Fusion Applications of Fast Discharging Homopolar Machines

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FOREWORD

This report gives the results of a study on fusion applications of fast discharging homopolar machines under Research Project 469, "Fast Discharging Homopolar Machines for Fusion Devices." Principle investigators are C. J. Mole and R. E. Stillwagon at Westinghouse (RP469-1), F. L. Ribe and K. I. Thomassen at LASL (RP469-2), and H. H. Woodson and H. G. Rylander at UT (RP469-3).

ABSTRACT

The use of fast discharging homopolar machines, with 1-5000 ms delivery times, are described for toroidal and linear theta pinches, toroidal z-pinches, liners, and tokamaks. Typical circuits and machine designs are described.

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Contributions to this study by H. Vogel and C. Swannack at LASL, H. Woodson, W. Weldon, Mr. Driga, and W. Bird at UT, and R. Stillwagon and B. Heck at Westinghouse are gratefully acknowledged.

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SUMMARY

A variety of applications of homopolar machines in power conditioning circuits for fusion devices will be described. In many cases these proposed systems are the best or only alternative for meeting the requirements. The transfer times for the systems described here range from 1 ms for liners, to ~30 ms for RTPR and Z-pinches, to ~300 ms for charging of intermediate inductive stores, to ~½-1 s for tokamak OH systems.

Many of the requirements here are only roughly defined, and the machines needed for each different application are widely varied. However, preliminary conceptual designs are available in many instances, allowing an assessment of the advantages and disadvantages. Further development work is underway to construct models of the 1 ms and 30 ms machines at the University of Texas and Los Alamos respectively. The University of Texas model machine, shown in Figure 19, has been constructed and is undergoing tests. It is designed to discharge its 360 kJ in 3 ms, or 90 kJ in 1 ms into a short circuit. The Los Alamos 10 MJ model machine has been designed by Westinghouse, with participation from LASL and the University of Texas, under EPRI sponsorship. Plans are being made for the construction of this machine during 1977-1979.

These models will allow a much better assessment of the role of homopolar machines in fusion systems. In particular, the cost and reliability advantages can be judged.

FUSION APPLICATIONS OF FAST DISCHARGING HOMOPOLAR MACHINES

Introduction

Large pulsed power supplies will be required for many of the fusion reactor systems presently under consideration. At the present experimental sizes of fusion machines, this energy comes from capacitor banks or conventional rotating machinery and switches. The salient feature of designs of many of the FTR (fusion test reactor) or EPR (experimental power reactor) systems is their almost universal need for new power conditioning apparatus, characterized by large stored energies (1 to 10 GJ) and rapid transfer times (1/2 ms to 1/2 s).

This interim report describes a number of these large fusion devices and their pulsed energy requirements. It also describes how a new type of fast discharging homopolar machine is uniquely suited to meeting these requirements, and in most cases it is either the best or only way to achieve them.

The fusion devices whose pulsed energy requirements are listed include the toroidal theta pinch, linear theta pinch, liner, toroidal Z-pinch, glass laser driven devices, and tokamaks. In the magnetic confinement systems the pulsed power supplies drive primary compression magnetic fields or induce ohmic heating currents. In the laser system the flash lamps are excited by the fast discharge of energy into them. If homopolar machines are used the energy can be supplied directly from the device if transfer times exceed a few milliseconds. For shorter times an intermediate inductive storage system is required, with the homopolar machine charging the inductive store on the 100-300 ms time scale. The energy is then switched to the experiment on the shorter time scale (down to tens of microseconds).

There are numerous advantages of a homopolar machine. First, it behaves as a capacitor in a circuit application, and that is ideal for resonating the energy into or out of the typical inductive load presented by the fusion device. In this application the energy transfer can be accomplished with high efficiency and it can be recovered. Further, the machines have large energy storage capacities consistent with fusion requirements. Finally, and perhaps most important, the potential cost savings over conventional ac generators with solid state switching is considerable.

This savings is attributable both to the elimination of much of the solid state switching and to the simplicity of the homopolar stator and rotor construction. The slots and windings in ac generators dictate much higher manufacturing costs, and incidentally, these slotted structures are not nearly as well suited to fast pulsed operation. Indeed, no such application of ac generators exists today, and in pulsed applications which come closest to these needs the fatigue life of the machines are limited by wedge loosening.

The applications described here, and the advantages claimed for the homopolar machine, are based in many instances on fairly detailed system studies. The homopolar machines for the Reference Theta Pinch Reactor (RTPR) have undergone several iterations,[1,2] and a very detailed conceptual design of the machine was recently completed[3] under an EPRI contract. A LASL and UT (University of Texas) design of a machine for a Linear Theta Pinch Hybrid Reactor (LTPHR) has been published,[4] and a Westinghouse study under an ERDA contract with LASL describes a cost optimization study of charging supplies for room temperature storage coils in the Scyllac Fusion Test Reactor (SFTR). A large cost savings over ac generators was shown in the SFTR study.[5] At present, the tokamak EPR designs are being reviewed under ERDA contract to LASL and UT to determine the optimum power system for the ohmic heating (OH) circuit. All three EPR designs presently envision homopolar machine driven supplies. The liner and laser flash lamp supply requirements have been determined but no systems studies of the machines have been made. However, the transfer times and energy levels are similar to those needed for the LTPHR, and the study for it and for the SFTR are both applicable in scoping the systems needed for their energization.

The Homopolar Capacitor

The basic features of a drum-type homopolar machine are described in this section, and formulas for the machine operation are derived. Figure 1 is a simplified illustration of the machine, showing the multiple drum rotors connected electrically through brushes. A radial exciting field is produced by coils imbedded in iron.

Voltage and current waveforms for an ideal machine (no internal resistance or inductance) are easily derived. Dimensions are given in Fig. 2, and the average radial field B is shown. The rotor is thin compared to its radius, and the return flux spacing d is small ($d \ll R$).

DRUM HOMOPOLAR MACHINE

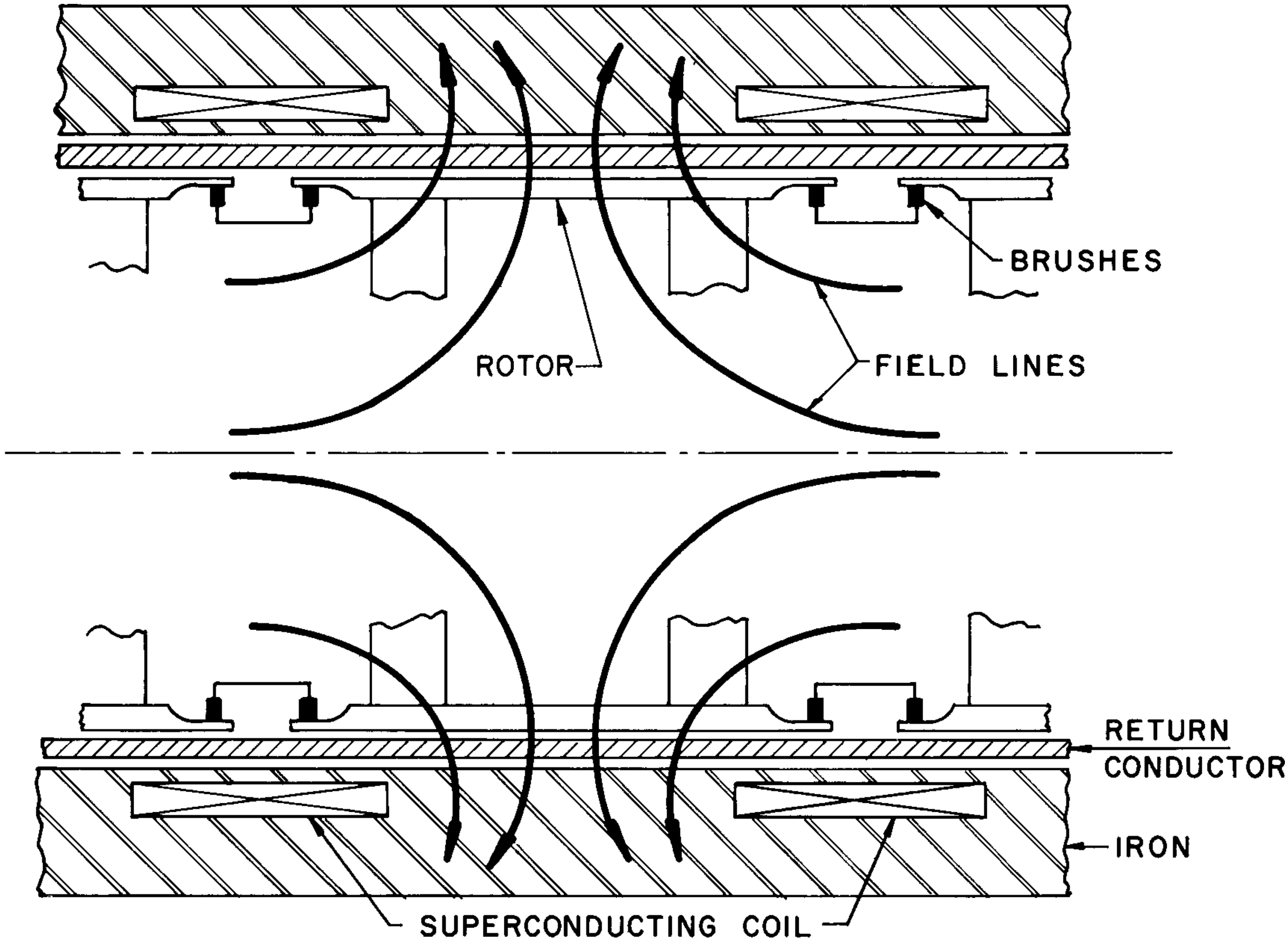


Fig. 1. Drum-Type Homopolar Machine.

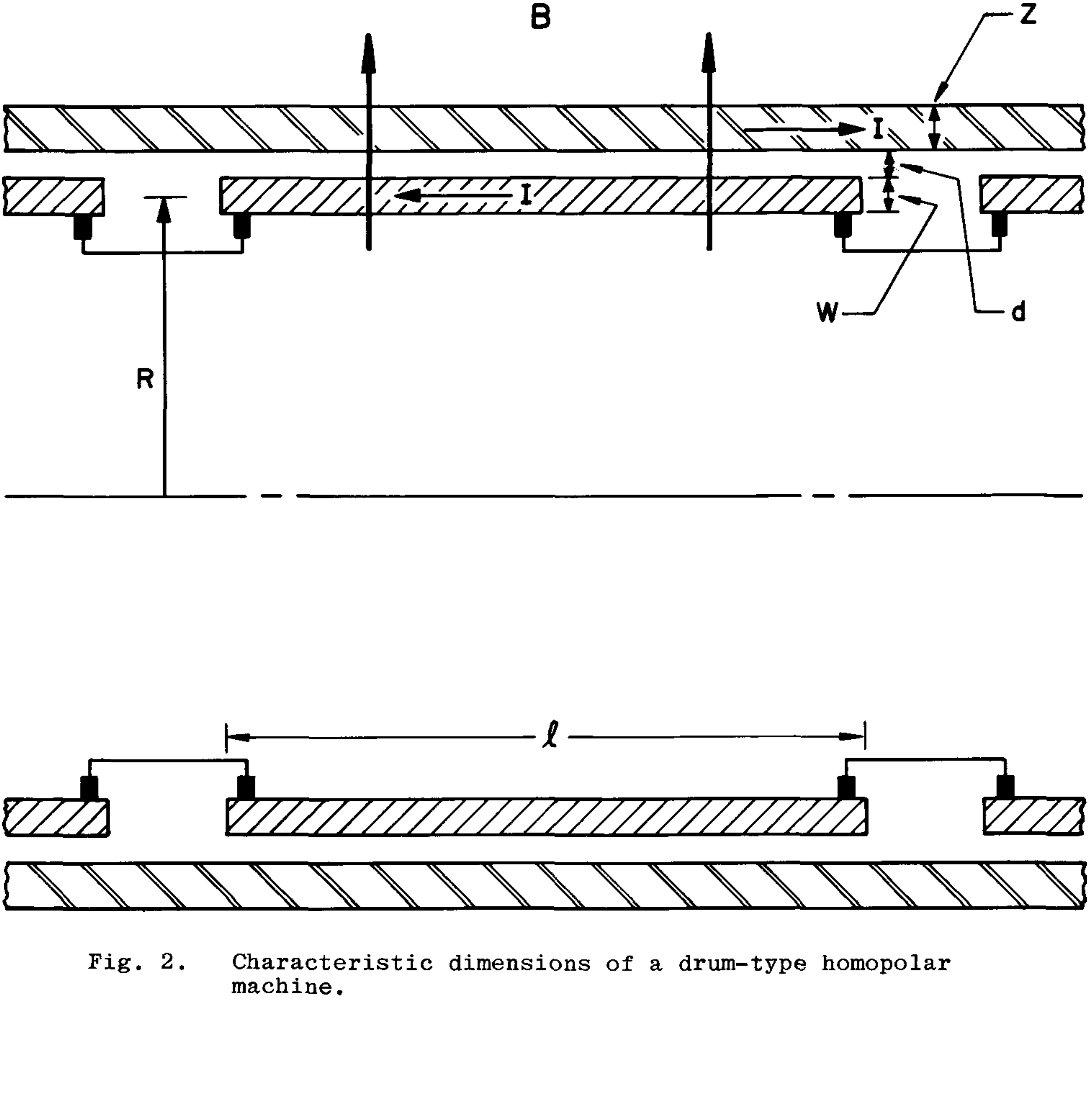


Fig. 2. Characteristic dimensions of a drum-type homopolar machine.

Each rotor developes a voltage

$$V = B\ell u(t) \tag{1}$$

where u(t) is the rotor surface velocity. The current is derived from the instantaneous power,

$$V(t)\; i(t) = \frac{dW}{dt} = \frac{d}{dt}\left[\tfrac{1}{2}\; I\left(\frac{u}{R}\right)^2\right]$$

with the inertia I given by

$$I = R^2 \cdot 2\pi R\ell w\rho$$

and ρ being the mass density. Thus,

$$i(t) = \frac{I}{(B\ell R)^2}\frac{dV}{dt} \tag{2}$$

Substituting the inertia into equation (2), which defines the machine capacitance C, gives

$$C = \frac{I}{(B\ell R)^2} = \frac{2\pi\rho Rw}{\ell B^2} \tag{3}$$

The possibility of varying the capacitance with the exciting field B is suggested by Eqn. (3).

Finally, the brush resistance R_b and the internal resistance R_i and inductance L_i can be added, with

$$R_i = \frac{\ell}{2\pi R\sigma}\left(\frac{1}{w} + \frac{1}{z}\right)$$

and

$$L_i = \mu_o \frac{\ell d}{2\pi R}$$

The circuit representation is now given in Fig. 3. A characteristic time $(LC)^{-\frac{1}{2}} = \tau$, given by

$$\tau = \sqrt{\frac{B^2}{\rho\mu_o}}\frac{1}{\sqrt{wd}}$$

is approximately the shortest time for discharging the machine into a short circuit.

<u>Toroidal Theta Pinch Reactor</u>

The Reference Theta Pinch Reactor (RTPR) is a modularly constructed torus of high aspect ratio, and is based on the principles of the toroidal Scyllac experiment.[6] The plant layout is shown in Fig. 4. The torus has a 56 m major radius and a 0.5 m minor radius to

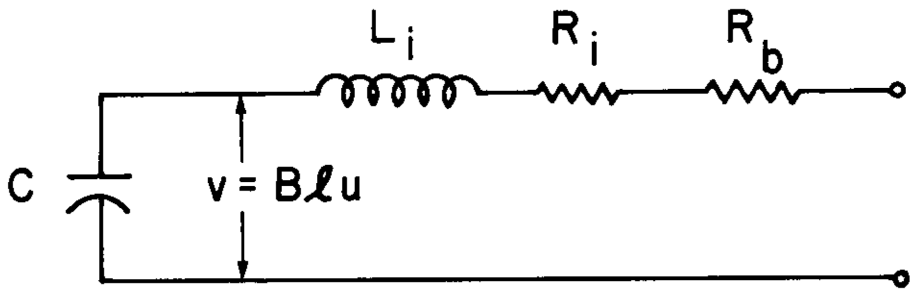


Fig. 3. Circuit representation of a homopolar machine.

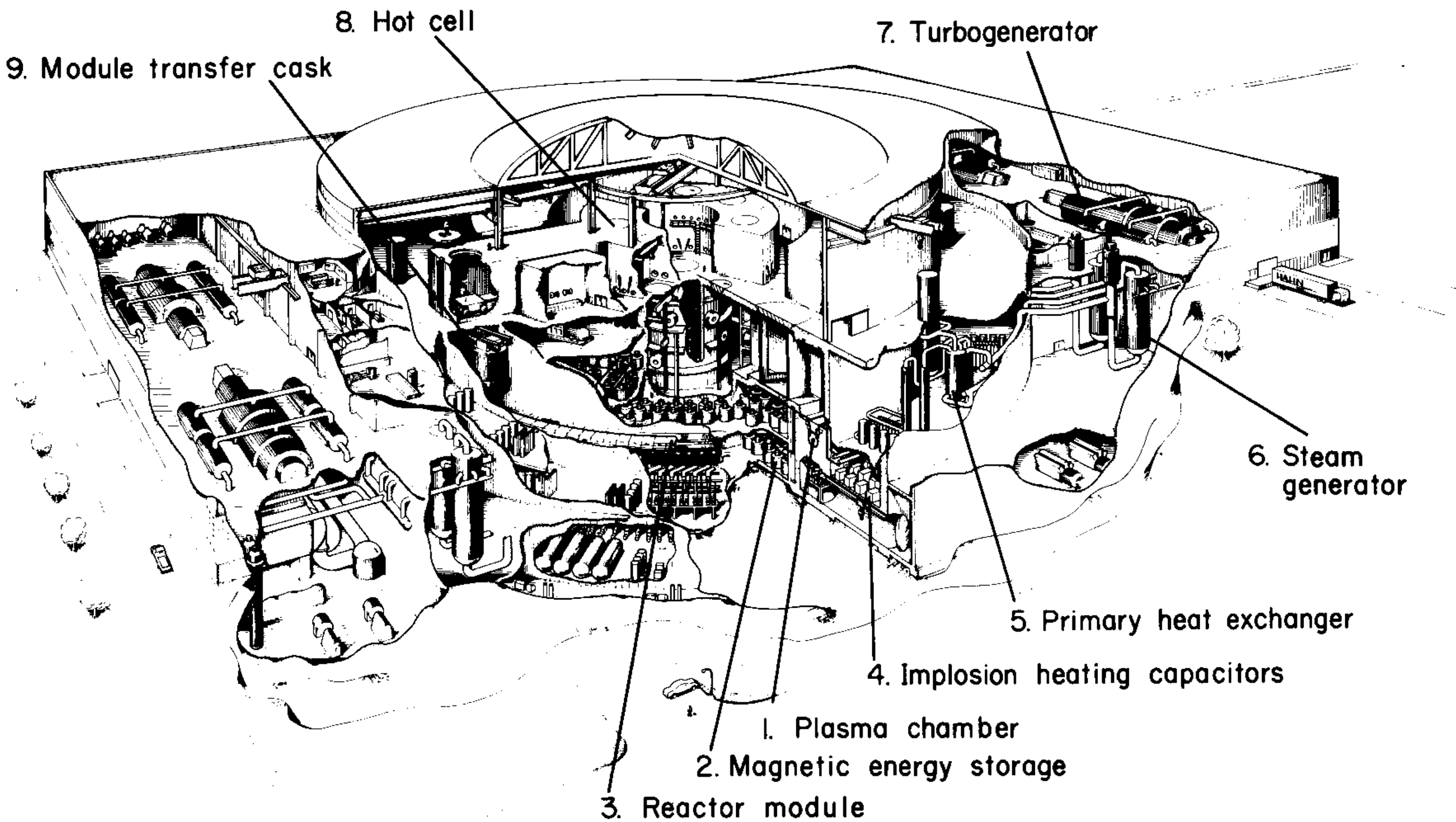


Fig. 4. Plant layout of RTPR, showing principle components.

the blanket first wall, and is composed of 176 modules, each two meters in length. This module is shown in Fig. 5, and consists of the implosion and compression coils surrounding the segmented blanket.

One of the major problems of the reactor design is the pulsed magnetic energy system for driving the compression coils. System requirements are listed in Table 1. The 63 GJ will be supplied by 50 homopolar machines rated at 1.3 GJ each, using the simple LC circuit of Fig. 6. The 11 kV, 12.25 MA output delivers the energy in 30 ms. The estimated future cost is 0.6 ¢/J, corresponding to a capital cost of $\sim$\$300/KW . Design of the machines was accomplished in an EPRI sponsored study by LASL, UT, and Westinghouse, and will be described briefly in this section. Complete design details are reported elsewhere.[3]

Major features of the design include superconducting excitation coils, high current density solid copper-graphite brushes, multiple aluminum drum rotors, and high surface speeds. A section of the machine, showing 2 of the 8 rotors, is depicted in Fig. 7. The coils are Nb_3Sn, and are imbedded in an iron structure in the stator which confines the flux. Under each coil is a set of brushes (11 rows on the inner surface of each end of each rotor) to collect the (axial) current. The current is driven by the circumferential motion of the drum through the axial field. A cylindrical drum encasing all eight rotors serves as the return conductor. By minimizing the spacing between the rotor surfaces and the return conductor the internal inductance is kept low, as is required for fast discharging. A three dimensional view of the machine in Fig. 8 shows some of the features more clearly.

These features are derived from the system requirements in a straightforward way. First, the high power (short transfer time) dictates a high volt-ampere product. However, to avoid extremely low impedances the machine voltage must be made as large as possible. Since the voltage is a product of rotor length ℓ, average radial field $\langle B_r \rangle$, and surface speed V_S, all three factors should be as large as possible. We use Nb_3Sn superconducting coils to produce $\langle B_r \rangle \sim 3T$, operate at $V_S \sim 277$ m/s, and put 8 rotors in series to get an active conductor length of 13 m.

The drum design, as opposed to a disk or spool, has a shorter path length between brushes, hence lower resistive losses. High efficiency in the machine operation is therefore more easily achieved with this drum design.

Finally, the high current density on the brushes, 1550 A/cm^2, is necessary to collect the current which results from the specifications of energy, voltage, and transfer time. The operation of multiple brushes at this

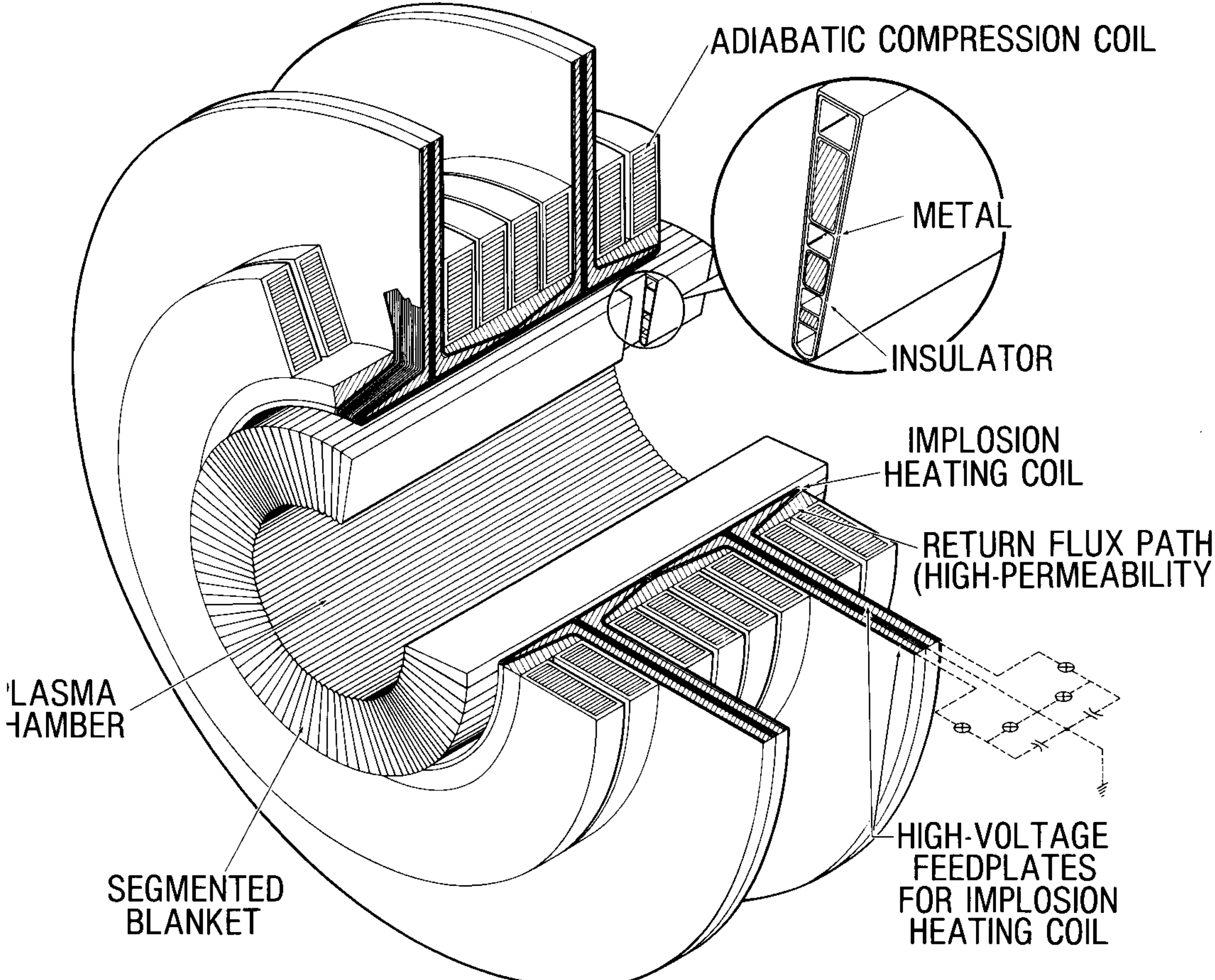
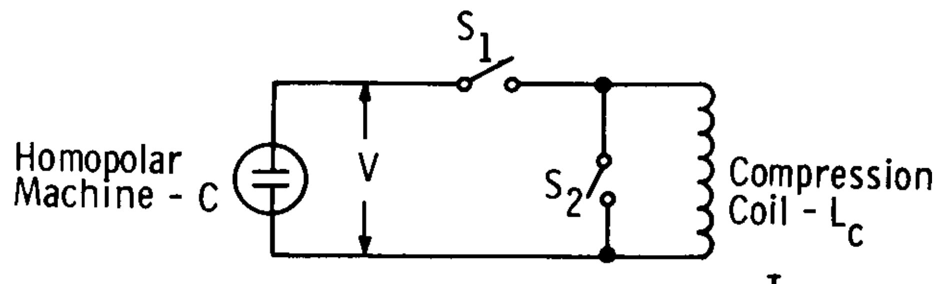


Fig. 5. An RTPR module showing the implosion and compression coils and the segmented blanket.

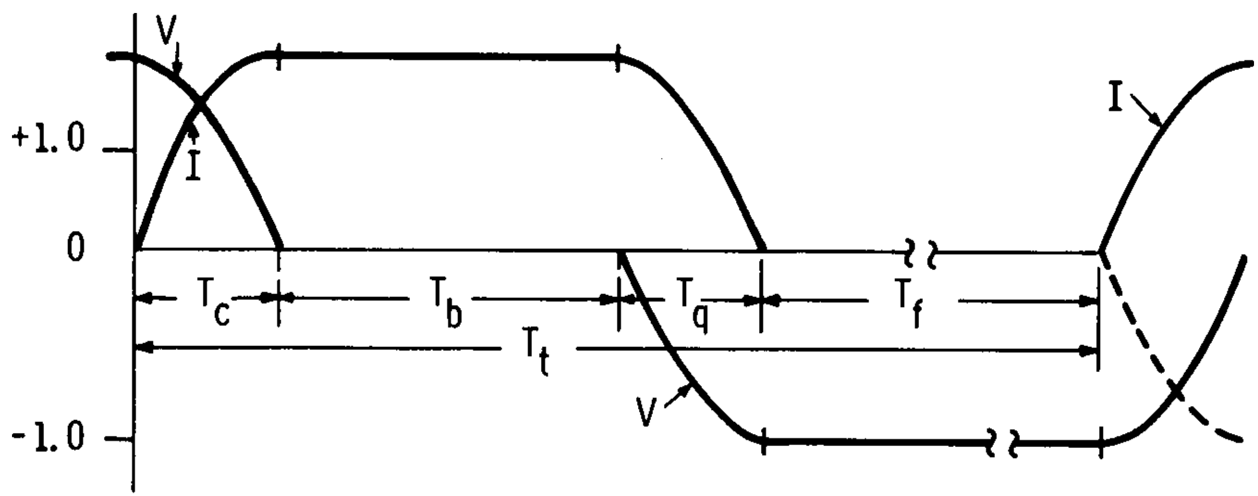
TABLE 1
RTPR
SYSTEM REQUIREMENTS

Operational	
Energy	63 GJ
Transfer Time	30 ms
Power (avg)	2100 GW
Cycle Time	10 s

Economic	
Cost	$\leq$ 1¢/J
Loss	$\leq$ 5%

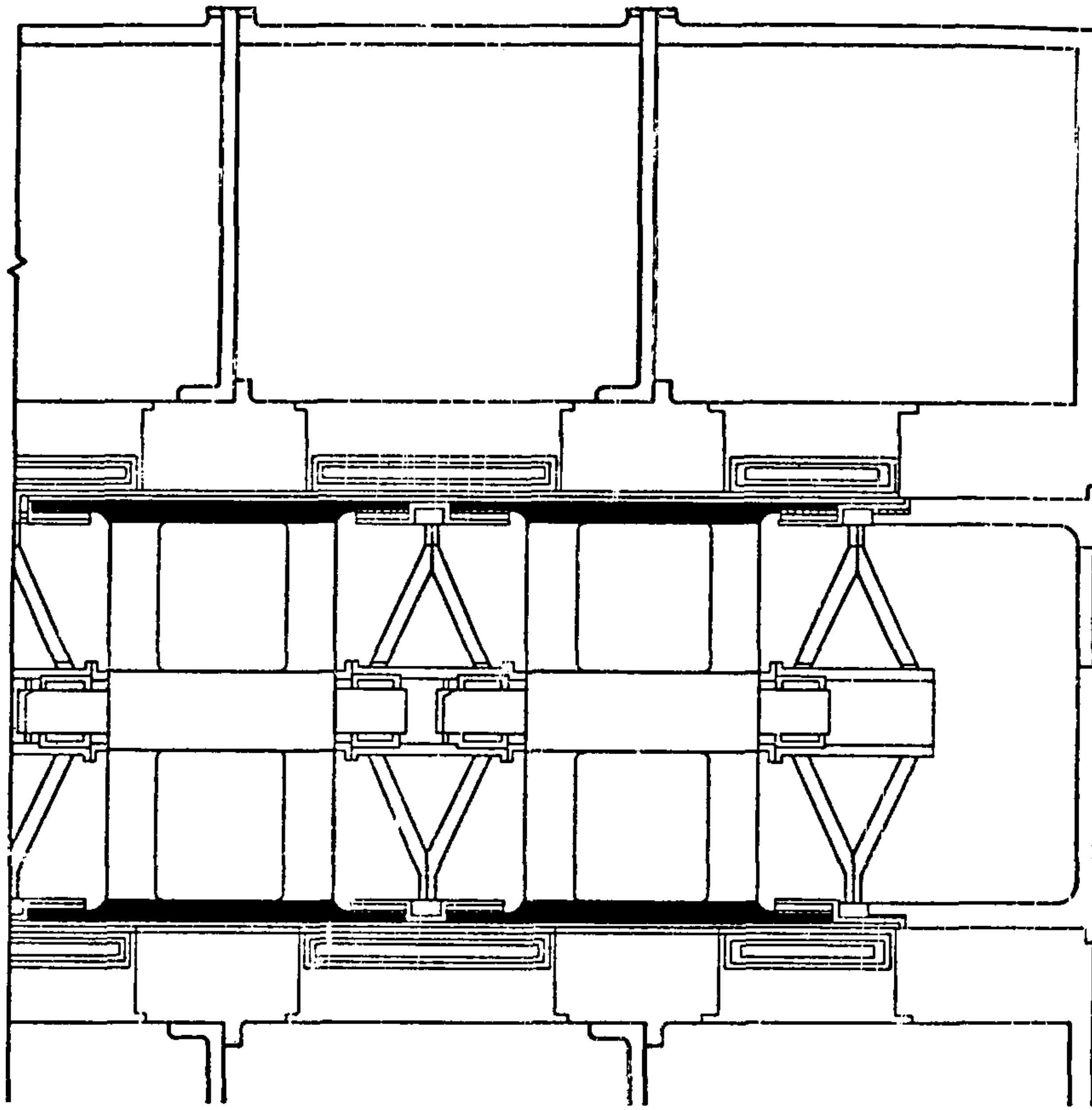


LC Circuit



Voltage and Current vs Time

Fig. 6. A homopolar L-C Circuit for driving the compression coils in RTPR. The charge and quench times T_c and T_q are 30 ms, and the burn time T_b is 70 ms. The total cycle time T_t is 10 s.



CAPACITY	1290 MJ	COLLECTOR LENGTH	0.25 m
No. ROTOR MODULES	8	STATOR OD	3.2 m
ROTOR DIAMETER	2.17 m	FLUX SHIELD OD	7.0 m
ROTOR PERIPHERAL VELOCITY	277 m/s	OVERALL LENGTH	20 m

Fig. 7. The two end rotors and structure of a 1-3 GJ homopolar machine.

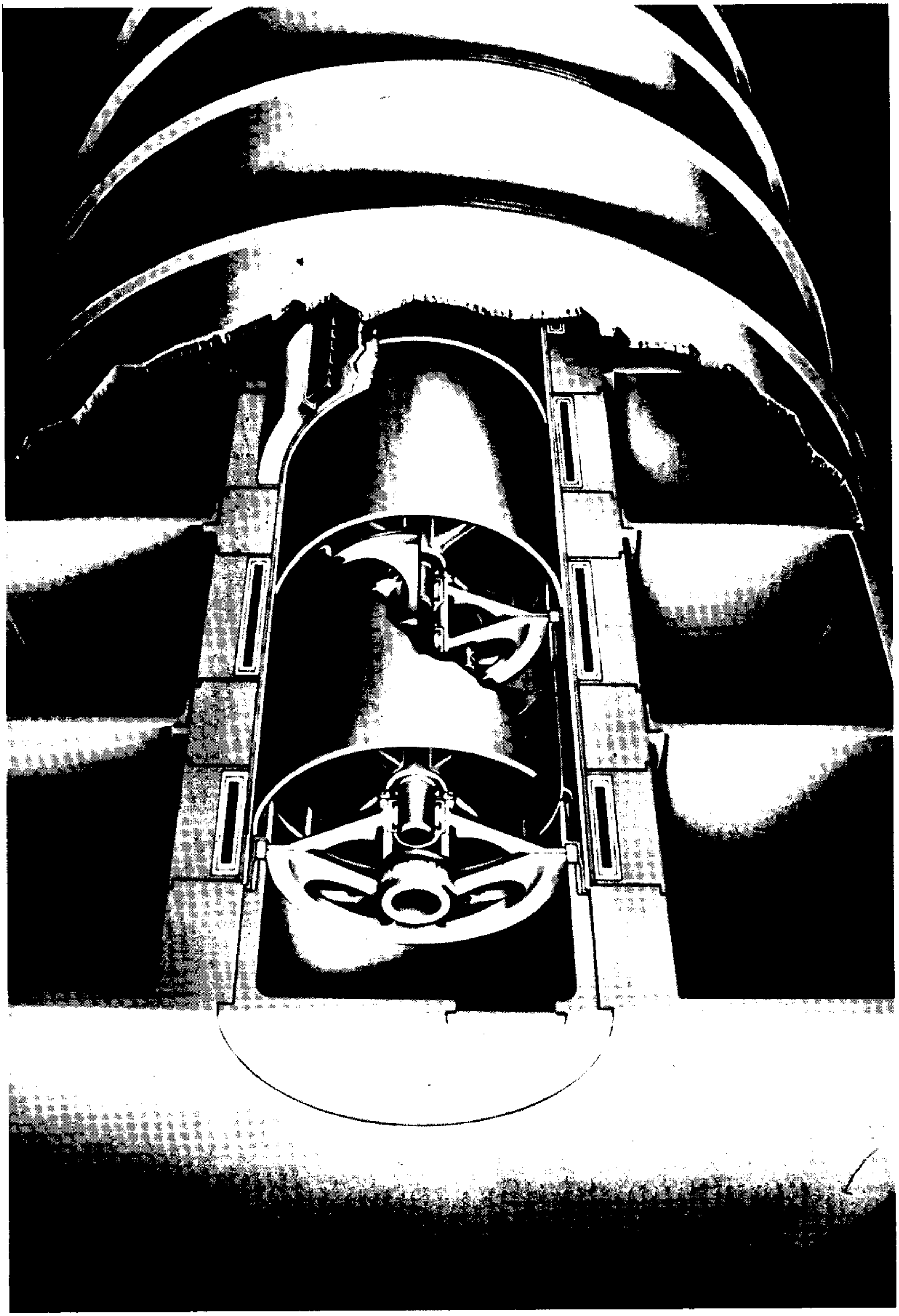


Fig. 8. A three-dimensional view of the RTPR 1.3 GJ homopolar machine.

current density and at these high surface speeds is a very difficult task, and to do so with acceptable wear rates and contact drops requires development work on the current collection system.

Scyllac Fusion Test Reactor

The Scyllac Fusion Test Reactor[7] is planned to be the first D-T burning toroidal theta pinch, and is designed to achieve "plasma breakeven" (neutron energy output in one pulse equal to the peak internal plasma energy). The design is again modular, as shown in Fig. 9, and bears great similarity to the RTPR. There are separate implosion and compression coils and supplies, and the compression coils require ∿500 MJ delivered in 0.7 ms. There are 1280 coils in the 40 m diameter torus.

At present, the SFTR design calls for 1280 superconducting storage coils to drive the 1280 normal load coils, but the high cost of the storage coil and its refrigeration system has forced the search for alternate solutions. One alternative is a large room temperature toroidal storage inductor charged from a rectifier set off the line. This option is ∿2.5 ¢/J for the coil and supply. Another alternative was advanced by Westinghouse,[5] and uses a homopolar to charge the storage ring. The advantage of a homopolar is that the coil can be energized rapidly, hence a lower L/R coil may be used, saving considerable money for the conductor. Since the cost of a homopolar decreases with increasing discharge time, there is an optimum transfer time and associated L/R time. Figure 10 illustrates the tradeoff.

From the Westinghouse study, which examined ac generators and both superconducting and normally excited homopolars for charging the storage ring, the cost advantages of homopolars are apparent. The comparative designs are characterized in Table 2, and the cost of ∿1.3 ¢/J for homopolars is ∿4 times lower than the 5.6 ¢/J for the a-c generator/rectifier system.

In Table 2, the transfer energy is delivered to the coil, but some of it is dissipated in the coil resistance before switching it to the load. Thus, in each case there are 4 of the listed machines to deliver the 488 MJ. Each machine drives one quadrant of the toroidal storage ring. The homopolars charge 1280 coils whose inductances match the load inductances.

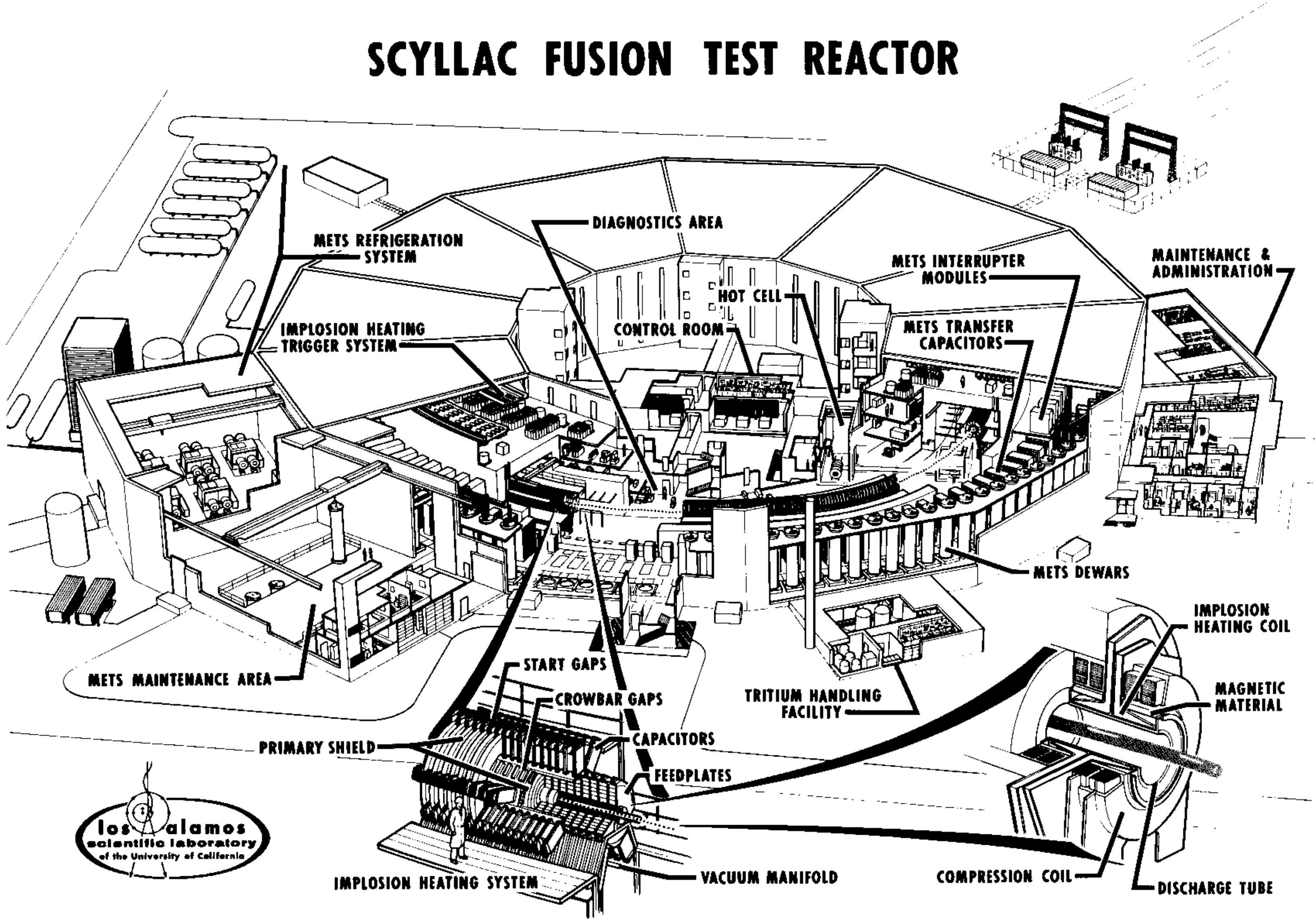


Fig. 9. The Scyllac Fusion Test Reactor Plant Layout.

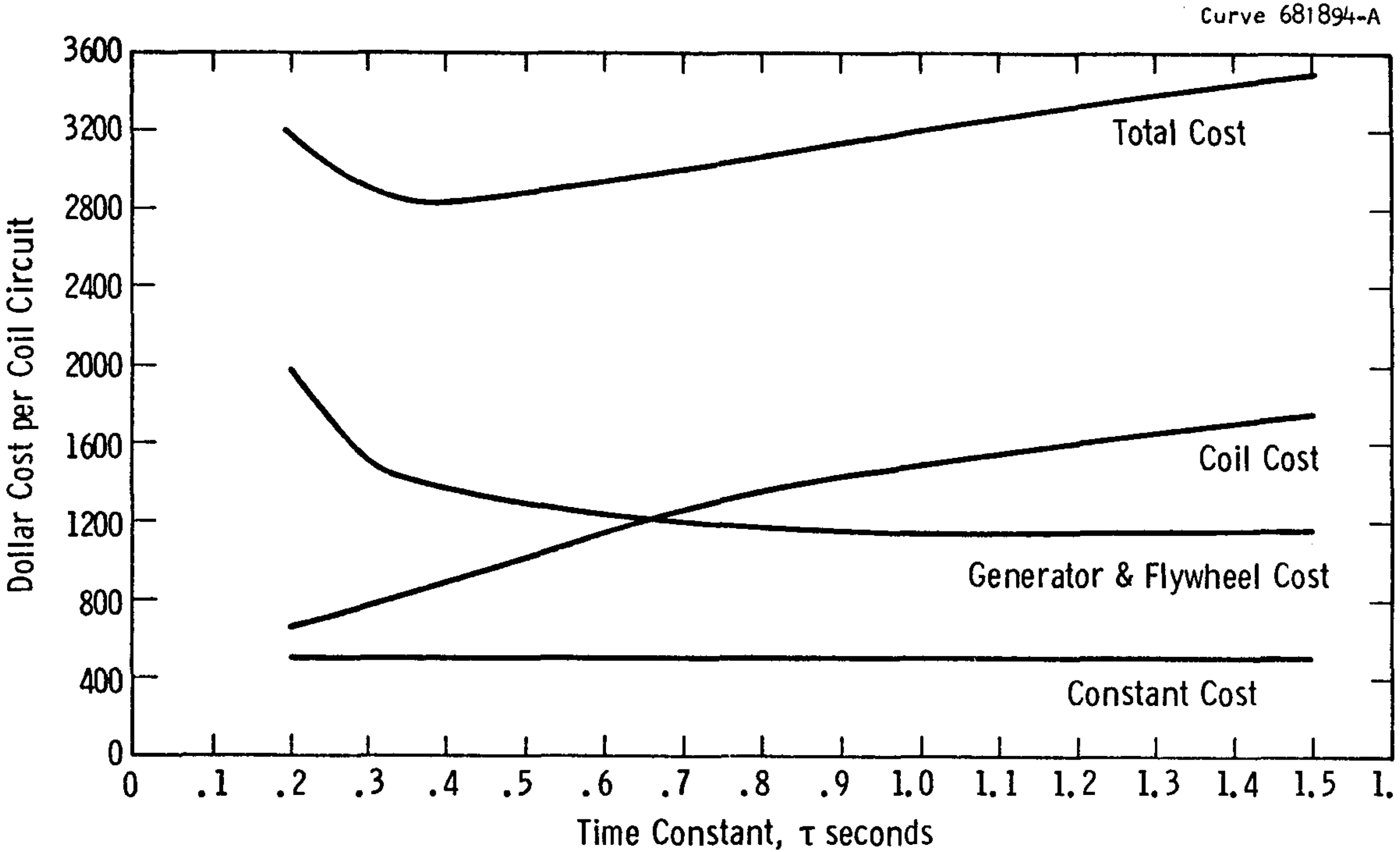


Fig. 10. Cost per coil circuit of the superconducting homopolar generator system for SFTR.

TABLE 2
Machine and Circuit Characteristics

Machine Characteristic	S.C. Homopolar	Non-S.C. Homopola	A.C. Generator
Av. Generating Capacity, MW	882.0	423.0	32.0
Output Voltage, Volts	267.0	123.00	252.0
Peak Current, KA	9060.0	9310.0	210.0
Transfer Energy, MJ	242.0	275.0	320.0
Transfer Time, ms	274.0	650.0	10000.0
Storage Coil Time Constant, s	0.4	0.8	6.0
Number of Coils in Series/Number of Parallel Circuits	1/320	1/320	40/8
Total System Cost, Millions of Dollars	3.13	3.64	13.67

The circuit for energizing the SFTR compression coils is shown in Fig. 11, which represents ¼ of the system. The 320 storage coils are charged in parallel from the homopolar, then the interrupting switches are closed to force the current to circulate in each parallel circuit. The homopolar is than isolated, the load coil isolating switches are closed, and the interrupters are opened. Current transfers to the load coil through the resonant capacitor bank, and is crowbarred into the load to decay with a 250 ms L/R time.

This application of fast homopolars, to charge intermediate storage coils for millisecond switching, is one of several where the required transfer time is too short for direct transfer. The limiting time is near 1-3 ms, and is determined by the machine internal inductance and the high surface stresses on the rotor material. Other such fast applications include glass laser flash lamp supplies and liners.

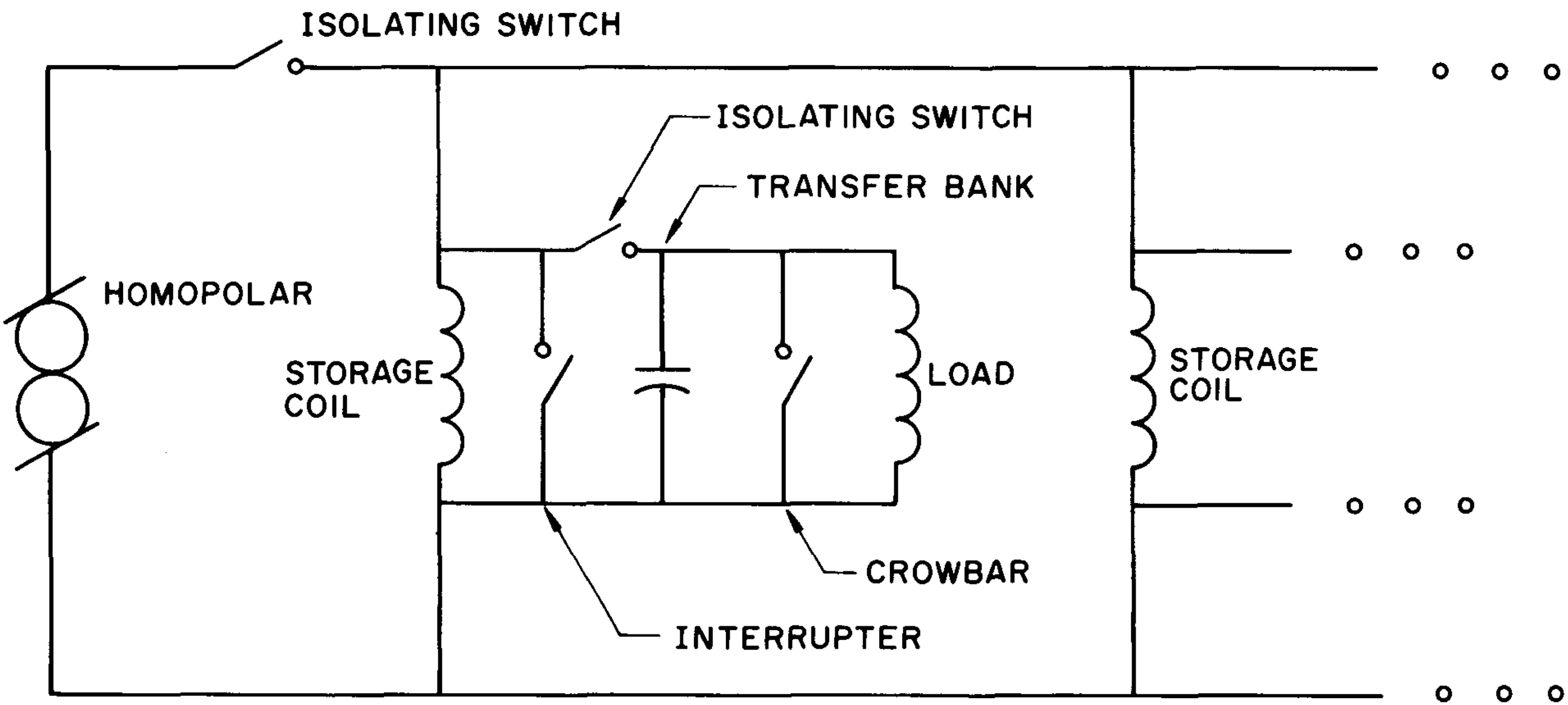


Fig. 11. SFTR circuit showing the homopolar charging of 320 parallel coils, and the resonant transfer system to energize the load (compression coils).

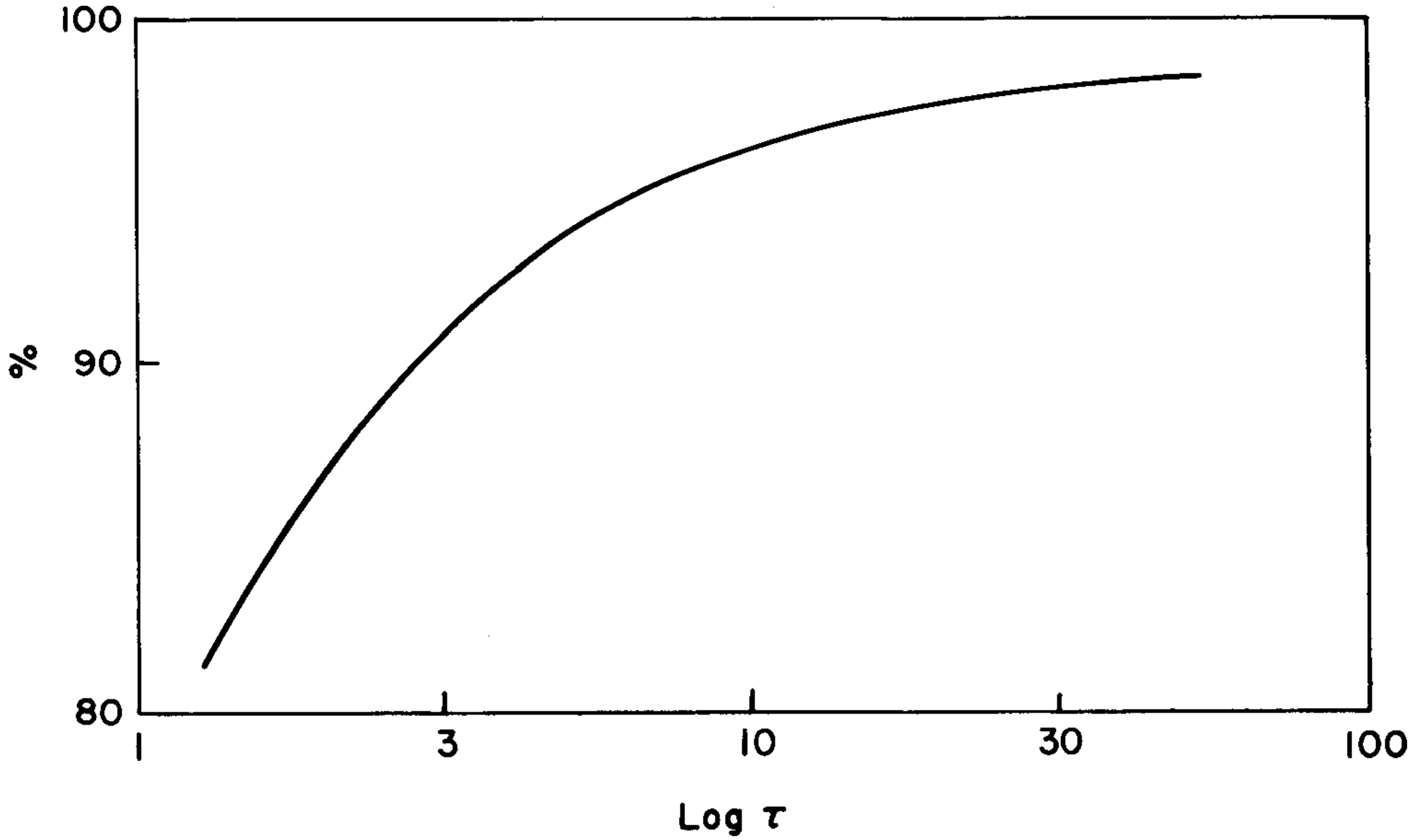


Fig. 12. Calculated homopolar generator efficiencies, for machines costing ∿5½ c/J, as a function of discharge time.

Linear Theta Pinch

Linear Theta Pinches have been proposed for both pure fusion and fusion/fission hybrids. While ignition temperatures have been reached in linear theta pinches, and scaling to longer systems is reasonably well understood, two outstanding problems must be solved before these systems are viable. The first is the problem of enhancing containment time by "end stoppering," and the second is the development of reliable, economic, efficient pulsed power systems for the compression coils.

There are two aspects to the circuit problem, the power supply and the switching system. One must produce the waveform of Fig. 6, but the risetimes must be as fast as possible, burn times are 3-10 ms, and 1-5 pps rates are required. These requirements are much more severe than those for RTPR, yet the same or even better efficiencies are needed. Further, the systems can be 1-10 km long, depending on end-stoppering, with ∿30 MJ/m of stored energy.

A study of the feasibility of homopolar supplies to energize the compression coils of the linear theta pinch was made by Vogel et al.[4] They considered a variety of machine designs and arrived at curves of efficiency vs discharge time for various allowed costs. Typical best efficiencies for machines costing ∿5½ ¢/J are plotted in Fig. 12. These are derived for spool-type machines, with brushes on the rims of the spool. The machines store ∿275 MJ each, and drive N parallel compression coils (N∿30) to a current of ∿450 kA each (25 T in a 28 cm bore, by 22.5 cm long coil of inductance 55 μH).

The cost of the machines influences the efficiency, and the relationship given by Vogel et al[4] is

$$\eta = \eta_{max}(1-\exp[-C/K])$$

where C is the cost in ¢/J, and K is a function of discharge time, decreasing monatomically from ∿3 at 1.5 ms to ∿0.4 at 30 ms. The maximum efficiency varies from ∿92% at 2 ms to ∿99% at 50 ms. So, if one desires lower costs, efficiency suffers. However, the numbers given here are encouraging of these systems for the linear theta pinch.

Another formidable problem is the switching, particularly the current interruption required to generate the waveform of Fig. 6. One can eliminate the need to interrupt current by using a half-sine waveform, but the reactor Q then drops by a factor of 2-3. Such a drop would

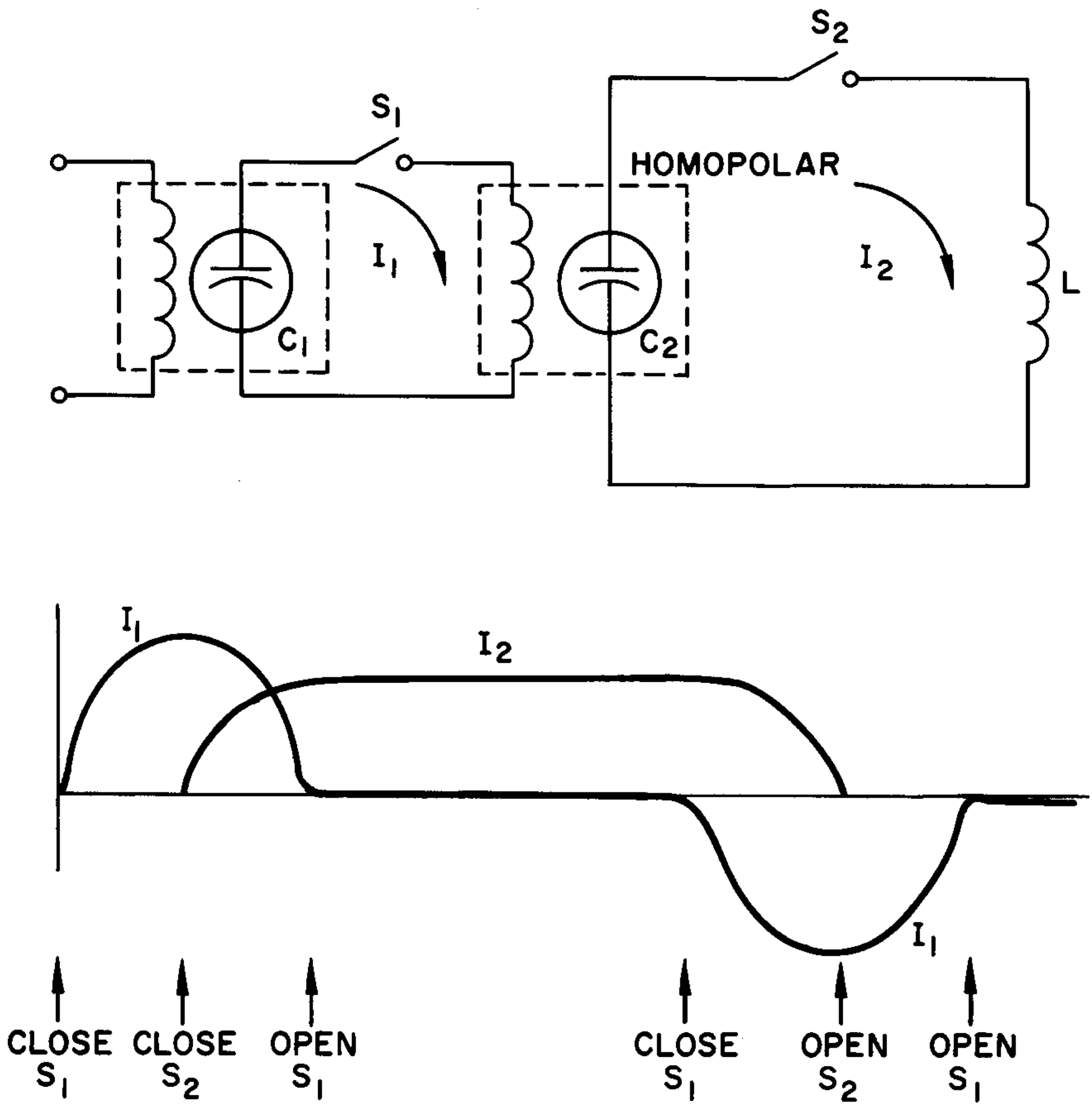


Fig. 13. Current waveforms and circuit for a "homopolar excited" homopolar machine to achieve a flattop current in a load coil.

ruin the energy balance, according to recent calculations. Ideally, one wants as fast a risetime as possible from the homopolar and a flat-top burn time of 3-10 ms.

One way to approximate the waveform is to vary the capacitance after the energy is transferred to the compression coil by reducing the exciting field to a low value. However, the energy stored in the exciting field is comparable to the stored inertial energy for modest transfer times ($\sim$30 ms) and exceeds the inertial energy for short discharge times. Therefore, the rapid removal of this energy is not feasible unless the exciting coil uses a normal conductor (not superconducting). Energy from this exciting coil could be transferred to another (superconducting) homopolar machine where it could be stored between pulses. Figure 13 illustrates the proceedure.

Homopolar C_1 charges the exciting coil of homopolar C_2 by closing S_1. At peak current I_1, S_2 is closed and C_2 spins down to some low rpm. Meanwhile, C_1 spins in the opposite direction and takes the energy back from the exciting coil. Switch S_1 now opens at a current zero. The LC_2 frequency is now very low so the current I_2 is essentially a flattop. To return the energy from L to C_2, S_1 is closed and a reverse field is applied to the exciting coil. Thus, the reverse voltage applied to C_2 by LdI_2/dt allows the machine to spin up in the same direction from low to high rpm. Machine C_1 meanwhile, goes through another half cycle and ends up spinning in the same direction as it was at the start of the cycle. It is probably necessary to keep machine C_2 spinning at low rpm during the "flattop" since full current is passing through the brushes.

This scheme might appear to be a complex solution to the problem, one which requires roughly twice the energy storage and two machines. However, the reliable operation of interrupting switches at the voltage and current ratings indicated here is an extremely difficult problem. Each compression coil carries $\sim$450 kA and developes $\sim$8 kV during the current rise, and there are 7 x 10 pulses/yr. Thus, the elimination of interrupting switches for these coils ($\sim$4000 coils/km) is highly desirable.

Liner Reactor Supplies

The only imploding liner reactor design group in the US is at NRL, and the requirements for liner systems are taken from their recent report.[8] The basic requirements are the delivery of 1-10 GJ with a ½-1 ms rise time and a 10 ms decay time. The burn times are less than 100 μs, but

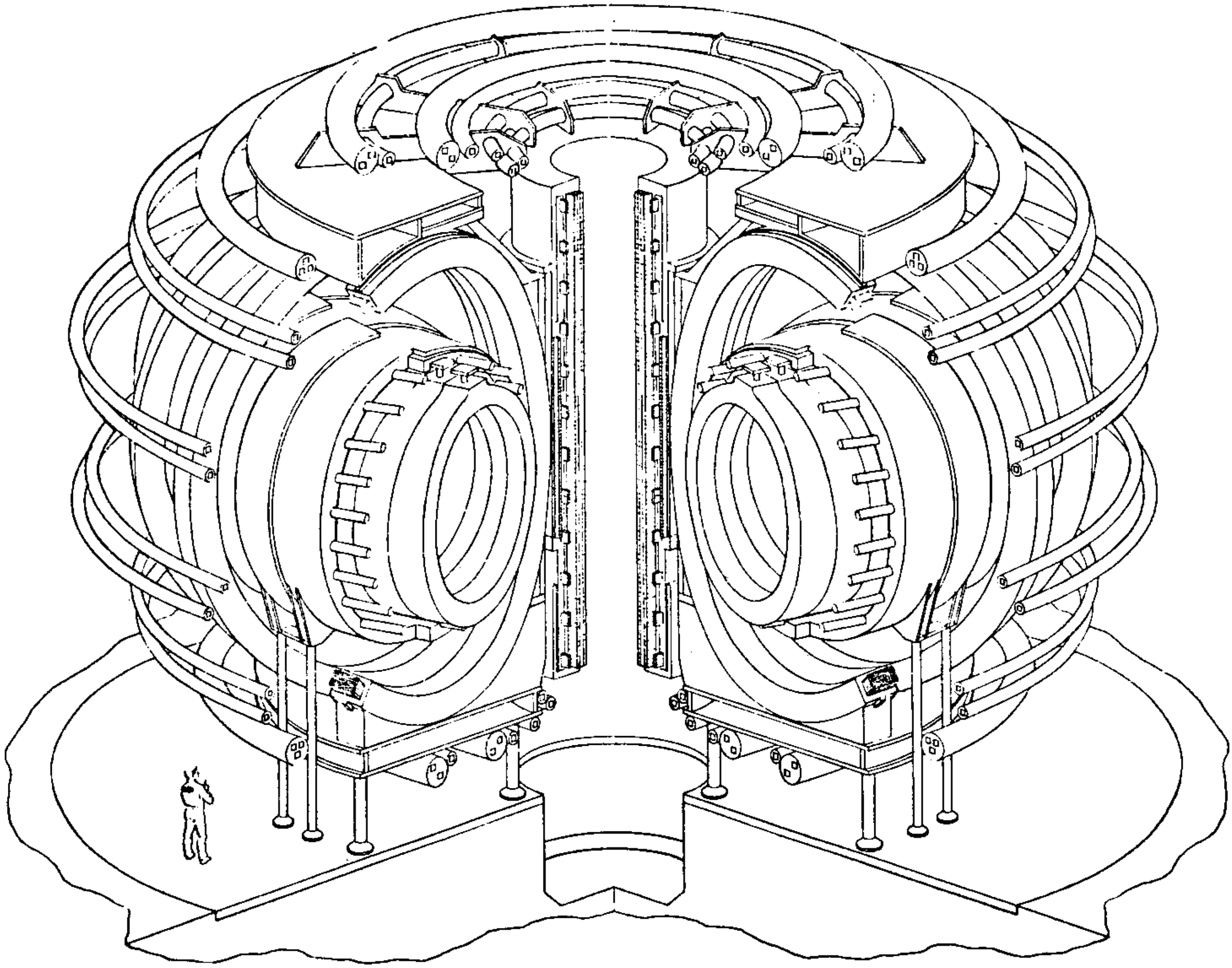


Fig. 14. Oak Ridge EPR Reference Design (Courtesy ORNL).

a pulse compression effect allows longer rise time. This time compression is provided by the liner run-in, which is on the 1 ms time scale. When the minimum liner radius is reached, the short burn occurs. During liner run-in the homopolar load is largely resistive.

The liner requirements are obviously quite similar to the LTPHR, and while there are no machine designs for this application it is easy to argue the merits of the homopolar machine since large quantities of energy must be transferred rapidly. There is a chance, as in SFTR, of direct homopolar charging of the compression coil or of the use of an intermediate inductive storage system with a slower machine. Direct drive would require machines with a ½ - 1 ms transfer time, hence they would be relatively inefficient (∿75-80%). This may be too low for a proper energy balance, so a more thorough system study is clearly required.

The use of an intermediate inductive storage system requires a large number of interrupting switches, as does the direct drive system with a flattop burn time. However, if a half-sine waveshape could be used, which seems likely, the direct drive system has the advantage of eliminating interrupting switches. More detailed analysis of machine and circuit configurations are required here, but the probable need for a homopolar machine is indicated.

Tokamak Ohmic Heating

Large tokamaks, as typified by the Oak Ridge Experimental Power Reactor (EPR) of Fig. 14, require large magnetic energy storage systems. The toroidal field set is of course the largest of these, with several hundred gigajoules in these superconducting coils for full scale reactors. However, the ohmic heating, vertical field, trim, and shield coils, collectively known as the poloidal field system, is equally demanding of technology. Like the toroidal system, the coils are superconducting, store large energies (1-2 GJ in EPR, 5-10 GJ in reactors) but are pulsed rather than steady state.

Generally, most of the energy is stored in the solenoidal stack of coils in the center, but the fields needed to maintain an equilibrium also contain significant energy. The exact magnetic configuration is determined by the plasma driving requirements and by engineering considerations like the need to minimize pulsed fields at the toroidal coils. In turn, the magnetic configuration has a large impact on the driving circuit requirements. The amount of stored energy and volt-seconds can vary by factors of two for different configurations.

In its most simple form, the poloidal field system is represented by a transformer coupled to the plasma, which is specified by its inductance and variable resistance. The primary current is then varied from $-I_1$ to $+ I_2$ as in Fig. 15, to induce the plasma current. The current is further increased slowly from $+I_2$ to $+ I_1$ to maintain resistive losses during the burn. Prior to the next burn cycle, the current is again reversed to $-I_1$ in an appropriate manner to allow shutdown.

Several constraints act to determine the currents and voltages on the primary. Basically however, the transfer time of ∿1 s and the transferred energy (∿1-2 GJ for EPR) sets the current-voltage product during this slow transfer, and plasma startup and burn determines the stored energy and transformer volt-seconds. However, it is extremely important to note that the initial rate of rise of current, up to perhaps 20% of the total current swing (I_1+I_2), must be done much more rapidly to overcome the high initial plasma resistance imposed by breakdown, ionization, charge exchange, and impurity line radiation. This rate of rise implies a much higher initial voltage on the coil, and also impacts the circuitry.

From Fig. 15 it is clear that the energy is removed from the poloidal system in ∿$\frac{1}{2}$ s, and then returned (the plasma I^2R dissipation requires little of the initial stored energy during the transfer time). Thus, whatever power supply is reversing the flux in the poloidal system it must do so with little energy loss. An a-c turbo-generator or salient pole machine, with a rectifier-inverter, could be used but the pulsed duty requires considerable alteration of standard machines to prevent fatigue problems. Also, the machine speed must vary to allow the machine to act as a capacitor. The cost of such a system may be high compared to costs for a homopolar, because an expensive rectifier set is required.

The homopolar machine is a more natural electromechanical device for handling this energy, since the machine directly accepts and returns the energy without recourse to a rectifier-inverter system. Inverter losses make that alternative less efficient, and efficiency is important though not crucial as in pulsed-high-β devices.

The circuit of Fig. 16 shows how a homopolar would be connected in a simple but practical scheme. The power supply (±V) charges the OH coil with R and C bypassed. On turning off this supply, R and C_H are switched in, giving an initial fast rising current. On crowbarring R the homopolar capacitor completes the energy transfer on the several second time scale and is bypassed during the burn.

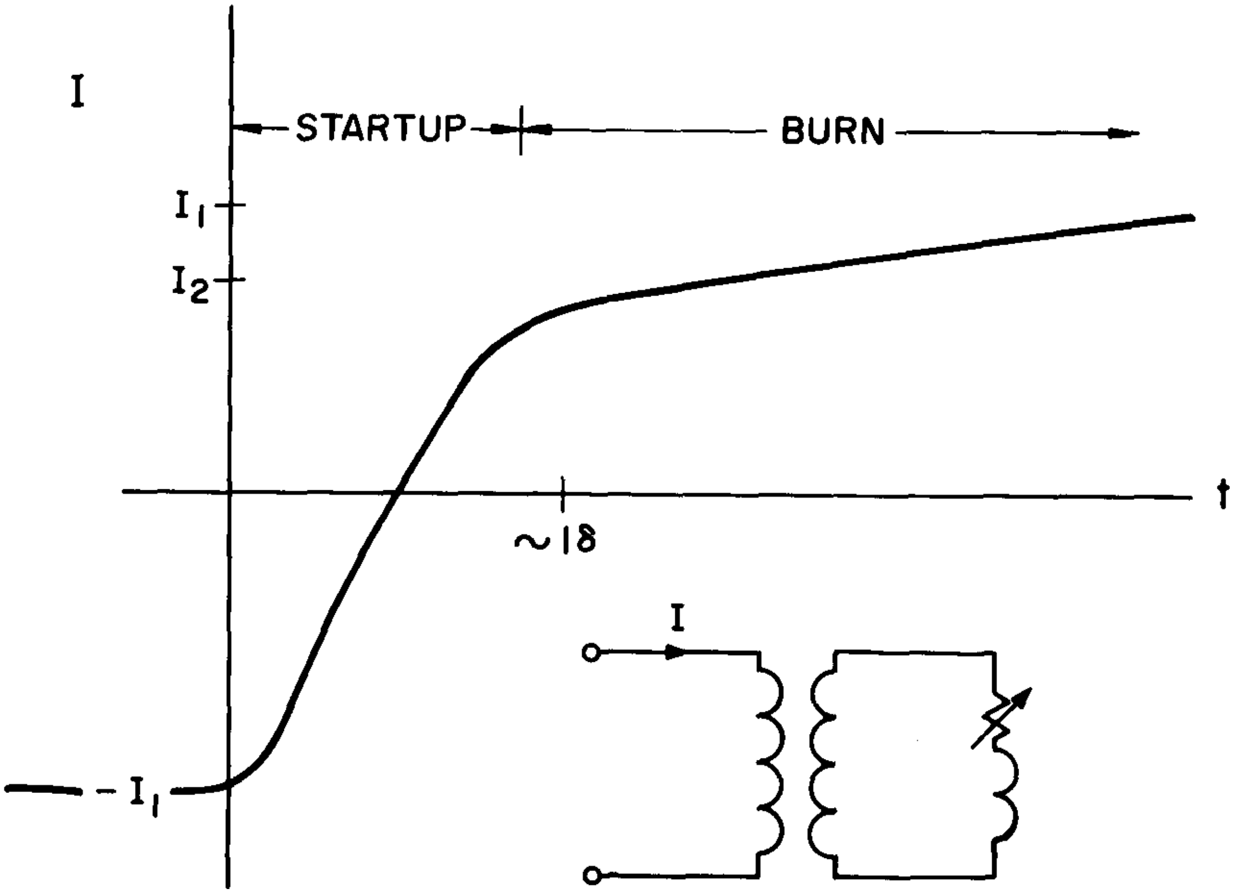


Fig. 15. Primary current waveform for the poloidal field system in a Tokamak.

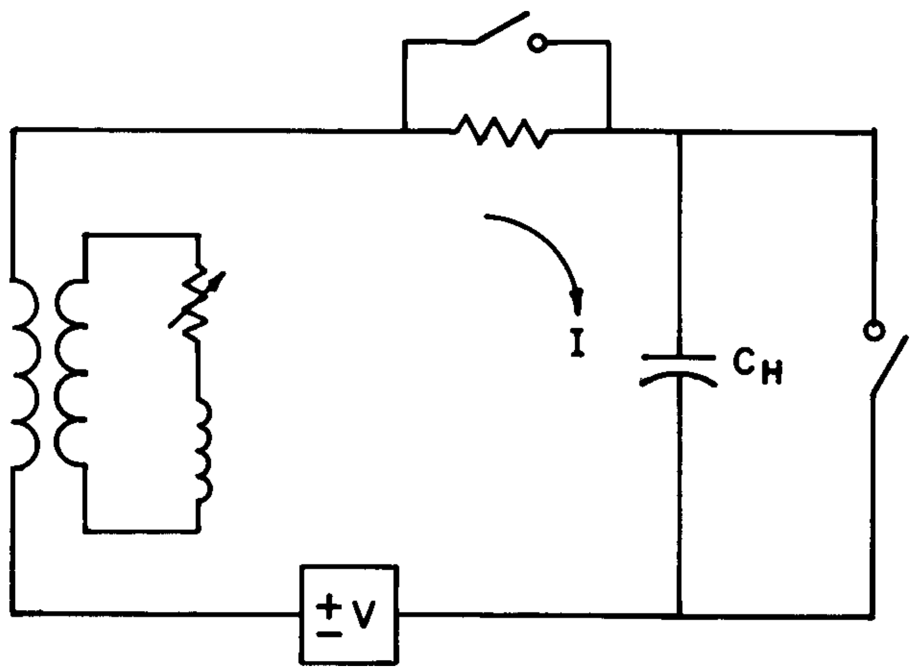


Fig. 16. A simple OH circuit using a homopolar capacitor.

A means of eliminating the interrupting switch, proposed by Inall,[9] is shown in Fig. 17. The capacitor C' is now charged to V, as is C_H, and $C' << C_H$. However, C' is large enough to hold up the voltage while the power supply SCR's are phased off. The blocking RL network has an L/R time of approximately the transfer time of ∿1-2 s, hence C' carries the initial coil current $-I_1$ while the power supply is phased off. A serious disadvantage of this circuit is that C' is quite large, and may be more expensive than the interrupting switch it is intended to replace.

Finally, Fig. 18 shows a more complex circuit, the one actually proposed by Inall, which allows series charging of the coils in the OH system, but parallel discharging. Paralleling n coils changes the impedance by n^2 from the series value, thereby making a better match to the homopolar. High currents are possible with homopolars, but high voltages (greater than ∿10 kV) become difficult to achieve. The circuit is similar to that in Fig. 17 except for SCR's (1), (2), (3), and (4) which are required for the series-parallel operation.

Initially, SCR's (1) are conducting and all others are off. When the coils are charged the power supply is phased off, with C' providing the reverse voltage. The series SCR's (1) are also reverse biased by C' when SCR's (2) are gated on, putting each coil in parallel with C'. Now, the coil current slowly decreases to zero, charging the homopolar, at which time SCR's (3) are gated on to allow reverse current through the coils. As the current reaches $+I_2$ (Fig. 15) the SCR's (4) are gated on and the power supply takes over the coil current, putting them in series again. At the end of the burn the reverse proceedure is followed except that the coil could remain in parallel to have a plasma turnoff time n times longer than startup in order to reduce thermal loads on the first wall.

The capacitor C' could store a few percent of the energy in the coil, and is therefore "large" (tens of megajoules). This "capacitor" could conceivably be a fast discharging homopolar (10-100 ms). The requirements on size must be determined by the rate and duration of the initial plasma current ramp needed for "startup." Since C' replaces an interrupter which is beyond the state-of-the-art, it will not be clear whether the interrupter or the fast homopolar C' should be used until cost and reliability are known for each of them.

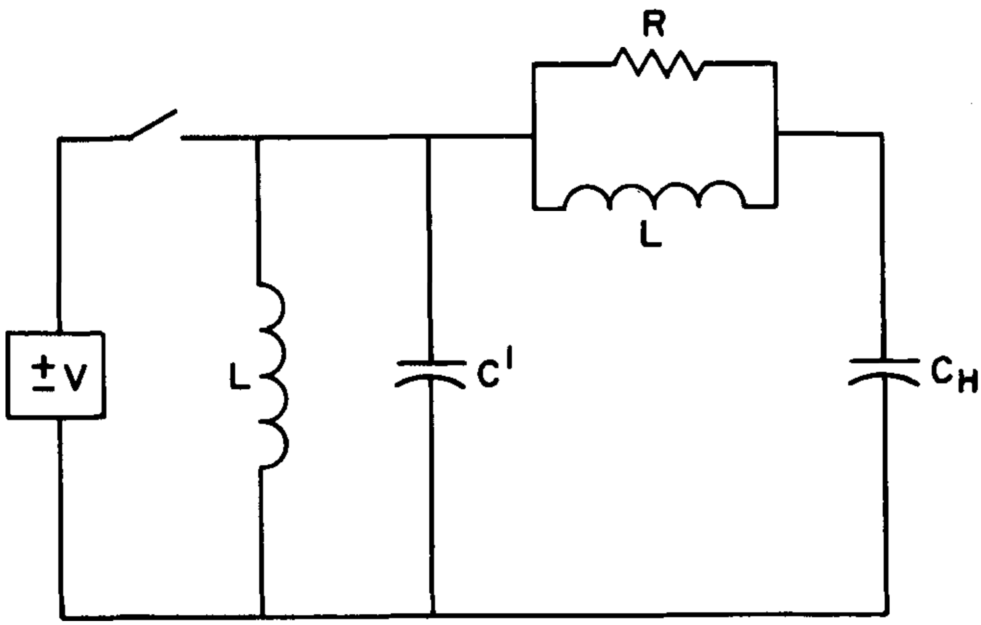


Fig. 17. A simplified Inall circuit.

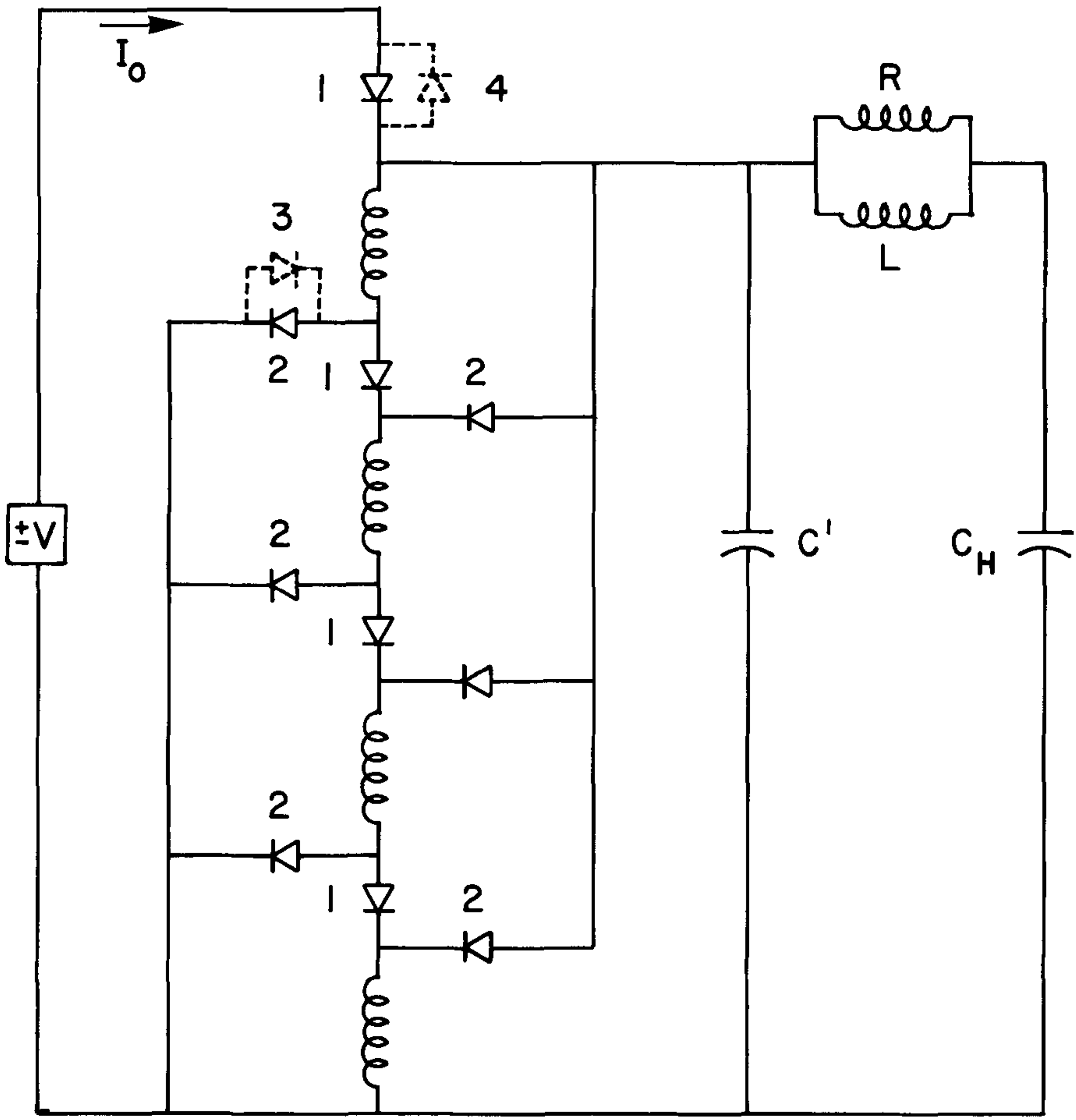


Fig. 18. The Inall circuit for energizing Tokamak OH coils.

Toroidal Z-Pinch

The toroidal Z-pinch is a medium aspect ratio (5-10) torus using both poloidal and toroidal fields for equilibrium. Like the tokamak, it is ohmically heated, but since it is a high density, high-beta plasma, the current density is high and it can be ohmically heated to ignition. Unlike the tokamak, the poloidal field is comparable to or larger than the toroidal field (typically $q = aB_T/RB \sim 0.1$) so the OH supply provides several times as much energy as the toroidal supply.

Preliminary Z-pinch reactor operating cycles have been examined by Hagenson.[10] Reactors in the 500-1000 MWe range store ∼3 GJ in the OH system, have burn times ∼1 s, and startup times of ∼10-30 ms.

The circuitry for this application is similar to that for the Tokamak, in that a separate toroidal system provides the bias toroidal field, while a pulsed coil provides the fast reversing toroidal field and the poloidal field. These pulsed fields must be brought on together. The pulsed coil current starts at zero rather than full reverse current. The initial rapid rate of rise of current will give way to a slower average transfer time as in Tokamaks, and the current will then be held by a separate low voltage supply during the burn. The circuit of Fig. 17 could be used by charging C' and C_H to full energy, with the auxilary supply off. The initial fast-rise is provided by C', with C_H completing the transfer. At full current, the power supply takes over and provides the near steady current for burn and the homopolar is at rest. Energy is removed from the coil by phasing back the power supply SCR's, thus charging the homopolar and C'.

Summary

A variety of applications of homopolar machines in power conditioning circuits for fusion devices have been described. In many cases these proposed systems are the best or only alternative for meeting the requirements. The transfer times for the systems described here range from 1 ms for liners, to ∼30 ms for RTPR and Z-pinches, to ∼300 ms for charging of intermediate inductive stores, to ∼½-1 s for tokamak OH systems.

Many of the requirements here are only roughly defined, and the machines needed for each different application are widely varied. However, preliminary conceptual designs are available in many instances, allowing an assessment of the advantages and disadvantages. Further development work is underway to construct models of

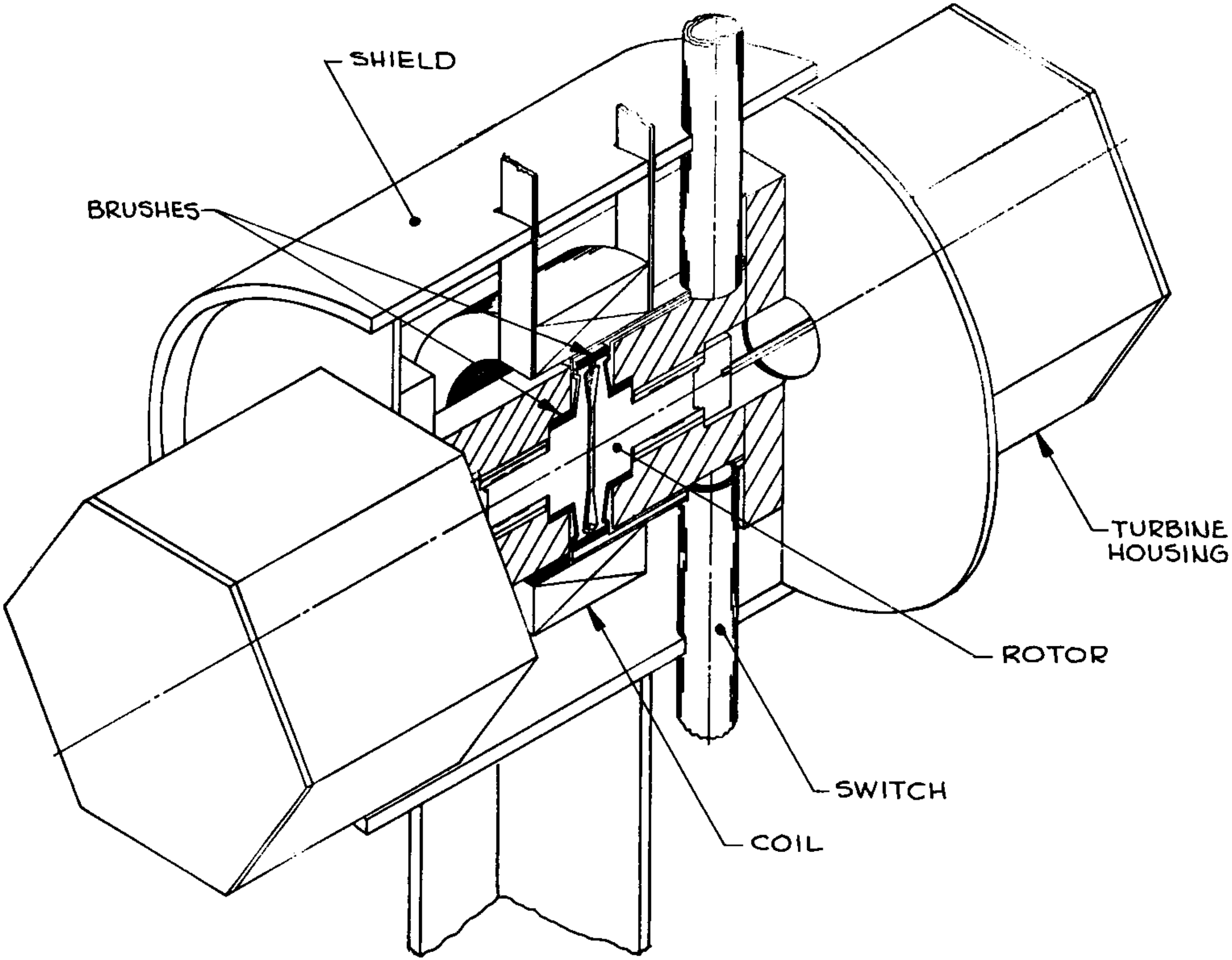


Fig. 19. A two-disc homopolar machine for ∿1 ms discharging, (Courtesy University of Texas, Energy Storage Group).

the 1 ms and 30 ms machines at the University of Texas and Los Alamos respectively. The University of Texas model machine, shown in Fig. 19, has been constructed and is undergoing tests. It is designed to discharge its 360 kJ in 3 ms, or 90 kJ in 1 ms into a short circuit. The Los Alamos 10 MJ model machine has been designed by Westinghouse, with participation from LASL and the University of Texas, under EPRI sponsorship. Plans are being made for the construction of this machine during 1977-1979.

These models will allow a much better assessment of the role of homopolar machines in fusion systems. In particular, the cost and reliability advantages can be judged.

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Fusion Applications of Homopolar Machines