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POWER SUPPLY REQUIREMENTS FOR A TOKAMAK FUSION REACTOR

by

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FUSION POWER PROGRAM

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February 1979

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
I. INTRODUCTION AND SUMMARY	2
A. Reactor Model	4
B. Computational Model	7
C. Requirements of a Conventional Power Supply System	12
D. Typical Burn Cycle Using a Conventional System	12
E. Sensitivity to Fuel Density and Oxygen Contamination During Startup	24
F. Sensitivity to Ramp Time and OH Field	27
II. NONCONVENTIONAL SYSTEMS	31
A. Homopolar-Generator System	31
B. Typical Burn Cycle Using an HPG System	33
C. HPG System - Sensitivity to Ramp Time and B_{OH}^{max}	36
D. Superconducting Energy Storage Inductor System	39
E. Dump Resistor System	41
III. CONCLUSION	45
ACKNOWLEDGMENTS	49
APPENDICES	
A. Cost Algorithms	50
B. Oxygen Contamination Model	52
FOOTNOTES	54
REFERENCES	55

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I	Reactor Model Parameters	6
II	Technology Requirements and Cost of Four Power Supply Systems for a Range of OH Ramp Time and for $B_{OH}^{max} = 8 T$	48

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1	Elevation view of 7-M reference reactor	5
2	Simplified equivalent circuit of driving system	9
3	Conventional power supply system	13
4	Current and voltage waveforms for a reference burn cycle using a conventional power supply system	14
5	Ion densities during the reference burn cycle	17
6	Ion temperature and gain and loss powers during the reference burn cycle	18
7	Plasma inductance, L_p , and poloidal beta, β_p , during the reference burn cycle	21
8	OH current and MGF set power, P_s , and energy, U_s , during the reference burn cycle	23
9	Contour plot of volt-second resistive losses during startup as a function of the degree of low-density startup and of the oxygen content of the DT fuel stream	26
10	Power, volt-second, and field change requirements for a conven- tional power supply system, as a function of the OH ramp time used for startup	28
11	Conventional power supply system cost, and reactor power output as a function of Δt_{OH}	30
12	HPG system	32

<u>No.</u>	<u>Title</u>	<u>Page</u>
13	Voltage and current waveforms for a typical burn cycle using a homopolar generator system	34
14	HPG power supply system cost and reactor power output as a function of Δt_{OH} and B_{OH}^{max}	37
15	Cost comparison of a conventional system and an HPG system	38
16	ESI system	40
17	Cost comparison of a conventional system and an ESI system	42
18	Resistor/switch network	44
19	Cost and reactor power output comparison of a conventional system and a dump resistor system	46

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ABSTRACT

The power supply requirements for a 7-M major radius commercial tokamak reactor have been examined, using a system approach combining models of the reactor and poloidal coil set, plasma burn cycle and MHD calculations, and power supply characteristics and cost data. A conventional system using an MGF set and solid-state rectifier/inverter power supplies was studied in addition to systems using a homopolar generator, superconducting energy storage inductor, and dump resistors. The requirements and cost of the power supplies depends on several factors but most critically on the ohmic heating ramp time used for startup. Long ramp times (≥ 8 s) seems to be feasible, from the standpoint of resistive volt-second losses, and would appear to make conventional systems quite competitive with nonconventional ones, which require further research and development.

I. INTRODUCTION AND SUMMARY

The power supply system will be one of the most important parts of future tokamak power reactors. This system will handle huge amounts of power, typically in the GW range, and will cost in the neighborhood of 100 M\$. Even though commercial fusion reactors will not be built for some time, it is important to assess their power supply requirements now, for several reasons. First, if nonconventional power supplies will be needed, their development should be started now because of the long lead times involved. Pre-commercial devices, such as TNS and EPR, should hopefully use power supply systems that are prototypical of later devices. Also, the cost of the power supply system and its effect on the reactor power production may strongly influence the overall reactor design and economics. To this end a study devoted to the goal of defining the requirements and cost of the power supply system for fusion reactors has been performed. The study should also serve as a guideline for cost goals of new technology if they are to be economically competitive with present technology.

Initially we have focused on the power supply needs for one specific type of tokamak reactor — a moderate size ($R = 7 \text{ M}$), moderate toroidal field ($B_T = 8.5 \text{ T}$) and beta ($\beta = 7\%$), and with a "conventional" superconducting ohmic heating (OH), and equilibrium field (EF) coil design [solenoidal OH coil, EF coils outside of the toroidal field (TF) coils]. Parametric systems studies have indicated that this type of reactor may well be the most economical.⁽¹⁾ In the future other reactor designs will be examined.

A conceptual design of a 7-M reactor, and a poloidal coil system, has been developed to serve as a test bed for the study. Plasma magnetohydrodynamic (MHD) equilibrium and burn cycle calculations have been made to compute the

power, volt-second, energy requirements, the cost of the power supply system, and the reactor performance, for a range of plasma physics and technological parameters. Four types of power supply configurations have been examined: a conventional system using a motor-generator flywheel (MGF) set and solid-state rectifier/inverter power supplies, and three nonconventional systems which incorporate respectively a homopolar generator (HPG), a superconducting energy storage inductor (ESI), and a dump resistor/interrupting switch. Cost algorithms described in Appendix A have been developed for each device and have been used to compare the economics of each system.

It has been found that while the startup period sets most of the power supply requirements, the main burn period and the shutdown period are also important, particularly for nonconventional systems. The most critical parameter for a conventional system is the ohmic heating ramp time used for startup. Previous studies⁽²⁻³⁾ showed an apparent restriction in this parameter to a range of about 1-4 s, because of plasma-resistive losses.

Recent experimental results which show classical plasma resistivity, more precise estimates of the oxygen contamination during startup, and improved radiation models, have been incorporated into this study and have lead to reduced estimates of the startup-resistive losses. In addition, the use of low-density startups have been found helpful, but not essential, in minimizing resistive losses. As a result of the lowered predicted losses, long ramp times, up to perhaps 20 s, appear to be feasible. The use of longer ramp times makes possible considerable reductions in the power requirements, and the cost of a conventional power supply system. It also appears that substantial reductions in power supply cost can be realized by not necessarily using the maximum value of OH coil field swing (typically ± 8 T), at the expense of a shorter burn time and somewhat less power production.

All of the nonconventional systems studied were found to be cheaper than the conventional system at short ramp times. At longer ramp times, however, the conventional system is either about the same or less expensive than the nonconventional systems. This would tend to imply that the development of nonconventional power supply systems might be helpful but not essential for tokamak reactors. Although more work is needed to verify the plasma physics models, and to extend the analysis to other classes of reactors, these results are encouraging for tokamak fusion reactors, in our opinion.

A. Reactor Model

The reactor model for this study was developed using the ANL Parametric Systems Code.⁽¹⁾ A plan view of the reactor is shown in Fig. 1. The design parameters and the major plasma parameters are listed in Table I. The OH and EF coil system was designed using a method⁽⁴⁾ that minimizes the coupling between them, minimizes the stored energy in the EF system, and provides for the proper plasma shape. The OH coil consists of a central solenoid, with a few external turns used for trimming. The EF coils are located outside the TF coils. Both coils are superconducting. The maximum value of the OH field is 8 T but it might be more economical to use lower values, as discussed later. In addition to the OH and EF coils, the reactor has a set of initiation-trimming (IT) coils, not shown in Fig. 1. These coils are used to produce breakdown and control the position of the plasma at the beginning and end of the discharge.^a

From the standpoint of the power supply system, there are two features of this reactor design, that are particularly important. First, the available space in the center of this reactor design for the OH coil ("hole in the doughnut") is large enough to permit a "comfortable" flux swing as opposed to a compact device ($R \approx 5$ M) where the limited flux swing may be a critical

Fig. 1. Elevation view of 7-M reference reactor.

TABLE I
Reactor Model Parameters

Major radius, R	7 M
Aspect ratio, A	3.0
Maximum toroidal field, B_T	8.5 T
OH coil radius, R_v	2.5 M
Beta, β	7%
Thermal power output	2350 MW
First-wall composition	Type 316 SS coated with beryllium
<u>Plasma Parameters</u>	
Plasma current, I_p	11.6 MA
Height-to-width ratio, K	1.3
Safety factor, q	3
Average ion temperature, T_i	8 keV
Average DT density, N_{DT}	$1.53 \times 10^{20} \text{ M}^{-3}$

limitation. Conversely, compared to a smaller device, the EF coils have fairly poor coupling to the plasma though this coupling is better than for large device.

The impurity control method for this reactor is assumed to be a limiter/vacuum system in which 50% of the particles diffusing from the plasma and hitting a system of limiters are reflected into adjacent vacuum ports and pumped out. This method permits a non-impurity limited burn. The details of this scheme are discussed in Ref. 5. The power supply requirements are fairly insensitive to the type of impurity control scheme used, provided that a non-impurity limited burn is possible, i.e. a burn limited only the available volt-seconds.

B. Computational Model

A spatial-profile-averaged, time-dependent, plasma code coupled to an MHD equilibrium code (see Ref. 3) and to a power supply/poloidal coil system code has been used to compute the power supply requirements over the burn cycle. The plasma burn cycle code solves particle balance equations for each constituent plasma ion species (D-T, alpha, wall-sputtered, and oxygen impurities) and solves energy balance equations for the ions and electrons. Plasma heating by alphas, neutral beam, and compressional heating is treated. Radiative (bremsstrahlung, line, recombination) and transport losses are treated, the former with a coronal equilibrium model⁽⁶⁾ and the latter with a multi-region (neoclassical ions/empirical electrons at large collision frequencies and trapped-particle mode at small collision frequencies) confinement model. The plasma MHD equilibrium code solves the Grad-Schranov and pressure-balance equations for the two-dimensional flux function. The coupled dynamics of the plasma, poloidal coils, and the power supplies have been simulated with the three-mesh equivalent circuit shown in Fig. 2. Both the OH and EF coil systems

are represented as a single equivalent inductance and the plasma is represented as a series combination of inductance and resistance, both of which vary with time. The EF coil is driven by an active power supply while the OH coil can be driven by an active power supply or a passive element such as a homopolar generator — these being labeled as a "transfer element" in Fig. 2. In Fig. 2 it is understood that the OH and EF supplies operate out of a central energy storage device as appropriate.

The coupled system of Fig. 2 is described by the following set of equations:

$$L_{OH} \frac{dI_{OH}}{dt} - M_{OH,P} \frac{dI_P}{dt} - M_{OH,EF} \frac{dI_{EF}}{dt} = V_{OH}, \quad (1)$$

$$L_P \frac{dI_P}{dt} + I_P \frac{dL_P}{dt} + R_P I_P = M_{OH,P} \frac{dI_{OH}}{dt} + M_{EF,P} \frac{dI_{EF}}{dt}, \quad (2)$$

$$I_{EF} = f(I_P, \beta), \quad (3)$$

$$L_P = g(I_P, \beta). \quad (4)$$

where β is the ratio of the plasma pressure to the toroidal magnetic pressure. The required current, I_{EF} , in the EF coil, needed to maintain MHD equilibrium, and the value of plasma inductance L_P are functions of I_P and β . These functions are determined by the MHD equilibrium code as the plasma evolves through a sequence of equilibria during the burn cycle.

The inductance matrix for the system was computed on the basis of the coil locations shown in Fig. 1. The values shown are normalized to the number of turns in the respective coils. The coefficients of coupling are defined in the normal manner as $K_{i,j} = M_{i,j} \sqrt{L_i L_j}$, where the values stated refer to the

**SELF-INDUCTANCE AND COEFFICIENT
OF COUPLING VALUES**

$$\begin{aligned}
 L_p^{\max} &= 14.0 \mu\text{H} \\
 L_{OH} &= 1.45 N_{OH}^2 \mu\text{H} \\
 L_{EF} &= 5.68 N_{EF}^2 \mu\text{H} \\
 K_{OH,p} &= 0.33 \\
 K_{EF,p} &= 0.27 \\
 K_{EF,OH} &= -0.01
 \end{aligned}$$

where

$$\begin{aligned}
 N_{OH} &= \text{No. of turns of OH coil} \\
 N_{EF} &= \text{No. of turns of EF coil}
 \end{aligned}$$

Fig. 2. Simplified equivalent circuit of driving system.

maximum plasma inductance. In practice the value of the mutual inductance between the plasma and the EF coil changes slightly during the startup and shutdown, but this change has been ignored. The value of $M_{OH,p}$ does not change. V_{OH} in Eq. (1) depends on whether a rectifier power supply, a homopolar generator, or a resistor is used. These devices are modeled respectively by an ideal voltage source, a capacitor, and a resistor. V_{OH} is therefore given by:

$$V_{OH} = \begin{cases} V_{OH} & \text{for a power supply with output voltage } V_{OH} \\ \frac{1}{C} \int_0^t I_{OH} dt & \text{for a HPG of equivalent capacitance } C \\ I_{OH} R_{OH} & \text{for a resistance } R_{OH} . \end{cases}$$

The power delivered to the OH coil, P_{OH} , and to the EF coil, P_{EF} is given by

$$P_{OH} = I_{OH} V_{OH} , \quad (5)$$

$$P_{EF} = I_{EF} V_{EF} , \quad (6)$$

where

$$V_{EF} = L_{EF} \frac{dI_{EF}}{dt} - M_{EF,p} \frac{dI_p}{dt} - M_{EF,p} \frac{dI_{OH}}{dt} \quad (7)$$

is the voltage across the EF coil.

The energy delivered to the respective coils are:

$$U_{OH} = \int_0^t P_{OH} dt , \quad (8)$$

$$U_{EF} = \int_0^t P_{EF} dt , \quad (9)$$

and the flux swing across the OH coil is

$$\Delta\phi_{OH} = \int_0^t V_{OH} \cdot dt \quad (10)$$

The OH flux swing required for startup can be found by integrating Eqs. (1) and (2) from $t = 0$ to a time " t_s " at the end of startup when all currents are at their maximum and using the fact that $I_p(0) = I_{ef}(0) = 0$ and that $M_{OH,p} \approx L_{OH}/N_{OH}^2$, which gives

$$\Delta\phi_{OH} = L_p^{\max} I_p^{\max} + \int_0^{t_s} R_p I_p dt - M_{EF} I_{EF}^{\max} - M_{OH,p} I_p^{\max} \quad (11)$$

The first term on the RHS of Eq. (11) represents the self-inductive volt-seconds linking the plasma; the second term is the resistive volt-second loss in the plasma during startup; the third term, $M_{EF} I_{EF}^{\max}$, is the flux supplied to the plasma by the EF coil; and the last term represents the reduction in the required OH flux swing because of the coupling between the plasma and the OH coil. In the burn cycle computations, Eqs. (1)-(4), are solved simultaneously with the plasma equations. Equations (5)-(11) are then used to compute the power supply requirements.

C. Requirements of a Conventional Power Supply System

A power supply and energy storage system using conventional hardware is shown in simplified form in Fig. 3. In this system a motor-generator-flywheel (MGF) set serves as the central energy storage device. Thyristor-type rectifier inverter power supplies (PS) are used to transfer energy back and forth between the MGF set and the OH and EF coils. Transformers (not shown) will probably have to be used between the MGF set and the power supplies to obtain

the proper voltage level, and these have been included in the cost algorithms (see Appendix A.) The neutral beam supply is a high voltage (180 kV) supply that also operates out of the MGF set. Although the beam supply has not been included in the cost analysis directly, the effect of the beam supply on the MGF set requirements has been taken into account. Energy losses in the system are resupplied from the utility grid through a substation connected to the motor.

The system of Fig. 3 also requires a switch to reverse polarity when the OH current goes through zero. However, since it is possible to take up to one-half second to reverse the OH polarity at the zero crossing point, a relatively inexpensive mechanical switch is more than likely adequate.

D. Typical Burn Cycle Using a Conventional System

A typical burn cycle using a conventional power supply system is shown in Fig. 4. The burn cycles studied were treated as having two major operating parameters: (1) the value of the maximum OH field, B_{OH}^{max} ; and (2) the length of the OH ramp used for startup, Δt_{OH} . The cycle shown has values of $\Delta t_{OH} = 8$ s, $B_{OH}^{max} = 8$ T, in addition to a low density startup where the initial fuel density is about one-third of the final density. The neutral beam is operated in three stages: an initial preheating stage of the first second of the cycle used to overcome high-impurity radiation; a main heating phase of 100 MW begun after the OH ramp; and a final phase of about the last 1 s of the cycle used to control the rate of plasma cooling during shutdown.

Prior to the start of the burn pulse the current in the OH coil is driven to a value of $I_{OH} = 110$ MA turns, corresponding to $B_{OH} = -8$ T. A 10-ms breakdown pulse from the IT coils follows; the features of the breakdown do not appear on the scale of Fig. 4. At the end of breakdown, $I_p = 0.3$ MA. The OH

Fig. 3. Conventional power supply system.

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Fig. 4. Current and voltage waveforms for a reference burn cycle using a conventional power supply system.

(ANL Neg. No. 190-79-19)

power supply is then set to maintain a constant voltage of about 12 V/turn of the OH coil (i.e. $V_{OH} = 12 \times N_{OH}$ volts), thereby ramping down the OH current.^b Plasma current is induced by the transformer action of the OH coil. By $t = 8$ s, the OH coil has supplied its required share of the plasma current, as determined by Eq.(11), and the OH current ramp is stopped by setting $V_{OH} = 0$. At this time, 100-MW neutral beam heating is turned on. By about 15 s the plasma has reached the operating temperature of 8 keV and the beam is turned off. This constitutes the startup period.

During the startup the EF current must be continuously increased to keep the plasma in MHD equilibrium. This requires fine control of the EF voltage as shown. The EF system must, therefore, use a device capable of variable voltage control, a requirement met by a phase-controlled solid-state supply but not by a passive device.

The resistive loop voltage of the plasma, $I_p \times R_p$, varies from about 4 V at $t = 0$ when the plasma is cool to about 0.1 V at $t = 15$ s when the plasma is hot. A total of 17.4 V-s are expended resistively during the startup. This is based on the experimentally verified classical Spitzer resistivity and is significantly less than would result from the use of the previous "anomaly" factors of 3-10 once though likely.⁽⁷⁾

During the main burn period the function of the OH power supply is to slowly ramp up the OH current so as to provide the volt-seconds needed to keep the plasma current constant. V_{OH} is set equal to the plasma resistive loop voltage during the burn, a value of $I_p R_p \approx 0.1$ V which is based on the neo-classical predicted resistivity, at low-collision frequency, of ≈ 2.5 times the Spitzer resistivity. As I_{OH} passes through zero the OH power supply is reversed across the OH coil by means of a switch.

For this conventional system there is nothing to be gained by using other than a symmetric swing of I_{OH} . Therefore, I_{OH} is ramped up to $I_{OH} = |I_{OH}(0)|$. This permits a burn of about 33 min.

Shutdown is accomplished by reducing the DT density (by controlling the refueling rate). Reducing the DT density lowers the fusion rate and cools the plasma. It appears to be possible to control the nature of the shutdown in a manner that allows the use of the same power supplies required for startup. During the first ~8 s of the shutdown, the OH supply is set to zero voltage, the DT density is reduced, and the plasma is allowed to cool from about 8 keV to 1.5 keV. During this period, I_p falls off somewhat because of plasma resistive losses. I_{EF} is ramped down as β falls. After this initial cooling-off period, I_{OH} and I_p are ramped down in two stages, a full voltage stage where $V_{OH} = -V_{OH}^{startup}$ and a half-voltage stage. The half-voltage stage is used to prevent I_p from decaying too quickly when the plasma is very cool and thereby necessitating a higher value of $|V_{EF}|$ than was used during the startup period. It might also be possible to ramp I_{OH} down immediately, without waiting for the plasma to cool, if there were no skin effect problems.

After shutdown, I_{OH} is further ramped down to -110 MA-turns; the vacuum chamber is pumped out; and preparations are made for the next burn pulse.

Some of the plasma physics features of this burn cycle are shown in Figs. 5 and 6. Figure 5 shows the behavior of the various ion densities in the plasma during the burn cycle. The use of a low-density startup is shown, where the plasma is initially fueled at about one-third the final equilibrium density, is fueled to about two-thirds value by the end of the ohmic heating phase, and then fueled to full value during the beam heating period. The value of N_{DT} is adjusted by varying the refueling rate (not shown). A low-density startup and subsequent refueling seem credible because of the success of gas-puffing

Fig. 5. Ion densities during the reference burn cycle.

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Fig. 6. Ion temperature and gain and loss powers during the reference burn cycle.
(ANL Neg. No. 190-79-22)

experiments.⁽⁸⁾ A low-density startup is helpful in reducing resistive volt-second losses, but not essential — as will be discussed. During the startup, helium builds up from fusion and beryllium from sputtering of the first wall. During the main burn, the impurity control system removes these impurities at the same rate as they are produced and so an equilibrium is reached.

The oxygen density is more critical to the startup than helium or beryllium because of the large line-and-recombination radiation from partially stripped oxygen ions at low temperature. Appendix B describes the oxygen transport model developed for and used in this study. In Fig. 5 at $t = 0$, an amount of oxygen equal to 0.015% of the DT density is present from two sources, initial desorption of physically bonded oxygen from the first wall, and contamination of the DT fuel. The oxygen density stays about the same until $t = 2$ s at which time the plasma is hot enough to begin sputtering oxygen, present in the form of a 5% beryllium oxide coating, from the first wall. The slope of the oxygen density versus time curve changes in response to the different particle containment times encountered as the plasma becomes less collisional.

The ion temperature T_i and the heating and loss terms during the burn cycle are shown in Fig. 6. ($T_e \approx T_i$ through the cycle.) At the end of the breakdown period, $T_i = 30$ eV. Some neutral beam heating is needed from 0–1 s to overcome the radiation loss due to the oxygen. The beam power is adjusted to give a net heating power, i.e. an excess of beam and ohmic heating over radiation and transport power, of 2 MW. The maximum beam power needed for this is ~7 MW, considerably less than the main beam heating power of 100 MW. The beam is turned off when T_i reaches 100 eV. Based on the present analysis, it seems probable that a beam-assisted startup will be required for future reactors although the exact power needed depends on the starting fuel density used and several other factors. Basically, future tokamak reactors will suffer from

an unfavorable scaling with major radius of ohmic heating power to radiation power, compared to present-day experimental tokamaks. However, aside from this initial beam heating, no supplementary heating is needed for the rest of the ohmic heating period. Supplementary heating would reduce the resistive volt-seconds but at the possible expense of preventing adequate current penetration in the plasma.

During the main beam heating phase the plasma is also heated by α -heating, and is also heated somewhat by compressional heating due to the conversion of plasma magnetic energy to thermal energy. This has been referred to as " $\dot{L}_p$ heating" since it arises from a change in plasma inductance as the flux surfaces move outward in major radius. During shutdown, $\dot{L}_p < 0$ and so this process cools the plasma. This effect is small compared to the beam. The behavior of L_p and the plasma-poloidal beta, β_θ , are shown in Fig. 7.

A beam power of 100 MW is not the minimum necessary for adequate heating of this reactor. It was found that 75 MW can heat the plasma adequately, with about 2 s more heating time required, and even 50 MW might be acceptable. Furthermore, lowering the beam power reduces the required value of EF voltage. However, a beam power of 100 MW has been used, as a reference value, for this study.

During shutdown, the reduction in alpha heating, due to reducing the fuel density, cools the plasma. At the end of the shutdown the plasma tends to cool too quickly and so the beam has to be turned on again to permit an orderly shutdown. As in the startup this cooling is due to line-and-recombination radiation which peaks at low temperatures. More supplementary beam power is needed during shutdown than startup because the plasma has acquired higher impurity concentrations during the burn. If a beam is not applied during the end of shutdown, the resultant fast cooling makes it impossible or prohibitive to reduce I_{EF} fast enough. (This could result in a plasma dump to the wall.)

Fig. 7. Plasma inductance, L_p , and poloidal beta, β_p , during the reference burn cycle.
(ANL Neg. No. 190-79-15)

The requirements on the OH and EF power supplies for this burn cycle are derived from the waveforms in Fig. 4. The maximum OH power required is set at the start of the burn cycle where both V_{OH} and $|I_{OH}|$ peak;

$$P_{OH} = V_{OH}^{\max} \times |I_{OH}|^{\max} = 1370 \text{ MVA.}$$

The EF power requirement is set during startup, during the main beam heating period; $P_{EF} = V_{EF}^{\max} \times I_{EF}^{\max} = 351 \text{ MVA.}$

The MGF set requirements consist of the maximum power supplied by the generator and the maximum energy stored in the flywheel. The power supplied by the MGF set, " P_s " and the stored energy " U_s " = $\int_0^t P_s$, for this burn cycle, are shown in Fig. 8. Initially, the flywheel is spun to a speed corresponding to $U_s = 3.0 \text{ GJ}$ to avoid mechanical resonance problems. During the OH ramp, $P_s \geq 0$ since energy is transferred from the OH coil to the flywheel, speeding it up. When the main beam heating starts, and concurrently when the EF coil is being charged rapidly, energy is removed from the flywheel and so $P_s > 0$. As shown, the peak power requirement occurs at $t = 0$ and, in fact, is equal to the OH power. During the main burn period, $|P_s| \leq 3.0 \text{ MW}$ and is not plotted on the scale of Fig. 8. It is not clear whether the MGF set would actually be used during the burn period or whether the OH supply would be run directly from the grid interface supply but in any event the burn period does not appear to set any critical requirement of the MGF set.

During shutdown the operation of the MGF set is basically the reverse of the startup. The power requirements for shutdown are less than those of startup. The stored energy requirement of $U_s = 11.8 \text{ GJ}$ occurs after shutdown as the OH current is being re-biased and goes through zero. At this point, most of the energy present in the OH coil has been transferred to the MGF set.

Fig. 8. OH current and MGF set power, P_s , and energy, U_s , during the reference burn cycle.
(ANL Neg. No. 190-79-13)

E. Sensitivity to Fuel Density and Oxygen Contamination During Startup

The sensitivity of the requirements of the conventional system to the degree of the low-density startup and to the oxygen contamination during startup was examined for a fixed value of $\Delta t_{OH} = 8$ s and $B_{OH}^{max} = 8$ T.

Changes in the fuel density and in the oxygen concentration were found to have two effects: the initial beam power requirement is changed; and the temperature-versus-time history of the plasma is changed, with a resulting difference in the resistive volt-seconds consumed during startup. The duration of the main beam-heating period and the requirements on the EF system are not significantly changed.

Different low-density startups were investigated using a linear DT density ramp of the form:

$$N_{DT}(t) = \begin{cases} N_{DT}^0 + (N_{DT}^1 - N_{DT}^0)t, & 0 \leq t \leq \Delta t_{OH} \\ N_{DT}^1 + \left[N_{DT}^{max} - N_{DT}^1 \right] (t - \Delta t_{OH}), & \Delta t_{OH} \leq t \leq \Delta t_{OH} + 4 \\ N_{DT}^{max}, & \Delta t_{OH} + 4 \leq t, \end{cases}$$

where N_{DT}^0 , N_{DT}^1 were varied independently; $\Delta t_{OH} = 8$; and $N_{DT}^{max} = 1.53 \times 10^{20} \text{ M}^{-3}$.

It was found that the starting volt-second consumption $\Delta \phi_R$ depends on the average value of N_{DT} during the OH period, $0 - \Delta t_{OH}$, i.e. to

$$\bar{N}_{DT} \equiv \int_0^{\Delta t_{OH}} N_{DT}(t) dt = (N_{DT}^0 + N_{DT}^1)/2$$

and is fairly insensitive to the specific end-point values $N_{DT}^0 + N_{DT}^1$ used. (However, the initial beam-heating requirement is sensitive to N_{DT}^0). The effect of the fuel density can therefore be expressed in terms of the ratio $\bar{N}_{DT}/N_{DT}^{max}$.

In analyzing the sensitivity to the oxygen concentration it was found convenient to vary only the amount of oxygen present in the fuel stream — the parameter f_{fuel} in the model of Appendix B. To first order, the concentration of oxygen in the plasma during the ohmic heating period scales linearly with this parameter. The other parameters were fixed as for the reference case.

The resulting dependence of $\Delta\phi_R$ on $\bar{N}_{DT}/N_{DT}^{\text{max}}$ and on f_{fuel} are shown in Fig. 9 in terms of a contour plot showing equal $\Delta\phi_R$ contours. For the reference values of $\bar{N}_{DT}/N_{DT}^{\text{max}} \approx 0.50$ and $f_{\text{fuel}} = 0.01\%$, $\Delta\phi_R$ equals about 17 V-s. Increases in $\Delta\phi_R$ have two effects: the OH power required for startup increases as $P_{OH} \sim (78 + \Delta\phi_R)/\Delta t_{OH}$; and, secondly, the available burn time decreases linearly with $\Delta\phi_R$.

For example, for $\Delta t_{OH} = 8$ s, each increase of $\Delta\phi_R$ of 10 V-s will increase P_{OH} by approximately 10%, and will increase the OH power supply cost by about 5 M\$. Each 10 V-s increase in $\Delta\phi_R$ will reduce the burn time by about 1.5 min. Considering these points there seems to be a significant latitude in the oxygen/fuel density parameter space where tolerable results can be obtained. A low-density startup is beneficial but is not essential unless the oxygen contamination is much higher, by an order of magnitude, than the estimated value. For example, for the reference value of f_{fuel} , a full-density startup, i.e. $\bar{N}_{DT}/N_{DT}^{\text{max}} = 1.0$ would increase P_{OH} by only $\sim 13\%$. If f_{fuel} were ten times the reference value, the difference between a half-density startup and a full-density startup would be about 20%. These conclusions apply only to the needs of the power supply system. Low-density startups may be required for adequate beam penetration, and to help get through an initial radiation barrier (9) and for other reasons as well.

Fig. 9. Contour plot of volt-second resistive losses during startup as a function of the degree of low-density startup and of the oxygen control of the DT fuel stream.

(ANL Neg. No. 190-79-25)

Another way to lower the resistive losses during startup might be to apply beam heating during the entire ohmic heating ramp. This option was examined for a range of oxygen and fuel density parameters, and beam powers. Using continuous beam heating was found to lower $\Delta\phi_R$ and, in fact, if enough beam power is used, $\Delta\phi_R$ can be made almost insignificant even for high concentrations of oxygen. This mode of operation has two possible disadvantages. First, the beam power must be carefully controlled so as to heat the plasma gradually; otherwise the EF requirements become prohibitive. (This is not the case after the OH ramp because $I_p \approx 0$.) Secondly, heating the plasma too much before all or most of the plasma current is induced may result in skin effect problems and/or problems with the density and temperature profiles, or MHD stability problems. These questions are not fully amenable to analysis at the present time.

F. Sensitivity to Ramp Time and OH Field

Figure 10 shows the OH and EF power, the maximum OH field change, $\dot{B}_{OH}$, and the startup volt-second requirements as a function of Δt_{OH} . Except for Δt_{OH} the burn cycles corresponding to Fig. 10 are similar to the reference cycle. In all cases it is the startup period that sets the power requirements for the OH and EF supplies. The required OH power scales as $P_{OH} \sim (\Delta\phi_{OH}/\Delta t_{OH})$. $\Delta\phi_R$ and hence $\Delta\phi_{OH}$ increases about linearly with Δt_{OH} , but this increase is small compared with effect of changing Δt_{OH} in the denominator. Over the range of $\Delta t_{OH} = 2\text{-}20$ s, there is about a 5:1 variation in P_{OH} . The maximum rate of change of the OH field is an important parameter for a superconducting magnet design. Since $\dot{B}_{OH} = (V_{OH}/\pi R_{OH}^2)$, where R_{OH} is the radius of the OH coil, and P_{OH} also varies as $P_{OH} \sim V_{OH}$, the variation in $\dot{B}_{OH}$ is also 5:1. The power requirement of the MGF set in each case of Fig. 10 is the same as P_{OH} . The

Fig. 10. Power, volt-second, and field change requirements for a conventional power supply system, as a function of the OH ramp time used for startup.
(ANL Neg. No. 190-79-16)

energy requirement of the MGF set is always set during shutdown (at 11.8 GJ) and so is independent of Δt_{OH} .

For $\Delta t_{OH} \geq 7$ s, the EF power requirement for startup is set during the beam heating period as in Fig. 4, and is therefore independent of Δt_{OH} . For $\Delta t_{OH} \geq 7$ s, P_{EF} set during the ohmic heating period and scales approximately as $1/\Delta t_{OH}$.

Figure 11 shows how the power supply system cost and the cycle-averaged net electrical power output vary as a function of Δt_{OH} as well as B_{OH}^{max} . The power supply covers the MGF set, the OH and EF power supplies, and all transformers and switches. The neutral beam supply cost is not included because it does not vary with Δt_{OH} or B_{OH} . The net electrical power, P_{net} , accounts for the production of electricity at a 35% conversion efficiency and for the power lost in the neutral beam, refrigeration, pumping, and power supply systems, and for the effect of downtime.

For a fixed value of B_{OH}^{max} , the system cost declines steeply as Δt_{OH} is increased. For $B_{OH}^{max} = 8$ T, the variation in cost is about 5:1 over the range $\Delta t_{OH} = 2$ -20 s. This behavior in cost basically follows the behavior of the individual power requirements shown in Fig. 10. As Δt_{OH} is increased the reactor duty factor (defined as the ratio of the fusion burn time to the total cycle time) decreases, first because the increase in $\Delta \phi_R$ reduces the allowable burn time; and, secondly, because more time is taken directly for startup and shutdown, and to rebias the OH coil between burn pulses. For example, for $\Delta t_{OH} = 2$ s, about 9 s are required for startup (2 s for the OH ramp and 7 s for beam heating), 14 s for shutdown, 30 s between low pulses (needed to pump out the chamber) and this permits a burn time of 34 min. For $\Delta t_{OH} = 20$ s, 29 s are needed for startup, 19.6 s for shutdown, 40 s between burn pulses (set by the time needed to recharge the OH coil, and only a 29-min burn is permitted. The resulting difference in P_{net}

Fig. 11. Conventional power supply cost, and reactor power output as a function of Δt_{OH} .

(ANL Neg. No. 190-79-20)

from 745 to 730 MW is small but in a reactor costing $1-2 \times 10^9$ \$, even a 1% reduction in power may not be insignificant. Still the substantial savings in power supply costs are a strong incentive to operating with a ramp time at least 10 s.

The variation in both cost and P_{net} with $B_{\text{OH}}^{\text{max}}$ are explained as follows: For a fixed value of Δt_{OH} , reducing $B_{\text{OH}}^{\text{max}}$ reduces $P_{\text{OH}}^{\text{max}} \propto B_{\text{OH}}^{\text{max}}$, reduces $P_{\text{MGF}} \propto B_{\text{OH}}^{\text{max}}$ and reduces $U_s \propto (B_{\text{OH}}^{\text{max}})^2$. Reducing $B_{\text{OH}}^{\text{max}}$ also reduces the cost of the OH coil although this has not been included.

Lowering $B_{\text{OH}}^{\text{max}}$ lowers P_{net} because the available volt-seconds and hence the burn time decrease linearly with $B_{\text{OH}}^{\text{max}}$, therefore lowering the duty factor. The determination of the best choice of $B_{\text{OH}}^{\text{max}}$ versus P_{net} must be left to a more general study in which the effects on the heat transfer system, first-wall cycling, OH coil costs, cost of electricity, etc., are considered. However, a preliminary estimate based on the data in Fig. 11 is that operation at or near $B_{\text{OH}}^{\text{max}} = 6$ T may be the most cost-effective.

II. NONCONVENTIONAL SYSTEMS

A. Homopolar-Generator System

A homopolar generator (HPG) is a device that combines the functions of energy storage and energy transfer in one unit. The type of HPG most feasible to work directly with the OH coil of a tokamak is the counter cyclonic generator.⁽¹⁰⁾ The cost of an HPG depends primarily on its stored energy; it is less sensitive to how fast that energy is transferred, i.e. the power. Reliable HPG devices are not commercially available and would have to be developed to a commercial level before they can be incorporated in reactor systems. A power supply system using an HPG is shown in Fig. 12. This system contains many of the same elements as the conventional system, with the addition of the

Fig. 12. HPG system

(ANL Neg. No. 190-79-65)

HPG but the functions and ratings of the MGF set and the OH power supply are different. The HPG has the equivalent circuit of a capacitor. For convenience, this system has been referred to as an "HPG system" even though the HPG is only one part of it.

With this system the HPG is used only for startup, to reverse the current in the OH coil. The OH power supply is used for the rest of the cycle, including shutdown. The operation of the EF supply is the same as for the conventional system.

B. Typical Burn Cycle Using an HPG System

The current and voltage waveforms for a typical burn cycle using an HPG system are shown in Fig. 13. This cycle was computed using similar plasma physics and beam heating parameters as the reference cycle for the conventional system. The OH ramp time, is $\Delta t_{OH} = 8$ s. The ohmic heating period, which for an HPG system corresponds to a current reversal period, differs from the conventional system in two respects: a symmetric swing of I_{OH} must be used; and secondly, the wave forms of I_{OH} and V_{OH} are approximately sinusoidal, because of the LC circuit formed by the OH coil and HPG.

The need for a symmetric swing of I_{OH} during startup is a disadvantage of the HPG system since about a third of the potential OH flux swing is wasted (by starting at ~ -3 T instead of -8 T). Also, the value of $\dot{B}_{OH}$ during startup will be higher than with a conventional system by a factor of about $\pi/2$, this being due to the sinusoidal nature of V_{OH} . Similarly, the peak value of V_{EF} for ramp times when it occurs during the ohmic heating period (not the case of Fig. 13) would be greater than for a conventional system. The resistive volt-second consumption, and the beam-heating requirements are about the same as for the conventional system.

Fig. 13. Voltage and current waveforms for a typical burn cycle using a homopolar generator system.
(ANL Neg. No. 190-79-24)

The maximum burn time for the HPG system, for the case illustrated, is only 16 min, about half the time obtainable with the full flux swing permitted by the conventional system.

The shutdown phase is of particular importance for the HPG system because it is during shutdown that the requirements for the OH power supply and the MGF set are established. These requirements would be minimized by using a long shutdown, i.e. by using a small $|V_{OH}|$. This is in contrast to the conventional system where the OH voltage used for startup is greater or equal to that needed for shutdown. Two things mitigate against using too small a value of $|V_{OH}|$ during shutdown. First $|V_{OH}|$ needs to be large enough so that the plasma can be shut down in a reasonable time and in a controllable fashion. For example, for the limiting case of $V_{OH} = 0$, i.e. the plasma current is allowed to just decay resistively, it takes almost a minute for I_p to fall off to 10% of its maximum value after which it falls off too quickly, resulting in prohibitive EF requirements. Secondly, after the shutdown, I_{OH} needs to be rebiased to its starting value for the next pulse time. The time needed for this depends on the rating of the OH supply.^c

Although an analysis of this subject suffers from uncertainties in plasma physics models during the shutdown; it was found that a value of $|V_{OH}| = 4 \times N_{OH}$ V appears to be about the minimum required for an adequate shutdown for this reactor. This value permits adequate control of the shutdown, as shown in Fig. 13. as well as the rebiasing of the OH coils (not shown) in about 30 s. Based on this voltage, the OH power requirement is $P_{OH} = 440$ MVA. The MGF set power for this case is $P_{MGF} = 684$ MVA. The EF power requirement is set during the beam heating phase and $P_{EF} = 351$ MVA.

C. HPG System - Sensitivity to Ramp Time and B_{OH}^{max}

The dependence of the HPG system cost and the net power output on Δt_{OH} and B_{OH}^{max} is shown in Fig. 14. The cost data is for the MGF set, OH, and EF power supplies, and the HPG. The cost of the HPG, in Fig. 14, is based on a 1.5¢/J cost algorithm. The variation in cost, with Δt_{OH} , is much flatter than for the conventional system primarily because of the insensitivity of the system to the OH power level handled during startup. The small cost peak at low Δt_{OH} is due to the increase of the EF power requirement. The slight upward slope in cost for long ramp times is due to the increased energy storage costs of the HPG (because of higher volt-second requirements).

For this system, reducing the value of B_{OH}^{max} does not affect the startup period since B_{OH} swings symmetrically and is always less than B_{OH}^{max} , for $B_{OH}^{max} = 4.5-8$ T. In contrast, the length of the burn cycle and the shutdown requirements are strongly affected by the choice of B_{OH}^{max} . Because of the limited flux swing associated with the HPG system, the net power output is roughly twice as sensitive to the choice of B_{OH}^{max} , as the conventional system. For $B_{OH}^{max} = 8$ T, the maximum P_{net} for the HPG system is about 3% lower than for the conventional system. For lower values of B_{OH}^{max} , P_{net} falls off rapidly. Furthermore, the cost savings with lower B_{OH}^{max} are less than for the conventional system. For these reasons, the choice of B_{OH}^{max} for a HPG system would tend to be higher than for the conventional although an optimum has not been determined. Clearly, however, a value of $B_{OH}^{max} = 4.5$ T is unacceptable and even 6 T is questionable.

Figure 15 shows how the cost of an HPG system compares to a conventional system permitting the same power output. The HPG system cost is based on $B_{OH}^{max} = 8$ T and the conventional system is based on $B_{OH}^{max} = 5$ T which results in

Fig. 14. HPG power supply system cost and reactor power output as a function of Δt_{OH} and B_{OH}^{MAX} .

(ANL Neg. No. 190-79-18)

Fig. 15. Cost comparison of a conventional system and an HPG system.

(ANL Neg. No. 190-79-23)

approximately the same burn time and net power output. A range of cost parameters for the HPG has been used in Fig. 15 to reflect uncertainties due to the lack of commercial manufacturing experience.

At low ramp times (≤ 4 s) the HPG system is much cheaper, by nearly a factor of two, than the conventional system. This is basically because the cost of the HPG system is weakly sensitive to the OH power level for startup while the OH supply and the MGF set of the conventional system are much more strongly sensitive to the power requirements. At longer ramp times ($\Delta t_{OH} \geq 8$) where power levels decrease, the advantage of the HPG system is lost; the conventional system becomes cheaper than the HPG system. As shown in Fig. 15, these conclusions are the same regardless of what the HPG will cost, at least for the 5:1 range of cost algorithms used. On the basis of this analysis, therefore, the worth of developing a homopolar generator, to the tokamak program, seems to depend critically on whether short ramp times will, for some reason, be necessary.

D. Superconducting Energy Storage Inductor System

A power supply system using a superconducting energy storage inductor (ESI) is shown in Fig. 16. In this system the ESI serves as the central energy storage element, in place of the MGF set. An ESI has no moving parts and little energy loss but must have a cryogenic system. The solid-state power supplies in this system are also somewhat different than those operating out of an MGF set since they operate directly between dc output of the ESI and the tokamak coils. While some development of this type of supply is needed, the unit costs are expected to be similar to the conventional converters with some reduction due to the fact that transformers are not needed.

The burn cycle using an ESI system is the same as for the conventional one since the OH and EF power supplies are operated the same way. Since the cost of an ESI is dependent on its stored energy and not on power, the ESI would be

Fig. 16. ESI system.

(ANL Neg. No. 190-79-74)

expected to be cheaper than an MGF set, for short ramp times. Also, the absence of transformers with the ESI system would save some money. The cost comparison between an ESI system and a conventional one is shown in Fig. 17. This figure is based on a $B_{OH}^{max} = 8 \text{ T}$, the trends are the same for other values of B_{OH}^{max} . Two estimates for the ESI cost in Fig. 17, as shown, have been used. In addition to cost differences there may be significant differences in operating costs, reliability, size, energy losses, and other factors between an MGF set and an ESI but these are beyond the scope of the present analysis.

If the ESI cost is 0.5¢/J, then the ESI system is only economical for short ramp times ($\Delta t_{OH} \leq 6 \text{ s}$), and is more expensive than a conventional system at larger times. If the ESI cost is 0.1¢/J, then the ESI system is always cheaper than a conventional one, although the cost differential diminishes for the longer ramp times. Based on these results, it would seem that an ESI cost of 0.5¢/J would require other redeeming qualities to recommend its use while an ESI cost of 0.1¢/J could, in addition, lead to a savings of $\geq 30 \text{ M\$}$.

E. Dump Resistor System

This system would have many of the same elements as a conventional one with the addition of some type of resistor-switch network in parallel with the OH coil. The resistor(s) would be used for startup and an OH power supply would be used for the rest of the cycle. The motivation is to use a cheap device, the resistor, instead of a more costly power supply, for the critical startup period. However, this system needs relatively expensive isolation switches, to connect and disconnect the resistor network from the OH coil, and this negates some of the cost advantages.

In analyzing the tradeoffs between using a single resistor or a bank of resistors it was found that the latter option is probably better. With a single resistor, the OH voltage decays exponentially during the ramp period;

Fig. 17. Cost comparison of a conventional system and an ESI system.

(ANL Neg. No. 190-79-21)

this results in a high peak-to-average value of V_{OH} which increases the switch costs as well as the EF power requirement. By using more than one resistor, and switching resistors into the current at appropriate times, the peak OH voltage can be kept much closer to the average. The reduced isolation requirements for this system offset the added complexity. The analysis of this system has therefore focused on the multi-resistor option. The exact form or size of an optimum resistor network has not been examined in detail but the circuit shown conceptually in Fig. 18 is a typical example. In this network, switches S_1, S_2, S_3 , and S_4 are solid-state isolation switches while S_0 can be an inexpensive mechanical switch. The switches are shown in their normal positions. At the start of the burn cycle (after breakdown) S_1 would be momentarily closed and the OH power supply would be isolated from the circuit (using its internal switching). Next, S_0 would be closed and S_1 opened causing the OH current to start to decay through R_1 . As I_{OH} decreases, switches S_2 - S_4 would be opened successively to increase the total series resistance and maintain a high value of V_{OH} . When I_{OH} decayed sufficiently, S_1 would be closed and S_2 opened thereby terminating the OH current ramp. The OH supply would then be connected and S_1 opened, removing the resistor network from the OH coil. Note that switch S_0 always opens and closes on zero voltage but this is not the case with the other switches. The resistors might typically be stainless steel, water-filled drums with electrodes on both ends, and a heat exchanger.⁽¹¹⁾ The price of the resistors is trivial compared to the switch costs.

In computing the performance and cost of a dump-resistor system, the assumption was made for this study that the burn cycles would be the same as those computed for the conventional system since V_{OH} during the current ramp will be approximately constant. The cost calculations for a dump resistor system were restricted to the case of $B_{OH}^{max} = 8$ T. For the network shown in Fig. 18, the

Fig. 18. Resistor/switch network.

(ANL Neg. No. 190-79-6)

total cost of the switches is approximately twice the cost of switch S_1 alone, considering the magnitude of the current swing during startup, and the need to maintain V_{OH} as constant as possible. The isolation requirement of switch S_1 is $I_{OH}^{max} V_{OH}$ and so the total network cost was therefore taken as $2 \times I_{OH}^{max} V_{OH} \times C_S$, where $C_S = \$0.008/\text{V-A}$ is the cost algorithm used for a solid-state switch.

Figure 19 shows the comparison between a dump-resistor system, computed on this basis, and a conventional system. For short ramp times the dump-resistor system is substantially cheaper than a conventional system. For longer ramp times there is no advantage to a dump-resistor system, within the limits of the approximations made here. As shown, the net power output of the dump-resistor system is lower than that for the conventional system because of the energy lost in the dump resistor during startup. This difference is about 12 MW.

III. CONCLUSION

This study has examined the power supply requirements for a typical 7-M tokamak reactor, for both conventional and nonconventional systems. A summary of the requirements and a cost breakdown of the system components is shown in Table II, for a range of ohmic heating ramp times.

A conventional system is composed of a central MGF set, and SCR-type power supplies used for the OH and EF coils. The cost of a conventional system is very dependent on the maximum power levels which in turn largely depend on the OH ramp time. Present-day tokamaks start up at a rate of roughly 5 MA per second. For this reactor this would correspond to a 2-s OH ramp time. The cost of a conventional system can be lowered very substantially by using longer ramp times, e.g. ≥ 8 s. This would involve only a slight penalty in the net power output. The cost can also be lowered, although less significantly, by

Fig. 19. Cost and reactor power output comparison of a conventional system and a dump resistor system.

(ANL Neg. No. 190-79-17)

TABLE II

Technology Requirements and Cost of Four Power Supply Systems for a Range of OH Ramp Time and for $B_{OH}^{max} = 87$

System	Requirements						Cost (M\$)						
	OH Power Supply:Power (MVA)	EF Power ^a Supply:Power (MVA)	MGF Set ^a Power (MW)	ESI ^b Energy (GJ)	HPG ^a Energy (MJ)	Shorting Switch Isolation Req. (GVA)	OH Power Supply	EF Power Supply	MGF ^e Set	ESI ^f	HPG ^g	Shorting ^h Switch	TOTAL
Conventional:													
$\Delta t_{OH} = 2 \text{ s}$	4840 ^a	720	4840				194 ^c	36 ^c	73				302
8	1330	351	1330				53	14	30				97
16	740	351	740				30	14	23				67
HPG:													
$\Delta t_{OH} = 2 \text{ s}$	440 ^b	1091	1424		763		18 ^c	43 ^c	32			11	104
8	440	351	684		950		18	16	23			14	69
16	440	351	684		1178		18	14	23			18	72
ESI:													
$\Delta t_{OH} = 2 \text{ s}$	3250 ^a	720		11.4			136 ^d	25 ^d		57/11			218/172
8	1330	351		11.4			37	10		57/11			104/58
16	740	351		11.4			21	10		57/11			88/42
Resistor/Switch:													
$\Delta t_{OH} = 2 \text{ s}$	440 ^b	720	1053			4.8	18 ^c	36 ^c	29			77	160
8	440	351	684			1.3	18	14	23			21	76
16	440	351	684			0.7	18	14	23			12	66

^aRequirements set during startup.

^bRequirements set during shutdown.

^cCost = \$0.04/V-A

^dCost = \$0.028/V-A

^eCost = 14.4 M\$ + \$0.012/W.

^f@ (0.5¢/J)/(0.1¢/J)

^gCost = \$0.015/J

^hCost = 2 × \$0.008/V-A

reducing the limits of the OH field swing over the cycle, but at a greater penalty in net power production. It appears that the shutdown period can be controlled so as not to exceed the power supply requirements for startup.

The plasma physics of the burn cycle is such that some supplementary heating (beams or RF) seems required at the very start and end of the cycle, to overcome radiation due to oxygen impurities. However, aside from this consideration, the oxygen contamination does not appear to be critical in setting the power supply requirements. A low-density startup can help reduce the resistive volt-second losses but is not essential to the power supplies.

A central question for future tokamak reactors is whether nonconventional power supply systems will have to be developed and used in order for fusion to be economic. At short ramp times a conventional system is much more expensive than any of the nonconventional systems. Assuming that long ramp times are, in fact possible, however, as is indicated by the profile average-time dependent analysis utilized here, then a homopolar generator-based system is seen to have very little prospect of competing with a conventional system. Not only would it cost more, but the limited flux swing associated with the system would lower the plant power output.

A superconducting energy storage inductor, while probably not essential, does offer the possibility of cost savings and could offer other advantages as well in reliability, ease of maintenance, etc., which need to be explored. To be economical, at long ramp times, a cost goal for an ESI would appear to be in the neighborhood of 0.1¢/J.

A dump resistor network, used for startup, does not appear to offer any substantial cost savings, for the longer ramp times, and has the disadvantage of wasting energy through the startup process. However, some form of variable resistor or a nonlinear resistor might lower the cost considerably — a subject needing further study.

These conclusions are, of course, dependent on uncertainties in the plasma physics, particularly as it pertains to the much larger devices of the future. Future work planned in this area is the extension of the analysis to different size reactors and the use of a one-dimensional transport code to further assess the feasibility of long startup times.

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APPENDIX A

Cost Algorithms

The cost algorithms described here are based on current prices where the systems involved, such as MGF sets and ac-dc converters, are commercially available; otherwise they are based on best-guess estimates extrapolated from similar installations when possible. A range of cost algorithms has been used for the nonconventional equipment to reflect uncertainties in technology development.

Solid-State (SCR-Type) Power Supply

The cost is determined by the maximum power requirement and includes the cost of transformers if needed. Transformers will probably be needed for operation with an MGF set but will not be required with a central inductor.

(1) With transformers

$$\text{Cost} = \$0.04/\text{V-A} .$$

(2) Without transformers

$$\text{Cost} = \$0.028/\text{V-A} .$$

MGF Set

The variable cost is primarily based on the maximum power requirement of the generator and the energy storage cost of the flywheel, while the fixed cost includes the cost of the motor.

$$\begin{aligned} \text{Cost} = & \$0.001/\text{joule (flywheel)} + \$0.012/\text{V-A (generator)} \\ & + 5\text{M\$ (motor)} . \end{aligned}$$

Homopolar Generator

The cost is determined by the maximum required energy storage of the unit rather than peak power.

$$\text{Cost} = \$0.005\text{--}0.025/\text{joule} .$$

Homopolar generators of the type described in this report are not commercially available, and as a result any cost projections are based on predicted technical complexity and the construction of other equipment with similar complexity.

Superconducting Energy Storage Inductor

The cost is based on the maximum stored energy.

$$\text{Cost} = \$0.001\text{--}0.005/\text{joule} .$$

ESI costs are based on extrapolation from existing large magnet systems. The estimates include all the cryogenic equipment and instrumentation.

Switch Costs

For a mechanical switch the costs are basically trivial and have been included in the fixed-cost portion of the other algorithms.

For the solid-state switch used in connection with the dump resistor, the estimated cost is based on the maximum isolation voltage and maximum series current handled by the switch.

$$\text{Cost} = \$0.008/\text{V-A} .$$

SCR switch costs used here are about one-fourth the cost per kVA of an ad/dc/ac convertor.

APPENDIX B

Oxygen Contamination Model^d

This model describes the buildup of oxygen impurity in a tokamak reactor. In this model oxygen comes from five sources: (1) oxygen present in the DT fuel; (2) oxygen present in the neutral beam; (3) real and virtual leakage including backstreaming from the vacuum pump; (4) desorption from the first wall of oxygen not pumped out from the last burn pulse and not chemically bonded to the wall; and (5) oxygen chemically bonded to the wall that is sputtered. The initial concentration of oxygen in the plasma at the start of the burn pulse is given by

$$N_x = f_{fuel} N_{DT} + N_x^{DES}, \quad (B-1)$$

where N_x is the average oxygen density in the plasma, N_{DT} is the initial DT density, f_{fuel} is the oxygen contamination fraction of the DT fuel and N_x^{DES} is the oxygen concentration due to desorption from the wall. The desorption is assumed to occur instantaneously.

The buildup of oxygen in the plasma during the burn cycle is given by

$$\frac{dN_x}{dt} = f_w S_z + f_B S_B + R_{leak} + f_{fuel} I_c - \frac{N_x}{\tau_x} (1 - R_x), \quad (B-2)$$

where S_z is the sputtering rate (in atoms/s) of the main wall coating (in this case beryllium), and f_w is the fraction of oxygen present in the coating. f_B is the oxygen contamination fraction of the beam, and S_B is the beam current. R_{leak} is the oxygen leakage rate from external sources. I_c is the DT refueling

rate. The minus term of Eq. (B-2) represents the loss of oxygen to the plasma by diffusion to the wall, τ_x is the confinement time of the oxygen, and R_x is the oxygen reflection coefficient at the first wall. In this study, τ_x has been taken equal to τ_{DT} and $R_x = R_{Be} = 0.05$ has been used. The other parameter values used are: $f_{fuel} = 1.0 \times 10^{-4}$, $f_w = 0.05$, $S_z = 0.314$, $f_B = 5.0 \times 10^{-4}$, $R_{leak} = 8.2 \times 10^{12} \text{ M}^{-2} \text{ S}^{-1}$, and $N_x^{DES} = 2.315 \times 10^{15} \text{ M}^{-3}$.

FOOTNOTES

^aWhile the breakdown period involves difficult plasma physics, the power supply requirements are both separate and much smaller than for the rest of the burn cycle, basically because breakdown involves ~1 V-s of flux swing compared to 100's of V-s for the main startup period. For this reason the focus of this analysis is on the post-breakdown stage.

^bNo advantage was seen in this analysis using a variable OH voltage during startup but the flexibility of being able to do this with a conventional system might be an advantage for actual conditions.

^cThis requirement could be eliminated if it were feasible to establish the plasma current in different directions on alternate burn cycle.

^dThis model was co-developed by Dale L. Smith of Argonne.

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