool immersed heat transfer and superconducting stability for small and intermediate size coils undergoing large current and field swings. The work and facilities at the MIT Magnet Laboratory will be evaluated to determine whether a complementary program to the present toroidal field coil work should be implemented at the Magnet Laboratory for forced flow cooled superconductor under simulated ohmic-heating conditions.

6. Test Coils

The ohmic-heating system development will rely on a model approach. Most of the design and superconductor and coil characteristics can be determined on small coils. The plan will be to have an industrial ohmic-heating proposal, design, and fabrication qualification program for coils of a maximum size to fit within the existing large LASL plastic dewar. The time scale for completion of this work is about twenty-four to thirty months. The initial proposal phase of the industrial participation is to include a conceptual design and a technical assessment of problems to be completed within the first six months. That work, together with early coil work to be done at LASL, will provide the basis for ongoing small scale superconductor tests and other small coil tests. These tests will be aimed at

conductor evaluation for heat transfer, stability and transient response, and energy losses under simulated ohmic-heating system current and field changes.

A conceptual test coil design of the size intended for the small coil industrial participation with potential for using either pool immersed ^4He cooling or forced flow cooling has been undertaken. The parameters are given in Table VIII. The current density value includes the structure.

Tests on the high field, 0.7-MJ small coil will first involve transferring energy from the coil into a resistor. This is the most easily accomplished and is efficient in time. The L/R discharge will be variable depending upon the size of external resistor used. The experiment will rely on the techniques already developed for the METS coil testing program.

Energy transfers out of a coil will be instantly followed by a determination of whether or not the superconducting cable has gone normal.

The ultimate test of returning the energy pulsed out of the coil, back into the coil will require a secondary energy store with a reasonably long time constant. Such a test might well be accomplished by a resonant L-C-L circuit as used in the METS system with the added provision that either a dual capacitor bank or a switching arrangement to change the capacitor bank polarity is used to handle the reversed voltage. Both systems will require crowbarbing the load coil to trap the energy temporarily while the capacitor bank switching occurs. The energy return to the superconducting coil would again be a METS type transfer initiated by interrupting the crowbarred current in the load coil.

The program will include devising and building a test facility to test the 0.7-MJ coil through the entire field swing.

The results of the quite small coil tests and the 0.7-MJ coil designs will be used as the basis for an ohmic-heating prototype large coil.

TABLE VIII

OH TEST COIL PARAMETERS

Current, kA	25
Current density, kA/cm ²	1.7
Field, max., T	6
Inside radius, cm	24
Outside radius, cm	40
Length, cm	140
No. turns	150
Energy stored, MJ	0.7

7. Prototype Large Coil, 10 MJ

Examination of a large coil design poses other problems. A single central coil segment of the ORNL tokamak can be used to demonstrate the difficulties related to meaningful tests. Such a segment will store about 60 MJ of energy; however, the maximum field on the conductor is reduced to 4 T. A summary of field and stored energy values is given in Table IX for a series of EPR like large coils for which the current carrying cross sectional area has been held constant at 107-cm length by 40-cm radial dimension. A 1.42 kA/cm² current density value to include structure was assumed to apply. Only the radius was varied. The first coil in the table is representative of an ORNL EPR single center coil segment.

TABLE IX

PROTOTYPE LARGE OH COIL STUDY

<u>Inside Radius, cm</u>	<u>Maximum Field, T</u>	<u>Energy Stored, MJ</u>
150	4.0	60
100	4.4	32
50	5.0	9.1
30	5.5	2.9

It becomes clear that high fields can be reached only with a small diameter, long coil if the energy is not to be excessive. Subsequent prototype large coil designs will make compromise selections of radius, length, turns per unit length, current density, field, and energy stored and transferred.

The LASL coil program proposes to design, fabricate, and test a prototype ohmic-heating coil with an energy level near 10 MJ. The coil is to have a relatively high field with other characteristics based upon the 0.7-MJ-coil industrial development work. A specific MDF proposal for this phase will be submitted at the appropriate time.

Testing of a high-field 10-MJ coil can be accomplished by pulse discharging into a resistive load. To transfer the energy out and back into the coil requires a more complex system. Three circuits for testing the coil are shown in Fig. 8. The upper circuit shows the arrangement for transferring the energy into a resistive load. The middle circuit is rather elaborate. It provides for a HETS resonant energy transfer into a load coil where the energy is temporarily stored by using the crowbar switch IG_{CB1} . This allows time for reversing the capacitor bank, C_T , with the reversing ignitrons, IG_R , to take the reverse voltage polarity. The crowbar, IG_{CB1} , series breaker is then opened and the energy transferred back into the TOH coil where it is trapped by the crowbar IG_{CB2} . The resistor, R , dumps the energy. This test circuit has certain disadvantages since it requires the use of a 5-MJ transfer capacitor. The lower circuit shows a transfer scheme as proposed to test the model 10-MJ HETS machine.²⁶ The superconducting coil would replace the load coil of that circuit. The HETS machine, operating into large inductances, has a natural transfer period of 1 to 2 s with correspondingly reduced maximum current output of 25 to 50 kA. The energy of the 9.1-MJ coil of Table IX could be transferred in about 1.7 s with the HETS machine near the coil design current. The homopolar shown in the top two circuits of Fig. 8 is representative of a continuous duty dc energy charging supply and is not a fast discharging machine.

During the early part of the program, studies will be undertaken to determine the best way to test a 10-MJ coil through the full field swing of energy store and transfer.

The possible use of the HETS machine as an energy store and transfer element to test the proposed 10-MJ prototype large ohmic-heating coil has been mentioned. Alternative homopolar energy supplies are discussed below. The consideration of a more appropriately designed homopolar machine to conduct tokamak ohmic-heating systems tests is an important element of any such program.

Figure 8. Tokamak ohmic-heating coil test circuits.

8. Prototype Large Coil, 50 to 100 MJ

As a part of the very long range program goal, a coil representative of a significant segment of a large tokamak ohmic-heating system must be made and successfully tested. It is presently contemplated that such a system will involve both a superconducting coil and homopolar machine in the 50-to 100-MJ range. Large coil conceptual designs are to be used to guide the work described just above. Conversely, any final coil design of the magnitude indicated here must be preceded by successful system tests at lower energy levels.

B. Superconducting Wire and Cable

The coil program dictates the need for superconducting wire and cable development. NbTi is the best available material for the superconductor of choice for the proposed field levels of 6 to 7 T for the ohmic-heating coils. This is about the practical limit of NbTi; and if other higher field, practical superconductors are developed, they need to be considered for more advanced designs. At 6 T the short sample critical current density for NbTi is 130 kA/cm² at 10⁻¹² ohm-cm resistivity. At high fields an appropriate maximum operating current density is about one-half of the short sample critical current density.

A 25-kA cable has been specified for the METS 400-kJ coil. A ten-kiloampere cable has been successfully tested in a METS 300-kJ coil at overdesign currents of 13.3 kA. The wire parameters for one of the METS coils, the ORNL, GA, and ANL EPR designs, and a LASL experimental conductor are given in Table X for comparison. Although the superconductors are intended to operate under considerably different conditions with high current density for the METS wire in a metastable condition, the differences are more nearly those of degree and not magnitude. The fabrication of 4- and 5- μ m diameter NbTi filaments in a composite matrix has been done but not on a totally reliable basis.

The LASL program will develop composite matrix superconductor for fabricating cables for ohmic-heating coils.

The actual wire design must consider stability of the conductor, the composite matrix composition, operating point, energy losses, and magneto-resistive effects.

TABLE X

COMPOSITE SUPERCONDUCTING WIRE

	<u>METS</u>	<u>ORNL</u>	<u>GA & ANL</u>	<u>LASL</u>
Diameter, mm	0.40	0.57	0.50	0.16
Matrix, NbTi/Cu/CuNi	1:2:1.5	1:3.5:0.5	1:2.1:0.77	1:2:1.5
Filament diameter, μm	15	4	5	5.8
Twist pitch, mm	3.4	5.2	6	3.6
No. of filaments	156	4106	2613	156

Some of the features of the superconducting cables for the GA and ORNL conceptual EPR designs have already been discussed with respect to the ohmic-heating coils, heat transfer, and stability. The details of the presently conceived cables are presented in Table XI.

TABLE XI

OHMIC-HEATING COILS SUPERCONDUCTING CABLE

	<u>GA</u>	<u>ORNL</u>
Cross section, cm^2	135	9.62
Void fraction	0.5	0.5
Structure fraction	0.25*	*
Superconductor fraction	0.25	0.5
Number of wires	17188	1369
Current per wire, A	26.2	18.3
Critical current per wire, A	69.5	36.1
Total current, kA	450	25

* Internal to conductor for GA; external to conductor sheath for ORNL.

These cables represent two very divergent design philosophies, namely immersion pool cooled cable by GA and forced flow cooled by ORNL. The large difference in current has already been discussed. Both designs have merit, although the 450-kA current level is an extreme extension of superconducting technology.

The two systems have distinct advantages. Sheathed cables have been tested by MITML using supercritical-pressure helium cooling and are conceptually feasible for ohmic-heating coils.⁴ The possibility of a

supercritical-pressure pool cooled system might combine the advantages of both.

Cable for ohmic-heating coils must provide a relatively large surface area for heat transfer and sufficient matrix material of good normal conductivity so the rate of removal of joule heating due to the transport current will permit the conductor to return to its superconducting state after having been perturbed. The sheathed cable, operated with a supercritical-pressure helium system, has the advantage of maintaining a homogeneous fluid phase as the heat transfer media in contact with the superconductor. This will prevent gas blocking of the cable to assure good heat transfer. A forced flow cooled magnet system might operate in a more stable mode as compared with an immersed pool cooled system. Consequently, the superconductor might also require less matrix material to be stable. Open structure cables to operate in a cryostable manner when immersed in a bath of helium will provide a potentially simpler system with more gas removal passages. This would decrease the overall current density.

The LASL program will evaluate industrially supplied superconducting cables from several suppliers. Both forced flow cooled and pool immersed cooled cables in simulated coil arrays will be evaluated for stability, heat transfer, recovery rates, and current-field operating limits. This work is not intended to duplicate that being done elsewhere. Additional attention will be given to the wire transposition, joints, current transposition or diffusion lengths at joints, and mechanical motion effects.

C. Switches

1. General Discussion

Switches for tokamak fusion devices must satisfy several functions and, hence, will be of different types. Switching operations for large tokamaks include plasma initiation in the ohmic-heating system, ohmic-heating current reversal, ohmic-heating coil crowbar, vertical field coil crowbar, and protection of the poloidal and toroidal field coils. Although the program emphasis of this proposal is on ohmic-heating systems, the technology and facilities development at LASL is such that probably every tokamak switching requirement can be evaluated. A set of typical parameters for switching functions is given in Table XII.

TABLE XII

TOKAMAK EPR SWITCHING FUNCTIONS

	Max. Current kA	Max. Voltage kV	Action	Type Switch
Plasma initiation	450* total 50/circuit	50-95 25	0	solid state, air blast, SF ₆ , vacuum interrupters, oil
OH reversal	450* total 50/circuit	25	0-C	solid state, air blast, SF ₆ , vacuum interrupters, oil
OH crowbar	450* total 50/circuit	50	C	ignitrons, spark gaps
VF crowbar	500	1	C	ignitrons, spark gaps
Poloidal protect	500	0.2	C	gas gap, explosive
TF protect	21	<10	0	air blast, SF ₆ , oil, vacuum interrupters
	21	< 2	C	spark gap, vacuum interrupters

* The 450-kA value comes from the GA design study;⁵ however, other studies place the upper limit at 200 kA.

For reliability, solid state switches, thyristors, are probably the best state-of-the-art devices available. To interrupt large currents and to withstand high voltages requires using many SCR's in series-parallel arrays. This is a costly solution for reliability as demonstrated in the EPR tokamak ohmic-heating study by University of Texas, Westinghouse, and LASL.⁷ Air blast, oil, and SF₆ circuit breakers and vacuum interrupters to interrupt large currents cost a small fraction of the equivalent solid state switch; however, their reliability is less or inadequately proven for particular dc operations. The saving to be made justifies considerable development and testing effort. Further, some maintenance cost might be acceptable to avoid the expensive solid state switches.

Vacuum interrupters are commercially available, have been traditionally designed for ac circuits and infrequent fault operations. Only recently have mechanical life tests of vacuum interrupters been run at LASL and a specific dc interrupter has been designed and fabricated by Westinghouse

for LASL. Operation of vacuum interrupters in parallel switching has been used on the Alcator at MIT; however, in that case any one of the interrupters would perform the operation.

The program proposal is to extend the present LASL vacuum interrupter switch testing to currents as high as 150 kA and to 100 kV. This will require using the interrupters in parallel and possibly in series for high reliability.

Electrode erosion in all types of mechanical switches is important to the reliability and number of maintenance free cycles. Inherent in current interruption is the need to counterpulse the current to zero to extinguish the arc. If the counterpulse is delayed until the contacts are fully open and the energy is low, then the arc exists for a long time. Under these conditions electrode erosion is aggravated. If large counterpulse energies are used, the current in the arc can be diminished by earlier and longer counterpulsing and electrode erosion is greatly reduced.

The potential advantage of larger counterpulse energies to minimize vacuum interrupter electrode erosion and the almost certain need of large counterpulse energies for air blast, oil, and SF₆ circuit breakers will form the basis of a part of the switch testing program to be conducted by LASL.

It is proposed that in addition to the vacuum interrupter development and testing, that air blast, oil, and SF₆ circuit breakers are to be tested for realistic tokamak ohmic-heating systems. Current and voltage conditions similar to those of Tables I and XII will be provided by a synthetic test circuit. This is a considerable broadening of the switch development program which presently exists at LASL for high beta fusion systems.

A compilation of the relative qualitative characteristics of switches is given in Table XIII. This table makes apparent the directions in which development and testing can provide the largest benefits. Obviously, the reduction in cost of solid state devices is paramount; improvement of maintenance and reliability of mechanical switches is important, to a lesser degree this applies to vacuum interrupters; and raising the unit ratings of vacuum interrupters is desirable.

TABLE XIII

SWITCH CHARACTERISTICS

	<u>Oil, Air, SF₆</u>	<u>Vacuum</u>	<u>Solid State/Plasma</u>
Unit ratings	H	I	L
Life and reliability	L	I	H
Cost	I	L	H
Availability	now	now	now/later
Maintenance	H	I	L
Size, weight, noise/unit	H	L	L*/I

H = high, L = low, I = intermediate

*

Low for solid state devices on a per unit basis; however, a large array is required to switch large currents.

2. Vacuum Interrupters

The switch development and testing work done to date at LASL has been primarily on vacuum interrupters to break 25 kA and to withstand 60 kV with a 3-ms switch opening time. Other work has been undertaken to develop a cryogenic disconnect as a no load switch to carry 25 kA in ^4He with resistance of $40(10)^{-9}$ ohms or less. In addition, a slow opening, oil immersed, 25-kA, 60-kV switch has been built.

The work done on the vacuum interrupters and presented in this subsection was stimulated by the requirements of a high-beta Scyllac Fusion Test Reactor (SFTR).^{14, 27} This work has been part of the LASL METS program.

Vacuum interrupters appear to be easily upgraded, are simple and rugged, can undergo thousands of operations, and their cost is low. These characteristics made them an attractive choice to meet the METS switching requirements.

Mechanical reliability tests without current interruption were run on three Westinghouse 7-in. vacuum interrupters. One interrupter was operated over 75 000 times and the other two over 10 000 times with no observed deterioration.

Tests on interruption reliability have been run on thirteen vacuum interrupters. The currents are listed in Table XIV for the 50% and 90% interruption reliability. Reliability tests at the 99% level requiring longer times with many more interruptions will be made when the new test facility is complete.

The first twelve switches are Westinghouse vacuum interrupters. The last switch is a General Electric experimental interrupter. Switches 11 and 12 are specially designed interrupters for dc operation. The other interrupters are ac fault switches. Switch 11 has an internal field coil which generates an axial field from the current through the switch and the switch was operated to the current limit of the test facility with 100% interruption reliability. Five other switches have been tested in an externally applied axial field of 0.15 T. The last column of the table gives the percentage increase in current at the same interruption reliability levels with the axial field. The >100% improvement for switch 12 results from no interruption failure up to the 37-kA current limit of the test facility.

TABLE XIV
VACUUM INTERRUPTER CURRENT INTERRUPTION RELIABILITY

<u>Interrupter</u>	<u>Diameter, in.</u>	<u>Current, kA</u>		<u>Axial Field % Improvement</u>
		<u>50% -</u>	<u>Reliability - 90%</u>	
1 WL23331	4	6	5	
2 WL32797	4	8	7	10
3 WL23340	4	13	12	25
4 RP903C	4	6	5	
5 WL23342A	5	17	14	
6 WL23346A	5	18	15	70
7 WL32710	5	16	14	80
8 WX32996	5	19	17	
9 WL23231	7	24	22	
10 WL32722	7	26	24	
11 Prototype 1	7	>37	>37	*
12 Prototype 2	7	15	13	>100
13 PV08A	8	28	26	

* Interrupter has an internal axial field coil.

Switches 9 and 10 have been operated over wide ranges of current levels. Their electrode erosion has been small. One interrupter has undergone over 1000 electrical interruptions and the other over 5000.

The high voltage limit of the standard 7-in. Westinghouse interrupters was enhanced by using an external plastic-fiber glass and bakelite-cloth shroud containing SF₆. With this shroud the switch was operated successfully to 66 kV without external breakdown.

To extend the ratings and life of vacuum interrupters the program plan will include

- a. Extended current measurements with axial-field switches,
- b. Determination of current limit dependence on voltage,
- c. Testing of series - parallel switches with inductors and transformers in the circuit to force current sharing,
- d. Improved switch designs with industrial participation,
- e. Operation of switches with longer counterpulse times initiated prior to electrode separation,
- f. Development of faster acting actuators, and
- g. Actual life testing of switches.

3. Mechanical Circuit Breakers

Three basic types of mechanical circuit breakers are available. These are air blast, SF₆ atmosphere, and oil immersed. Their advantage is that the cost per ampere of current is low. This is offset by higher maintenance and short life as compared with solid state switches. These advantages and disadvantages are discussed more thoroughly above.

Advanced air blast breakers have been primarily a development of the European market to satisfy power utility needs and are used in generator circuits. As such they are often called generator breakers. A survey of air blast generator breakers has been made; and their performance capacities are given in Table XV.

The AEG breaker has been tested²⁸ at KEMA, a test facility at Arnhem, Netherlands. (See Table XV.) The breaker has been considered for the ohmic-heating circuits of the Joint European Torus (JET) and the GA Doublet III.

TABLE XV
GENERATOR BREAKER CAPACITIES

Type		Brown-Boveri		Delle-Alsthom	AEG	
		DBVG ²⁹	DR ^{30,31}		ac duty ^{35,36}	dc duty ²⁸
Receiving voltage	kV	24	30	10	17	>24
Continuous current rating	kA	5	32	15		
1- to 3-s current rating	kA	50	200	150	>100	>100
Closing current	kA	180	600	400	270	380
Interrupting current (symmetrical)	kA	72	250	250	80	125 (73 test)

All ac voltages and ac currents are given as rms values. The crest values of interrupting currents are approximately $1.8\sqrt{2}$ times the symmetrical rms current value.

The table shows typical interrupting currents. The receiving voltages are higher for some cases not shown in the table for somewhat reduced interrupting currents.

The literature has been reviewed and an analysis made. The study is included as an appendix to this proposal.

The conclusion of that study is that a potentially economical solution to the ohmic-heating switching lies with air blast generator breakers. To minimize erosion, precise opening times and carefully made mechanical linkages will be required. Dry air or LN_2 boil-off gas at 80 bar are required to operate the AEG breaker and an ancillary gas handling system will be needed.

Compact designs of SF_6 breakers for high voltage are available. The operating pressure of these breakers is in the range of 4 to 6 bar as compared to 50 to 100 bar for air blast breakers. The cost of an SF_6 breaker is 60 to 75% of that for a comparable air blast breaker. The savings are mainly due to the simpler compressor system of SF_6 breakers with their closed loop gas cycle. The interrupting current of existing SF_6 breakers is limited to values of approximately 80 to 100 kA (ac symmetrical). This is less than for air blast breakers. The possibility of extending SF_6 breaker ratings by unusual counterpulsing techniques or by breaker redesign warrants exploration. The redesign work would be done with industrial participation.

D. Dewars and Refrigeration

The small coil tests described in Section III A6 of this proposal are to be conducted in an existing plastic-fiber glass dewar.³⁷ The dewar was specially fabricated for the METS program and is ideal for this new work. The heat leak with He is 10 W. The dewar is superinsulated and has an intermediate thermal shield. The metallic superinsulation and shield are etched vertically to eliminate coupling and are neither shorted layer to layer nor form a closed electrical turn in any one layer. These precautions were taken to minimize coupling and energy losses in the dewar itself. A second similar dewar is to be obtained for back-up purposes.

Dewars for larger coils will be integrated into the coil designs and will be proposed as a result of the design studies for those coils.

The 0.7-MJ small test coil described in Section III A6 has an estimated loss per pulsed energy cycle of less than 3 kJ. The existing 700-W, 4.5-K refrigerator presently being installed at LASL as part of the METS program was designed to take pulsed loads. If the 3-kJ heat release occurs in times of the order of one second as expected, then the refrigerator can carry the load every five seconds. This is well within the design range of the refrigerator.

The estimated pulsed energy loss of the 10-MJ prototype coil of Section III A7 is between 8 and 13 kJ. The 700-W, 4.5-K refrigerator pulsed load capacity is rated to be at 60 liters of He vaporized to the saturated state every seven minutes. This is equivalent to an effective 360-W refrigeration capacity over the 700-W base design level. The refrigerator has a low temperature surge dewar to take the pulsed gas load. The 60 liters every seven minutes corresponds to a pulsed load rating of 153 kJ every seven minutes. The rating is reduced because of refrigeration inefficiencies if the gas is superheated. Thus, the energy loss for a 10-MJ coil can be readily accommodated by the existing refrigerator approximately one hundred times per hour for the condition that the boil-off gas is returned to the refrigerator cold box at 4.5 K.

The steady state capacity of the refrigerator is more than ample to cover the normal heat leaks and load from 25- to 50-kA vapor cooled electrical leads into a dewar.

Reference 4 gives the heat load for the entire central ohmic-heating solenoid to be 90 kJ per cycle. This is for six coils, each of which will store about 60 MJ of energy. Thus the energy loss from one such coil could be covered by the existing refrigerator.

E. Equipment and Facilities

1. Existing Equipment and Apparatus

This part of the proposal presents in a brief manner unusual equipment and the facilities needed for the program. Some of the equipment is already available and is listed immediately below.

- a. Homopolar 6 V, 15 kA
- b. Rectifier 20 V, 12 kA, <3% ripple
- c. Battery power supplies (2), fully variable 0-5 kA, 2 V
- d. Dipole, 3.8-cm free bore, 5.5 T
- e. Dipole, 9.55-cm free bore, 6 T, in construction
- f. Flux pump, 35-kA secondary
- g. Flux pump, 65-kA secondary
- h. Dewar, plastic, 60-cm i.d. x 120-cm deep
- i. Dewar, plastic, 110-cm i.d. x 305-cm deep
- j. Dewar, stainless, 43-cm i.d. x 305-cm deep with high voltage insulating liner
- k. High voltage test bay, 100 kV, automated
- l. Hi-pot tester, 150 kV
- m. Electrical leads, vapor cooled, 2 pair, 15 kA, 60 kV
- n. Electrical leads, vapor cooled, 1 pair, 25 kA, >60 kV
- o. Refrigerator, He; 700 W, 4.5 K steady state and 360 W, 4.5 K pulsed load; or 250 liters/hr liquefier, being installed
- p. Interrupter test facility, 300 kJ, 30 kA, 60 kV
- q. Loss measurement apparatus, 3 T, $3(10)^3$ T/s

The two dc power supplies, items a and b, are arranged to operate in parallel for a 25-kA test capability. The delta-Y connected rectifier ripple has not affected coil tests since the coil inductance has served as a filter.

The flux pump, items f and g, currents are limited to about 30 and 45 kA respectively with practical size conductor samples. The flux pumps

can be used in conjunction with the dipoles, items d and e, to measure conductor and cable limiting transport currents. The large dipole has an eddy current shield of high purity aluminum in the magnet bore to avoid quenching of the magnet when test samples go normal.

The dewar, item i, is described in Section III D. The smaller plastic dewar, item h, was built with somewhat similar precautions taken to avoid losses in the superinsulation. The smaller dewar has a stainless steel top end flange whereas the larger plastic dewar does not.

A limited description of the refrigerator is given in Section III D.

The interrupter test facility was originally developed to test HVDC vacuum interrupters and to conduct capacitive energy transfer operations to test superconducting, 300-kJ coils, both for the METS program.³⁸

The interrupter test facility is shown in Fig. 9. Its operation is as follows:

The power supply on the left charges the energy storage capacitor C_1 to a voltage whose maximum is 20 kV. The maximum energy stored is $\frac{1}{2} C_1 V_1^2 = 720 \times 10^{-6} \times (20 \times 10^3)^2 = 288 \text{ kJ}$.

The switches J_1 and J_2 , the shorting balls SB, and R_{C_1} and R_3 are used to switch the supply, to dump the energy on a misoperation, and to monitor the voltage on C_1 .

On a trigger signal, ignitron I_1 dumps the stored energy into the storage coil L through the closed vacuum interrupter VI. When the storage capacitor C_1 is discharged, ignitron I_2 maintains the current through L and VI so that it decays exponentially with a time constant, L/R , of about 200 ms.

Capacitor C_2 is meanwhile charged to the opposite polarity at a voltage V_2 .

At the appropriate time, about 5 ms after I_1 is triggered, I_3 is triggered. This causes the energy stored in C_2 to flow through VI in the opposite direction to the current already present. If the voltage across C_2 is correctly

$C_1 = 1440 \mu f$

$C_2 = 100 \mu f$

$L = 0.4 mH$

$X = \text{saturable reactor}$

Figure 9. Interrupter test facility circuit.

chosen, the combined current flowing through VI will pass through zero, allowing its interruption at a low value of dI/dt . The time during which the combined current is held near zero depends upon the stray inductance in the loop containing C_2 and VI. The sinusoidal oscillation of this "counterpulse" circuit is observed to have a period of about 160 μs , and thus the stray inductance can be calculated to be

$$\frac{1}{C_2} \left(\frac{I}{2\pi} \right)^2 = \frac{10^6}{100} \left(\frac{80 \times 10^{-6}}{\pi} \right)^2 = 6.4 \mu H.$$

If this period is not long enough to keep dI/dt low enough, it can be lengthened by inserting extra inductance in the circuit at X in the form of a saturable inductance. Normally, a reactor with a flux rating of about 0.01 Vs is used. When the current is interrupted in VI, it keeps flowing in the same direction through L, but flows now through I_3 into C_2 . C_2 charges up to its maximum voltage, V_2 , such that $V_2 = V_1 \sqrt{C_1/C_2}$, in a time given by $\pi/2 \sqrt{LC_2} \cong 314 \mu s$. When $V_1 = 20$ kV, V_2 is 76 kV. The current then reverses and in another 314 μs it has flowed through I_4 , L, and the still conducting I_2 to reach approximately its original value. If $V_1 = 20$ kV, I is

$$\sqrt{C_1/L} V_1 = \sqrt{\frac{1.44 \times 10^{-3}}{0.4 \times 10^{-3}}} 20 \times 10^3 = 38 \text{ kA}.$$

The four ignitrons, I_5 , are now triggered so that the current in L is crowbarred through them and the resistor R. The energy is dissipated in R.

The loss measurement apparatus,³⁹ item q, is unique in that it uses a superconducting switch in series with the superconducting field coil to initiate the field sweep. The apparatus uses two sensing coils connected in opposition in the bore of the solenoidal field coil. The superconducting sample to be tested is mounted in one of the sensing coils. The differential signal from the coil gives a current versus integrated voltage

plot and the area within the closed loop for original and final current at zero represents the energy loss. The superconducting switching technique used in the apparatus was an early technology development of the METS program. The apparatus is to be modified to go to 7 T with 0.1- to 3-s discharge times.

2. Power Supply

A new high current, low voltage power supply and substation will be needed to do coil testing. The coils will operate at currents ranging from 25 to 150 kA. It is presently planned to design individual coils to operate at the 25-to 50-kA level. Some tests for parallel operation of coils will be run; hence, higher currents will be required. The long range possibility of developing superconducting cables up to 100 kA or more should not be precluded because of an inadequate current source. It is planned to obtain a 10-to 15-V, 100 to 150-kA, continuously variable controlled current, twelve-phase equivalent delta-Y connected, rectifier and substation for a power supply.

The new facilities installations are shown in Fig. 10. They are shown in relation to an existing building. Included are the rectifier-substation location, the HETS machine area, the tokamak ohmic-heating coil test area, the new 2-MJ interrupter test facility location, and the 700-W, 4.5 K refrigerator location.

3. Interrupter Test and Magnetic Energy Transfer and Storage Facilities

The current levels required for tokamak systems are higher than those used in the METS program. These increased ratings for switches have been discussed in Section III C. To be able to conduct appropriate tests for the switch program two additional interrupter test facilities are planned. These serve a double function and are also used as the circuit to conduct capacitive energy transfer experiments on superconducting coils.

The first expansion of an interrupter test facility is nearly identical to the existing facility. See Section III E1. It is being installed now and is located adjacent to the existing facility. The facility will provide for simultaneous testing of switches at the present 30-kA, 60-kV level and for testing of one switch assembly at a time at

Figure 10. Equipment and facilities layout.

about 60 kA and capacitive energy transfer experiments up to 1.1 MJ with the two facilities connected together. One of the two facilities will be dedicated most of the time to life and reliability testing.

A 2-MJ interrupter test facility is being designed. It is planned to operate at test levels up to 100 to 150 kA and 100 kV. The circuit to be used will be similar to that of Fig. 9. The capacitors for the energy storage bank and one of the two power supplies are available. Half of the capacitor bank with as much as 1 MJ of energy will be available for large counterpulse energies. Controls for the test facility will be optically isolated to minimize maintenance and for safety. A large load inductor with a long time constant will be designed for use in the facility. The installation and operation of the high-current interrupter test facility will make necessary the development of crowbar switches for the 50-to 150-kA current level to withstand 100 kV. This is a reasonable extension of the present 31-kA, 66-kV METS ignitron crowbar technology.

4. Homopolar

The tokamak ohmic-heating systems study⁷ points to the need for homopolar machine development. With the elimination of the excessive costs associated with SCR switching, homopolar machines would be the preferred pulsed energy source. This requires heavier rotor, higher voltage homopolars than the pulsed, fast discharge 10-MJ model HETS machine;²⁶ but it shares in an essential way the common elements of high-peripheral-speed rotors and high-current-density brush collection systems. The 30-ms, 10-MJ fast discharge machine can be operated over a longer discharge period at reduced currents merely by increasing the inductive load. This will provide important test data bearing on machine performance and its subsystems. The possibility of using the fast discharge HETS machine to test the 10-MJ prototype large coil was discussed in Section II A7. The original HETS machine proposal²⁶ considered applications of the machine to tokamak ohmic-heating systems. The machine was to be retrofitted with a heavy rotor to store as much 30 to 50 MJ of energy for slow discharge periods of 250 ms to 1 s.

The program proposed here will require a homopolar machine as a facility device to test large coils. It should have an energy transfer and storage

capability of at least 50 MJ. To be useful it must operate with high efficiency.

The entire HETS machine program should be evaluated to determine whether it should be redirected immediately to become a tokamak ohmic-heating power supply. This evaluation is in the early discussion stage and a decision has not been reached.

F. Tokamak Ohmic-Heating System Studies

1. EPR Ohmic-Heating System Studies

A study⁷ of ohmic-heating circuits for EPR size tokamaks was carried out jointly by LASL, the University of Texas, and Westinghouse during 1976. The purpose of the study was to define possible circuits and power systems for driving the ohmic-heating coils and to estimate cost for these systems. It was first necessary to identify the essential functions which the ohmic-heating power supply must perform.

These functions are:

- a. To provide a plasma initiation voltage early in the start-up phase to heat the plasma beyond the line radiation barrier,
- b. To provide a plasma maintenance voltage to complete the plasma ohmic heating and to bring the plasma current to its full value, and
- c. To provide a plasma voltage during the burn to make up for joule losses.

Other functions such as shut down of the burn or resetting of the ohmic-heating system are assumed to be within the capability of any circuit which can handle the three functions listed above. The circuit combinations in which the three modules could be connected were examined, and the necessary current and voltage ratings of the components determined. The more promising circuits were selected for further study, and finally three circuits were costed. One of these three circuits made use of homopolar generators, another of salient pole ac generators, and the last made use of a round rotor ac generator of the type used with steam turbines.

To understand better the voltage and current requirements of the ohmic-heating system, a zero-dimension burn code was written to predict the plasma resistance during the ohmic-heating phase of the tokamak cycle. Most of the programming effort was directed toward the earliest part of the start-up where complex radiation and ionization processes must be considered to predict plasma behavior. This computer code was especially useful for calculating the magnitude and duration of the initiation voltage needed for rapid heating of the plasma within the first 50 ms of the ohmic-heating period. If this plasma initiation voltage, sometimes called the "blip," is applied to the primary ohmic-heating coils through solid state switches it is a very costly undertaking. Tables II, III, and XVI give a summary of the ohmic-heating circuit costs of references 7 and 9. An interesting point is the large cost of solid state switches in the total cost of the circuits and the relatively small cost of the generators. The very costly item called "resistor switches" is used only to form the plasma initiation voltage blip at the start of the ohmic-heating cycle.

TABLE XVI

SUMMARY OF EPR OHMIC-HEATING CIRCUIT COSTS

<u>Homopolar Generator Based System</u>	(\$'s x 10 ⁶)
Homopolar generators	18.4
Generator switches	54.7
Resistor switches	90.8
Resistors and rectifiers	<u>12.3</u>
	176.2
<u>Turbo-Generator Based System</u>	
Generators	13.0
Generator rectifiers	58.6
Resistor switches	59.2
Generator rectifier switches	33.2
Line rectifiers, resistors, and generator drives	<u>6.3</u>
	170.3
<u>Salient Pole Generator System</u>	
Generators	19.4
Generator rectifiers	54.8
Resistor switches	55.3
Generator rectifier switches	31.0
Line rectifiers, resistors, and generator drives	<u>7.0</u>
	167.5

2. TNS Ohmic-Heating System Studies

The ohmic-heating studies begun on EPR have been extended to TNS by a collaboration of the University of Texas and the Los Alamos Scientific Laboratory. An independent study of the entire TNS system has already been completed by Westinghouse.⁴⁰ One goal of the LASL-UT collaboration is to investigate methods of reducing the cost of the circuitry which generates the plasma initiation voltage blip. A method which has been suggested is to couple the voltage blip into the ohmic-heating circuit through a pulse transformer rather than produce it with a voltage drop in a resistor. Another method is to couple the initiation pulse into the plasma with an extra set of coils more closely coupled to the plasma.

Other areas which will be investigated are the comparison of half-biased, ohmic-heating coils to full-biased coils, and the comparison of superconducting to normal conducting coils. Different schemes for connecting the ohmic-heating coils in series and parallel combinations will also be investigated.

3. Future Studies

A continual evaluation of circuit components and corresponding costs will be necessary in the light of new technological developments. This is especially true in the area of switching technology where the opportunity for great cost savings has been recognized. As the design of the ohmic-heating coils becomes more firm and as necessary developments in homopolar technology are verified, better cost estimates can be made for these circuit elements. Improvement in the performance and lowering of the cost of solid state switches might also occur and thereby lower the cost of the ohmic-heating circuit.

IV. PROGRAM SUMMARY, EXPERIMENTS, AND SCHEDULE

The discussion of Section III suggests a program more by implication than by specific statements of planned events, goals, and schedules. The discussion has emphasized particularly the major components of the tokamak ohmic-heating system. Relevant technology and technology deficiencies were presented. The discussion has pointed to the need for an integrated approach to technology development in several areas. A program with an evolutionary three step model coil development is suggested. This section outlines and summarizes a specific experimental program with a schedule for accomplishment.

The elements of the program are combined into a number of major groups for organizational and logical development. These are superconducting energy storage coils, superconducting wire and cable, switches, facilities, system studies, and miscellaneous and ancillary technology. The program outline follows with detail given for these major divisions of work.

A. Superconducting Energy Storage Coils

1. LASL design and fabrication of several 100-kJ test coils at 25- and 50-kA current levels to evaluate cable, heat transfer, stability, recovery, and mechanical motion effects - extended effort FY's 78 thru 80.
2. 0.7-MJ coils, industrial design and fabrication, two coils - 25 and 50 kA, 75 to 100 kV, 6.5 T, forced flow and pool immersion cooled.
 - a. Conceptual design 10- and 50-MJ coils 10/77 - 3/78
 - b. Design and proposal 0.7-MJ coil 10/77 - 7/78
 - c. Fabricate 0.7-MJ coils 8/78 - 2/80
 - d. Tests by LASL 3/80 - 1/81
3. Prototype Large Coil, 10 MJ, industrial design and fabrication, two coils.
 - a. Design of two coils 10/78 - 2/80
 - b. Fabrication of two coils 3/80 - 2/82
 - c. Tests by LASL 3/82 - 3/83

4. Prototype Large Coil, 50 MJ, industrial design and fabrication.

a. Design of two coils	5/82 - 7/83
b. Fabrication of one coil	8/83 - 8/85
c. Tests by LASL	9/85 - 9/86

The program is intended to model a number of coils in a sequential manner going from 0.7-MJ to 50-MJ energy storage sizes. To minimize delay and to provide continuity, design of each successive generation of coils is overlapped with both the fabrication and testing of the preceding generation. All the work is to be done with extensive industrial participation.

Small test coils are to be designed and built by LASL to observe cable behavior - heat transfer, stability, mechanical motion, and magnetic flux flow effects. Experiments not duplicating those done by either MITML or ORNL will be performed on both forced flow and pool immersed cooled magnets. High voltage insulation and stand-off will be evaluated. It is planned to test coils with both 25-and 50-kA superconducting cable. This work is conceived as being a continuing effort for several years.

The 0.7-MJ coils, to be designed and fabricated by industry, represent the largest size coil which can be tested at LASL with equipment presently available or currently being installed. The plan to have two coils designed and fabricated reflects early choices on the options available from combinations of both 25-and 50-kA current levels and forced flow and pool immersed cooled coils. Test facilities at LASL are presently limited to 25 kA. Their expansion to 50 kA will occur in FY79 if the capital equipment funding is available. The scheduling of this capability could set the current level of the first coils at 25 kA with a subsequent coil made to operate at the 50-kA level.

The plan allows the narrowing of options as each subsequent generation of coils is tested and decisions can be made.

The FY78 program includes 10- and 50-MJ coil conceptual design studies. These studies are to provide guidance for the 0.7-MJ coil designs and to establish costs for the 10- and 50-MJ coils. The conceptual design work

will also provide detailed and realistic schedules for these large coils.

Testing of the 0.7-MJ coils will first be done by dumping the stored energy into a resistor. Immediately after transfer, measurements will be made to determine whether or not the superconducting cable has gone normal. A more advanced test will be conducted by building a test facility similar to those shown in the top two circuits of Fig. 8. The test will be a half biased or bipolar operation with field swings from 6.5 T in one direction to a reverse field of 6.5 T.

Tests of the 10- and 50-MJ prototype coils will be similar to those for the 0.7-MJ coils. The higher energy levels make energy transfers, which are nondissipative and are intended to give a field reversal, dependent upon a homopolar machine as depicted in the lower circuit of Fig. 8. The test coil replaces the load coil of this circuit. A facility, most likely to include a homopolar machine, is to be built to test the prototype coils. Early in the program, analyses and design will be undertaken to establish the facility details and components.

B. Superconducting Wire and Cable

1. Design low loss superconductor (first)	6/77 - 8/77
2. Purchase low loss superconductor (first)	10/77 - 6/78
3. Evaluation low loss superconductor (first)	7/78 - 10/78
4. Design 25- and 50-kA cable (first)	6/77 - 2/78
5. Purchase 25- and 50-kA cable (first)	7/78 - 3/79
6. Evaluation of cable (first)	4/79 - 10/79
7. Redesign of superconductor (second)	10/78 - 11/78
8. Purchase redesigned conductor (second)	12/78 - 8/79
9. Evaluation of redesigned superconductor (second)	9/79 - 12/79
10. Redesign cable (second)	1/79 - 4/79
11. Purchase redesigned cable (second)	9/79 - 4/80
12. Evaluation of cable (second)	5/80 - 1/81

The schedule for obtaining wire and cable provides for a first and second iteration for design, procurement, and evaluation. The second iteration becomes unnecessary if the wire and cable evaluations are satisfactory from the first. The wire and cable development is conducted in parallel with

the coil design and fabrication in such a way that the wire evaluation for each iteration precedes or coincides with the very early portion of the coil fabrication for both the 0.7-MJ and 10-MJ coils. Cable evaluation parallels the coil fabrication and the results will have bearing on the interpretation of the coil tests and the successive coil designs.

Wire and cable designs will be done by LASL in consultation with industrial participants who are working on coil designs at times coinciding with the wire and cable schedule. All wire fabrication and cabling, sheathed and unsheathed, is to be done by industry. Wire and cable is to be obtained from several suppliers. The program will first focus on NbTi with Cu-CuNi matrix. Large scale, 8-inch extrusion billet, production capability is to be developed. Quantities of superconducting wire will be obtained initially from proven procedures which use small billets. This wire will be used for cabling and testing while the 8-inch billet program is being established. No explicit elements are incorporated in this program proposal for Nb₃Sn. The judgment has been made to defer any such activity until such time as the dc, high field superconducting coil program demonstrates substantial progress and a specific technical demand exists. The demand would arise from either tokamak designs requiring high fields or the need for a greater field-temperature margin to preserve superconductivity during the energy transfer for present designs at the 6-T level.

The superconducting wire and cable procurement for industrial fabricated coils is to be integral to that part of the program and is not listed separately here.

Experiments with individual wire strands will include short sample critical current determinations, loss measurements under simulated energy transfer conditions, stability as a result of mechanical motion and magnetic flux flow in 5-to 7-T fields, recovery from the normal to superconducting state at high fields with external heat sources, and heat transfer analysis of the wire undergoing transient joule heating. Some of these experiments will be performed in the field of the large bore dipole presently being built. Its maximum field is expected to be above 6 T.

The experiments to be conducted on the cables have been discussed briefly in Section IV A under the small test coils. In addition, limiting transport current measurements will be made on the cables at high fields and full current. The large bore dipole will provide the fields; and a high current, one-shot flux pump will be utilized to supply the current when the cable test sample configuration does not have a high inductance.

C. Switches

1. Purchase vacuum interrupters, saturable reactors, transformers	10/77 - 1/78
2. Purchase special dc vacuum interrupters (several)	1/78 - 6/79
3. Test vacuum interrupters and circuits	present - 10/78
4. Purchase air blast breaker	10/78 - 4/79
5. Test air blast breaker	5/79 - 9/79
6. Modifications and retest of air blast breaker	10/79 - 8/80
7. Purchase SF ₆ breaker	10/79 - 3/80
8. Test SF ₆ breaker	4/80 - 2/81
9. Modifications and retest of SF ₆ breaker	3/81 - 10/81
10. High speed actuator development	present - 10/79

The ohmic-heating coil development program will in itself require that switches carry 25 to 150 kA. The high number corresponds to coil operations in parallel. Withstand voltages may be as high as 100 kV. Items 1 through 3 represent an extension of the present vacuum interrupter test program to these higher current-voltage levels. Items 4, 5, and 6 and 7, 8, and 9, respectively, are for new switch testing and development of mechanical breakers. Item 10 is considered to be an ongoing effort which will be related primarily to vacuum interrupters. Fast actuators, to the extent that they do not appreciably shorten the mechanical life of a switch, can shorten the arcing time and contact erosion.

The work to be conducted on the switches includes the following:

- a. Extended measurements of current and voltage limits on individual vacuum interrupters, air blast breakers, and SF₆ breakers;
- b. Reliability tests on the same types of switches;
- c. Life tests of the same types of switches;

- d. Series-parallel operation of vacuum interrupters to increase the switching capacity;
- e. Development of saturable reactors and other circuit compensating components;
- f. High speed actuator operation;
- g. Variable counterpulse operation to determine the effects on reliability and life expectancy tests;
- h. Development of special dc and axial field vacuum interrupters;
- i. Optimization of mechanical switch design for dc operation;
- j. Development of hybrid switches or switching circuits incorporating different types of switches; and
- k. Development of high current, high voltage crowbar switches.

The above list is not exclusive or limited. Intercomparison of data will be made. Switch developments will affect electrode designs and materials, voltage shields, air blast channels, mechanical structure and linkages, noise elimination, analysis of jitter, evaluation of dI/dt and dV/dt capabilities, etc. The long range result will be essentially two-fold with respect to tokamak applications. The first will be to identify alternative solutions to tokamak switching requirements, not just those related to ohmic-heating; and the second will be an economic and engineering optimization capability resulting from comparative analysis of the resulting test data and knowledge of switch costs.

Two major types of switches are not discussed here as receiving extensive evaluation. These are solid state and plasma devices. The studies^{7,9} made on ohmic-heating circuits indicate the greatest gains are to be made with mechanical switches and vacuum interrupters. Plasma valves or switches are inordinately expensive and have not been developed to the point that they switch enough current to offset the cost. SCR's are expensive because of the quantity required to switch large currents. Regardless, for SCR's an array of such size to be equivalent to at least a typical vacuum interrupter will be assembled along with its auxiliary components and will be tested to determine I^2t ratings for tokamak applications.

D. Facilities

1. Installation of 300-kJ, 30-kA, 60-kV switch and energy transfer test facility	present - 7/77
2. Installation of 2-MJ, 150-kA, 100-kV switch and energy transfer test facility	10/77 - 9/78
3. Purchase 150-kA, 15-V dc power supply	10/77 - 9/78
4. Install item 3 and busbar	10/78 - 4/80
5. HETS machine ²⁶	
a. Design, develop, test, fabricate, inspect, etc.	present - 7/80
b. Test facility design, components, construction, and check-out	present - 6/80
c. Install and test machine	7/80 - 3/81

The new switch test facilities are listed as items 1 and 2. Items 3 and 4 are the low voltage, high current dc power supply and its installation. Item 5 is a summary listing of the events for the HETS, 30-ms discharge time homopolar machine as presently planned on its own program. The homopolar is listed here as an adjunct to the tokamak ohmic-heating program and will be used for testing the superconducting coils. The final testing schedule for the homopolar is in advance of the first prototype 10-MJ coil test scheduled to start in September 1981. See Section IV A 3c. The possibility of obtaining, on the same time scale, a homopolar tailored to tokamak ohmic-heating tests is being assessed.

E. Systems Studies

The systems studies will be a long range continuing effort to cover several years and will occupy one to two man-years initially. The first studies will be conceptual in nature and will proceed to engineering detail as they progress and as the application for a TNS or other tokamak becomes better established.

The first studies have been completed and are documented.^{7,9} Current systems analyses are being done in collaboration with ORNL and GA. The University of Texas at Austin is assisting with circuit computations. The studies are inherently somewhat evolutionary in nature. This, of course, alters the direction of the study and the results as information is developed. Appendix B is an outline of the work program presently planned

by LASL on the ORNL TNS poloidal field system study. A similar work program is to be developed for studies on the GA TNS system.

In the ORNL TNS study a confirming magnetic field analysis was first made of a flux-conserving tokamak point design. The equilibrium field coil placement and number of coils is being evaluated. Alternatives for creating the plasma initiation blip by use of a set of coils separate from the ohmic-heating coils are being considered. Other alternative circuits are to be studied. These use high current homopolars and segmented-rotor low current homopolars. These, in turn, may have either intermediate or low voltage outputs. Optimized circuits, conceptual engineering, the beginning of detailed engineering for the coil-dewar components of this program, selection of other circuit components, and cost analyses will complete the immediate studies with ORNL and GA.

F. Miscellaneous and Ancillary Technology

The program carries with it certain ancillary technology developments to include such items as low-loss superconducting joints and high-voltage, high-current leads. These types of development are important to the success of the effort but usually are performed with a rather low profile. It is impossible to foresee all of the many small items of the kind just mentioned and no attempt is made to anticipate and list them as a part of the proposal.

Figure 11 gives a schedule for the major items of this program. Letters and numbers on the schedule lines refer to completion dates for the work of the subsections of the written discussions in this main section. Figures 12 and 13 give the schedules for the HETS machine as set out in its program.²⁶

Figure 11. Schedule for tokamak poloidal field system development program.

Figure 12. 10-MJ, 30-ms model homopolar machine construction and test schedule.

LASL TEST PROGRAM	FY 77	FY 78	FY 79	FY 80	FY 81
DESIGN FACILITY	△	△			
ORDER COMPONENTS	△	△			
CONSTRUCT FACILITY		△	△		
CHECKOUT FACILITY		△		△	
TEST 30-ms HOMOPOLAR				△	△
REPORT				△	△

Figure 13. LASL homopolar facility and machine test schedule.

V. COSTS

The tables of this section give a program cost breakdown by years. The individual major procurement items represent large purchases and contracts for industry for expense items and machine shop costs. The tables of this section are based upon the schedules of Section IV. The items of these cost tables are topically related to those of Section IV by title.

The summary cost table includes staff, major procurement, and capital equipment.

Present LASL FY77 funds will support, in part, TNS studies with ORNL and GA. Supplemental funds are to be provided for this work. Funds for FY's 77 through 80 will also provide for a modest level of active interaction with other laboratories to conduct tests of tokamak switches. The burden is not expected to be large in FY77, and hardware purchases are being made by the outside laboratory when the tests require unique components or materials. It is expected that this type of interaction will increase somewhat, and it is planned that staff support be maintained by direct ERDA funding for the LASL program. Uncertain fragmented funding through other laboratories on a long term basis is not and should not be considered.

TABLE XVII

MAJOR PROCUREMENT COST DETAILS FOR FY78 (\$10³)

1. Small test coils	150
2. 6.5-T, 0.7-MJ coils (2)	
a. Conceptual design 10- and 50-MJ coils	250
b. Design 6-T, 0.7-MJ coils	225
3. Low loss superconductor (first)	120
4. 25- and 50-kA superconducting cable (first)	60
5. Switches	
a. Vacuum interrupters, saturable reactors, transformers	60
b. Fast actuator	75
c. 2-MJ test facility	30
6. 25- to 50-kA electrical leads	25
7. High field magnet for loss measurements	<u>30</u>
	1025

TABLE XVIII

MAJOR PROCUREMENT COST DETAILS FOR FY79 (\$10³)

1. Small test coils	100
2. 6.5-T, 0.7-MJ coils (2), fabricate	400
3. 10-MJ, prototype large coil (2), design	200
4. Low loss superconductor (second)	120
5. Superconductor for item 2	150
6. 25- and 50-kA superconducting cable (first)	125
7. Switches	
a. Air blast breaker	270
b. Fast actuator	50
8. 25- to 50-kA electrical leads	25
9. Plastic dewar	<u>70</u>
	1510

TABLE XIX

MAJOR PROCUREMENT COST DETAILS FOR FY80 (\$10³)

1. Small test coils	100
2. 6.5-T, 0.7-MJ coils (2), fabricate	180
3. 10-MJ, prototype large coils (2), complete design and start fabrication (to include dewar, electrical leads, and superdonductor)	1000*
4. Superconductor for item 2	160
5. 25- and 50-kA superconducting cable (second)	160
6. Switches	
a. Airblast breaker, modify	50
b. SF ₆ breaker	<u>165</u>
	1815

* Estimate, to be better defined by the studies scheduled in Section IV A 2a in FY78. This item will be submitted in a separate proposal for review and approval.

TABLE XX

MAJOR PROCUREMENT COST DETAILS FOR FY81 (\$10³)

1. 10-MJ, prototype large coils (2), complete fabrication	2500*
2. LASL facilities modifications for testing 10-MJ coils	200
3. 2He transfer lines	150
4. Switches, modify SF ₆ breaker	<u>60</u>
	2910

* See footnote to Table XIX.

TABLE XXI

MAJOR PROCUREMENT COST DETAILS FOR FY82 (\$10³)

1. 10-MJ, prototype large coil tests	300
2. 50-MJ, prototype large coils (2), start design	<u>400</u>
	700

TABLE XXII

MAJOR PROCUREMENT COST DETAILS FOR FY83 (\$10³)

1. 50-MJ, prototype large coils (2), complete design	450
2. 50-MJ, prototype large coil (1), start fabrication	*
	450

* No fabrication cost estimate is made. Realistic values will be obtained from the studies scheduled in Section IV A 2a in FY78. The design of the 10-MJ, prototype large coil scheduled in Section IV A 3a in FY79 will further aid the scoping of cost for the 50-MJ coil. This item will be submitted in a separate proposal for review and approval.

TABLE XXIII

COST SUMMARY FOR TOKAMAK POLOIDAL FIELD PROGRAM (\$10³)

	<u>FY77</u>	<u>FY78</u>	<u>FY79</u>	<u>FY80</u>	<u>FY81</u>	<u>FY82</u>
Staff-Salaries, direct,	200	615	1185	1560	1715	1890
indirect, material & services *						
Major procurement	<u>-0-</u>	<u>1025</u>	<u>1510</u>	<u>1815</u>	<u>2910</u>	<u>700</u>
Total expense cost	200	1640	2695	3375	4625	2590
Capital equipment	<u>-0-</u>	<u>475</u> **	<u>400</u> **	<u>500</u> **	<u>100</u>	<u>100</u>
Total cost	200	2115	3095	3875	4725	2690

* The large increases in staff reflects the termination of the METS program and increased TOH effort with personnel reassignment.

** Purchase and installation of a 150-kA, 15-V dc power supply included. See Table XXIV.

TABLE XXIV

COST FOR 150-kA, 15-V DC POWER SUPPLY (\$10³)

	Equipment	Installation*
Rectifier	400	100
Busbar	150	150
Switchgear, 13.2 kV	6	
Transformer, 13.2 kV to 2.4 kV, 500 A	18	
Circuit breaker	<u>12</u>	<u> </u>
Total	586	250

Contingency and engineering at 40%. Total cost \$1170.

* Installation costs for all items are lumped under two listings.

VI. MANPOWER AND ADMINISTRATIVE ARRANGEMENTS

The work of this program is to be performed by the personnel of group CTR-9 under the direction of John D. Rogers, who will serve as Project Manager. Philip Thullen will be the Assistant Project Manager for technical matters, and Edward Kemp will be the Assistant Project Manager for administrative matters. CTR Division Office supervision will be provided by G. A. Sawyer and K. I. Thomassen. An administrative organizational chart is shown in Fig. 14.

The present FY77 budgeted level of personnel support for the METS, HETS, and TOH programs is 14-1/2 staff and 9-1/2 technicians (includes secretarial). Of these, 12 professional staff, one industrial staff member, and 6 laboratory technicians are in the direct day-to-day CTR-9 activities. The major fraction of these persons is currently supported under the METS program. By 1980 the METS program will have been terminated, and it is planned to have the following percentages of the staff funded by the TOH program: 41, 71, and 80 for FY's 78, 79, and 80, respectively. Because of contemplated FY78 funds curtailment, in the absence of increased tokamak ohmic-heating funds for staff, it will be necessary to plan reductions in personnel. If the funds indicated herein for staff are not met, then only a very limited program can be conducted. This proposal is based upon personnel levels corresponding to those budgeted for FY77.

Figure 14. Administrative organizational chart.

REFERENCES

1. M. Roberts and E. S. Bettis, eds., "Oak Ridge Tokamak Experimental Power Reactor Study-Reference Design," Oak Ridge National Laboratory Report ORNL/TM-5042, November 1975.
2. "Experimental Power Reactor Conceptual Design Study," General Atomics Corp. Eng. Staff, GA-A13534, July 1975.
3. W. M. Stacey et al., "Tokamak Experimental Power Reactor Studies," Argonne National Laboratory Report ANL/CTR-75-2, June 1975.
4. J. K. Ballou, R. L. Brown, R. B. Easter, C. G. Lawson, W. C. T. Stoddart, H. T. Yeh, "Oak Ridge Tokamak Experimental Power Reactor Study - 1976, Part 3 Magnet Systems," Oak Ridge National Laboratory Report ORNL/TM-5574, February 1977.
5. "Experimental Fusion Power Reactor Conceptual Design Study, Volumes I, II, and III," General Atomic Co., San Diego, CA, Report GA-A14000, July 1976; and Electric Power Research Institute, Palo Alto, CA, Report EPRI ER-289, December 1976.
6. "Tokamak Fusion Test Reactor Final Conceptual Design Report," Westinghouse Electric Corporation Report TFTR-TR-001, October 1975.
7. K. I. Thomassen, H. F. Vogel, D. M. Weldon, W. L. Bird, M. D. Driga, D. J. Mayhall, F. M. Heck, E. I. King, R. E. Stillwagon, "Ohmic-Heating Systems Study for a Tokamak EPR," Los Alamos Scientific Laboratory internal document, February 1977.
8. H. F. Vogel, K. I. Thomassen, W. Bird, F. M. Heck, "Pulsed Energy and Switching Requirements for Tokamak Ohmic Heating," IEEE Int. Pulsed Power Conf., Nov. 9-11, 1976, Lubbock, TX.
9. F. M. Heck, E. I. King, R. E. Stillwagon, "Experimental Power Reactor Ohmic-Heating Energy Storage Study," Westinghouse Report WFPS-TME-038, November 1976.
10. "Fusion Power by Magnetic Confinement Program Plan," ERDA Division of Magnetic Fusion Energy Report ERDA-76/110/1, July 1976.
11. M. O. Hoenig, D. B. Montgomery, "Dense Supercritical-Helium Cooled Superconductors for Large High Field Stabilized Magnets," Applied Superconductivity Conference, Sept. 30-Oct. 1, 2, 1974, Oakbrook, IL; IEEE Trans. Mag. MAG-11, No. 2, 569 (1975).
12. J. D. Rogers, "Superconducting Magnetic Energy Storage," Pulsed Power Systems Workshop, Sept. 20-22, 1976, White Oak, MD; Los Alamos Scientific Laboratory internal document.
13. J. D. Rogers, "Inertial and Inductive Energy Storage for Fusion Systems," in Proc. 2nd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Sept. 21-23, 1976, CONF-760935-P.4, p. 1201.

14. K. I. Thomassen et al., "Conceptual Design Study of a Scyllac Fusion Test Reactor," Los Alamos Scientific Laboratory Report LA-6024; Los Alamos, NM, January 1976.
15. G. A Miranda, J. D. Rogers, IEEE Trans. on Mag. MAG-11, No. 2, 582 (1975).
16. J. D. G. Lindsay, D. M. Weldon, "Loss Measurements in Superconducting Magnetic Energy Storage Coils," Los Alamos Scientific Laboratory Report LA-6790-MS.
17. M. N. Wilson, "An Improved Technique for Measuring Hysteresis Loss in Superconducting Magnets," Cryogenics 13, 361-363 (1973).
18. Edward J. Lucas, Technical Proposal P-1001-22, Magnetic Corporation of America (June 1975).
19. H. H. Kolm, Proc. of the Int. Symp. on Mag. Tech., U.S. Dept. Commerce, Springfield, VA, p. 611 (1965).
20. V. Arp, Adv. Cryog. Eng., 17, 342 (1972).
21. R. D. Cummings, J. L. Smith, "Boiling Heat Transfer to Liquid Helium," Int. Inst. Ref., Commission I, Boulder, CO, June 1966, Paper I-3.
22. S. S. Kutateladze, "Heat Transfer in Condensation and Boiling," State Sci. and Tech. Pub. of Lit. on Machinery, Moscow (AEC Translation 3770, Tech. Info. Service, Oak Ridge, TN).
23. P. J. Giarratano, V. Arp, R. V. Smith, Cryogenics 11, 385 (1971).
24. M. O. Hoenig, J. W. Lue, D. B. Montgomery, Francis Bitter National Magnet Laboratory, Cambridge, MA, to be published.
25. M. O. Hoenig, Y. Iwasa, D. B. Montgomery, M. J. Leupold, "Single-Phase Helium as Coolant for Superconducting Magnets," 1975 Int. Cryog. Materials Conf., Kingston, Ontario, Canada.
26. J. D. Rogers, K. I. Thomassen, C. J. Mole, "A Proposed 10-MJ Fast Discharging Homopolar Machine for Fusion Reactor Systems," Los Alamos Scientific Laboratory Report LA-6402-P, July, 1976.
27. F. L. Ribe, R. A. Krakowski, K. I. Thomassen, T. A. Coultas, "Engineering Design Study of a Reference Theta-Pinch Reactor (RTPR)," Special Supplement on "Fusion Reactor Design Problems" to Nuclear Fusion; International Atomic Energy Agency, Vienna, 1974.
28. P. Dokopoulos, K. Kriechbaum, "DC Circuit Breaker for 73 kA, 24 kV," translated by H. F. Vogel, Nov. 1976, Los Alamos Scientific Laboratory internal document.
29. "Airblast Circuit Breakers for Installation Indoors," Brown Boveri general pamphlet.

30. E. B. Scruggs, H. E. Weinrich, "Generator Breakers for Large Nuclear, Fossil-Fired and Pumped Storage Power Systems," ASME/IEEE Pro. Joint Power Generation Conf., New Orleans, Sept. 17-19, 1973.
31. P. Burckhardt, E. Vadaszi, M. Seidel, "DR Generator Breakers for Extremely High Service and Short-Circuit Currents," Brown Boveri Rev. 4, April 1975.
32. E. Thuries, B. Mallez, P. van Doan, R. Jeanjean, "Compressed Air, the Solution for Generator Breakers Problems," IEEE Conference Paper F 76 022-4, Oct. 24, 1975.
33. E. Thuries, "Air Cooled Generator Circuit Breaker," Pro. Joint Power Generation Conf., New Orleans, Sept. 17-19, 1973.
34. E. Thuries, P. van Doan, "L'Accroissement du Pouvoir de Coupure des Disjoncteurs à Air Comprime pour Reseaux Haute Tension," Rev. Gen. d' El. 6, 81 (1972).
35. K. Kriechbaum, "A Half-Cycle Air Blast Generator Breaker for High Power Testing Fields," IEEE Conference Paper C 57-PWR-2-3, May 1971.
36. K. Kriechbaum, "En Hochspannungs-Leistungschalter für Hochste Ausschalt-Leistungen," ETZ-A No. 4 (1976).
37. C. R. King, K. D. Williamson, W. Goree, "Development of Large Fiber Glass Reinforced Plastic Dewars for Superconducting Magnets at 4 K," 1976 Winter ASME Meeting, Nov. 28-Dec. 3, 1976, NY, NY.
38. C. E. Swannack, R. A. Haarman, J. D. G. Lindsay, D. M. Weldon, "HVDC Interrupter Experiments for Large Magnetic Energy Transfer and Storage (METS) Systems," Proc. 6th Sym. Eng. Problems Fusion Research, San Diego, CA, Nov. 18-21, 1975; IEEE Pub. No. 75CH1097-5-NPS.
39. J. J. Wollan, "High $\dot{B}$ Losses in Multifilament Superconducting Wires," 6th Int. Cryog. Eng. Conf. and Exhibition, Grenoble, France, May 11-14, 1976.
40. "TNS Engineering Quarterly Progress Report," Westinghouse Electric Corporation, Fusion Power Systems Report WFPS-TN-027, October 1976.

APPENDIX A GENERATOR BREAKERS

by

Herbert F. Vogel

The most economical method of frequently interrupting high currents appears to be found in the utilization of generator breakers. These are air blast breakers specially designed to be integrated with the three phase ~ 36-kV output buses of large station generators. Historically, the use of generator breakers was customary when the generator capacities were still modest; however, the current interrupting capacities of breakers did not, in the U.S., keep in step with the growth of turbogenerators as shown in Fig. A-1.

Fig. A-1. Trends in ratings of turbogenerators as function of year of construction.^{A-1}

Figure A-2 at the top shows a block diagram of a central generating station with two ac generators, transformers, auxiliary power system, high voltage or EHV transmission line system, and generator breakers. By contrast, Fig. A-2 in the lower circuit shows a block diagram of a station

Fig. A-2. Generator station circuits with generator breakers above and start-up transformer below.

without generator breakers with a start-up transformer instead. The start-up transformer is needed because auxiliary (i.e., 6.9-kV) power must be available before the generators can be started and before they can be synchronized with the bulk power transmission system. There is a significant cost difference as shown in Table A-I between systems with and without generator breakers. This cost difference has provided an important incentive in Europe for development of the generator breakers and the testing facilities for them. There are two testing facilities for generator breakers in Europe. These are KEMA at Arnhem, Netherlands, sponsored by the EEC's electric utility industry, and the R and D Station of the EDF (Electricité de France) at Les Renardières.

TABLE A-I

POWER PLANT COSTS WITH AND WITHOUT GENERATOR BREAKER

A. Plant Equipment Cost (transformers, breakers)	\$1 024 000	
B. Switchyard Costs	343 800	
C. 230-kV Start-Up Circuit Costs	143 500	
Total Cost of Start-Up Transformer Scheme		\$1 511 300
D. Cost of Generator Breakers	\$1 354 000	
E. Main Transformer Cost Savings	258 000	
Total Cost of Generator Breaker Scheme		1 096 000
F. Net Savings using Generator Breakers		\$ 415 300

The cost comparison as shown in Table A-I has been compiled by a European manufacturer^{A-1} for a 1000-MVA generating plant. There are technical advantages to the scheme with generator breakers in addition to the cost savings. The generator breaker is capable of interrupting the current in four cycles, i.e., 0.07 s as compared with 3 s for the case that the 230-kV breaker is used for short-circuit clearing on the HV or EHV bus.

The reason for using the air blast method for generator breakers is mainly to obtain maximum arc cooling to dissipate the arc energy. Air blast breakers are superior in this regard to any other breaker type. If the heat dissipation is marginal, then the arc temperature is greater and the statistical certainty of clearing the arc is reduced. This leaves only the air blast breaker for interrupting with certainty the large currents

Fig. A-4. Switch resistance versus current.

Fig. A-5. Switch resistance versus time.

The breaker currents are shown for both cases in Fig. A-6. Curve 1 is for constant arc resistance of $10^{-8}\Omega$, and curve 2 is for the changing arc resistance case indicated above. It can be seen that the time during which the breaker current is held near zero by the counterpulse circuit is lengthened by approximately 20% as a result of the arc resistance. The breaker current during the time interval $0.14 < t < 0.33$ or 0.35 ms varies between the limits $-5 < I < 1000$ A for case 1 and $9 < I < 1000$ A for case 2. The fact that the current in case 2 is never brought to exactly zero is not significant because a small increase in initial voltage on the counterpulse bank will cause two zero-crossings of the breaker current. The current rise shown in Fig. A-6 for times $t > 0.35$ ms will obviously not occur if the arc is cleared as expected.

Figure A-7 shows the arc voltage as function of time, where the rising branch at $t > 0.35$ ms should again be ignored because the arc is expected to clear earlier with the result that the open contact voltage will then rise to the value existing at that instant on the counterpulse capacitor C_1 as plotted in Fig. A-8.

The flux in the saturable reactor of the counterpulse circuit is plotted in Fig. A-9 as a function of time. The saturating flux is marked and amounts to 0.6 Vs, which implies a cross-sectional area of the laminated core of 0.25 m² leading to a coil i.d. of 60 cm with a saturating flux density of 2.4 T for the assumed transformer grade sheet steel (Armco grade M5). A plot of the saturating reactor's inductance versus time is shown in Fig. A-10, which shows the steep increase of the inductance at $t \approx 0.14$ ms responsible for forcing the current to $I \approx 0$.

It is noted that the average rate of current change as shown in Fig. A-6 is approximately -520 A/ μ s for $0 < t < 0.14$ ms. The rate of change slows to approximately -270 A/ μ s just before the contacts are parted at $t = 0.14$ ms. At the parting instant, the rate changes to -620 A/ μ s, which helps to decrease the current very rapidly from the small value already attained to zero.

Another significant point to be made concerns the ohmic energy going into the arc which integrates to 3.4 J at $t = 0.2$ ms and 10.9 J at $t = 0.34$ ms. This corresponds to an average power dissipation of 54 kW. These small numbers are responsible for the modest contact erosion observed.

at the generator terminals. An additional advantage is seen in the relatively large arc drop resulting from air blast cooling. The 60-Hz short circuit current may not have any zero-crossings if the circuit's L/R ratio is large. This ratio is significantly reduced by the air blast circuit breaker's arc drop with the beneficial result that current-zeros will occur after no more than 10 to 20 cycles.

In the case of current interruption for tokamak ohmic-heating, it is shown below that the energy fed into the arc is 3 to 10 J per switch opening. This would cause such small contact erosion that some contacts are estimated to be able to last for 10^4 operations.

Generator Breaker Interaction with Its Counterpulse Circuit

The reflexive effects of the arc resistance on the breaker voltage and current were studied by modeling the counterpulse circuit with the SCEPTRE code for the AEG air blast breaker tested at KEMA. The principal parameters of the model circuit, Fig. A-3, were those reported by Dokopoulos and Kriechbaum,^{A-2} and given in Table A-II.

TABLE A-II
COUNTERPULSE CIRCUIT PARAMETERS

	<u>Circuit Element</u>	<u>Value Reported by Kriechbaum</u>	<u>Value Used</u>
I ₀	constant current source	(73 kA)	73 kA
R _s	circuit breaker resistance		see text
C ₂	capacitor	5 μ F	5 μ F
R ₂	damping resistor	10...20 Ω	15 Ω
R ₅	current transfer resistor	0.33 Ω	0.33 Ω
L ₅	inductance of R ₅	1...10 μ H	5 μ H
L ₃	saturable inductor	0...1 Vs, 0...1 mH, 1...10 μ H saturated	0.6 Vs; 0...30 mH 0...1.6 μ H
C ₁	counterpulse capacitor	0.7...1.6 mF, 25 kV	0.7 mF, 19 kV
L ₁	inductance of capacitor bank	30 μ H	30 μ H

Fig. A-3. Generator breaker and counterpulse circuit.

The circuit was run in two versions, i.e.,

1. With $R_S = 10^{-8} \Omega = \text{constant}$ to show the circuit performance when the significant arc resistance is neglected; and
2. With $R_S = 10^{-8} \Omega$ for the time interval $0 \leq t < 0.14 \text{ ms}$ before the contacts separate, and with

$$\left(\frac{R_S}{R_O} \right) = \frac{I_O}{I} \mp 1$$

for $t > 0.14 \text{ ms}$ and $I \ll I_O$ where $I_O = 484.9 \text{ kA}$ and $R_O = 7 \text{ m}\Omega$, which is the arc resistance as function of current I reported by Thuries^{A-3} for a generator circuit breaker. The negative sign is used for air blast breakers and the positive sign for vacuum interrupters and SF_6 breakers.* The resulting breaker resistance is plotted in Fig. A-4 as function of breaker current I and in Fig. A-5 as function of time. The descending branch at $t < 0.35 \text{ ms}$ seen in Fig. A-5 does not exist if the arc clears as expected at $0.14 < t < 0.35 \text{ ms}$.

* The corresponding numbers for vacuum interrupters connected in parallel for 73-kA operation from measurements at LASL are expected to be $I_O = 19.6 \text{ kA}$ and $R_O = 0.423 \text{ m}\Omega$. Similarly, for SF_6 breakers $I_O = 250 \text{ kA}$ and $R_O = 1 \text{ m}\Omega$.

Fig. A-4. Switch resistance versus current.

Fig. A-5. Switch resistance versus time.

The breaker currents are shown for both cases in Fig. A-6. Curve 1 is for constant arc resistance of $10^{-8} \Omega$, and curve 2 is for the changing arc resistance case indicated above. It can be seen that the time during which the breaker current is held near zero by the counterpulse circuit is lengthened by approximately 20% as a result of the arc resistance. The breaker current during the time interval $0.14 < t < 0.33$ or 0.35 ms varies between the limits $-5 < I < 1000$ A for case 1 and $9 < I < 1000$ A for case 2. The fact that the current in case 2 is never brought to exactly zero is not significant because a small increase in initial voltage on the counterpulse bank will cause two zero-crossings of the breaker current. The current rise shown in Fig. A-6 for times $t > 0.35$ ms will obviously not occur if the arc is cleared as expected.

Figure A-7 shows the arc voltage as function of time, where the rising branch at $t > 0.35$ ms should again be ignored because the arc is expected to clear earlier with the result that the open contact voltage will then rise to the value existing at that instant on the counterpulse capacitor C_1 as plotted in Fig. A-8.

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It is noted that the average rate of current change as shown in Fig. A-6 is approximately $-520 \text{ A}/\mu\text{s}$ for $0 < t < 0.14$ ms. The rate of change slows to approximately $-270 \text{ A}/\mu\text{s}$ just before the contacts are parted at $t = 0.14$ ms. At the parting instant, the rate changes to $-620 \text{ A}/\mu\text{s}$, which helps to decrease the current very rapidly from the small value already attained to zero.

Another significant point to be made concerns the ohmic energy going into the arc which integrates to 3.4 J at $t = 0.2$ ms and 10.9 J at $t = 0.34$ ms. This corresponds to an average power dissipation of 54 kW. These small numbers are responsible for the modest contact erosion observed.

Fig. A-6. Switch current versus time.

Fig. A-7. Switch (arc) voltage versus time.

Fig. A-8. Counterpulse capacitor voltage versus time.

Fig. A-9. Saturable reactor flux versus time.

Fig. A-10. Saturable reactor inductance versus time.

Conclusion

A potentially economical solution to the tokamak ohmic-heating circuit with its high switching rate seems to be available in a design with generator breakers. Their potentially small contact erosion is the most important prerequisite for successful operation. A requirement to minimize erosion will be the design of a precision mechanism permitting operation in reasonable coincidence with the counterpulse circuit. High quality design of the mechanical links and other moving parts of the breaker is also required.

The arcing times measured on the AEG breaker when interrupting 65...73 kA at KEMA were 50...100 μ s; the jitter in contact separation was within ± 40 μ s. Air flow requirements are 1.8 m³ (SPT) for opening and 0.5 m³ (SPT) for closing. The required operating pressure for the arc chamber and the air entering it is 80 bar. Cost of the breaker, including a control cubicle but not including commutating circuit and compressor system, is approximately \$220 000. The cost of the compressor system is substantial but probably a LN_2 boil-off system costing approximately \$50 000 may be considered.

References

- A-1. A. Eidinger, J. H. Mosele, "Simplification in Power Station Switchgear by Using Generator Breakers," IEEE Conf. Paper 70 CP 513-PWR, July 1970.
- A-2. P. Dokopoulos, K. Kriechbaum, "DC Circuit Breaker for 73 kA, 24 kV," translated by H. F. Vogel, Nov. 1976, Los Alamos Scientific Laboratory Report LA-TR-77-27.
- A-3. E. Thuries, "Air Cooled Generator Circuit Breaker," Pro. Joint Power Generation Conf., New Orleans, Sept. 17-19, 1973.

APPENDIX B

LASL - ORNL TNS POLOIDAL FIELD SYSTEM STUDY

I. General Requirements

- A. Ampere turns, volt seconds, peak voltage
- B. Half bias
 - 1. Ampere turns
 - 2. Voltage
 - 3. Stress
- C. Full bias
 - 1. Ampere turns
 - 2. Voltage
 - 3. Stress
- D. Connection methods
 - 1. Peak current
 - 2. Power supply requirement
- E. Alternative blip circuits
- F. Radiation heating

II. Superconducting Coils

- A. Half bias
 - 1. Current levels
 - 2. Conductor design
 - a. Cooling
 - b. Mechanical support
 - c. Cryostability
 - d. Insulation
 - e. Losses
 - 3. Refrigeration
 - 4. Power supplies
- B. Full bias
 - 1. Current levels
 - 2. Conductor design
 - a. Cooling
 - b. Mechanical support
 - c. Cryostability

- d. Insulation
- e. Losses
- 3. Refrigeration
- 4. Power supplies

III. Cost of Superconducting Systems

- A. Half bias
 - 1. Coils
 - 2. Support structure
 - 3. Dewars, leads, etc.
 - 4. Refrigerator
 - 5. Power supplies
- B. Full bias
 - 1. Coils
 - 2. Support structure
 - 3. Dewars, leads, etc.
 - 4. Refrigerator
 - 5. Power supplies

IV. Normal Coils

- A. Half bias
 - 1. Current levels
 - 2. Conductor design
 - a. Cooling
 - b. Support
 - c. Insulation
 - 3. Power supplies
- B. Full bias
 - 1. Current levels
 - 2. Conductor design
 - a. Cooling
 - b. Mechanical support
 - c. Insulation
 - 3. Power supplies

V. Cost of Normal Systems

A. Half bias

1. Coils
2. Support structure
3. Cooling
4. Power supplies

B. Full bias

1. Coils
2. Support structure
3. Cooling
4. Power supplies