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Tokamak Power Plant Burn Cycle Options*

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June 1994

* Work supported by the United States Department of Energy, Office of Fusion Energy, under contract W-31-109-Eng-38.

To be presented at the 11th Topical Meeting on the Technology of Fusion Energy, June 19 - 23, 1994, New Orleans, Louisiana. (invited talk)

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TOKAMAK POWER PLANT BURN CYCLE OPTIONS

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ABSTRACT

Experiments show that tokamaks can operate in various fashions. Economic analyses show that steady state is most attractive provided the physics and technology of current drive (CD) can be modestly improved. Even with very conservative CD assumptions a hybrid operating mode seems superior to conventional, simple inductive operation.

I. EXPERIMENTAL PROGRESS

Since 1968 experimental tokamak discharges have extended the achievable pulse length by two orders of magnitude each decade, so today minute-long pulses are possible (on JET and Tore Supra). See Figure 1. With pure noninductive current drive, discharges lasting more than an hour have been achieved at modest current (Triam), and a goal of TPX will be steady state operation at ~2 MA. With purely inductive current drive, multipulse operation at high duty factor was achieved in a DC mode (toroidal current always in the same sense) at 200 kA on the Tokamak de Varennes and in the AC mode at 2 MA on JET. See Figure 2. Moreover, radio-frequency current drive (RFCD) has been used to initiate as well as ramp up current on devices such as PLT; and RFCD has permitted transformer recharge at constant current (ohmic current opposing the RF current) on ASDEX, Alcator C, and JET (the last at 1.5 MA). These experimental successes encourage us that considerable flexibility is at hand as we attempt to optimize the operation of commercial tokamaks.

II. BURN CYCLE COMPARISONS

Although a variety of operating modes are possible for future power plants, we will focus attention on three candidates which illustrate the cost and performance trade-

offs offered to fusion engineers: i.) pure ohmic current drive with alternating toroidal current direction each pulse (ACOH), ii.) hybrid operation with ohmic current drive during fusion burn and periodic transformer recharge with low density RFCD, and iii.) pure steady state operation with RFCD. Since unit costs vary with inflation and are difficult to predict for commercial designs of the future, our results are valid only to the extent that we are comparing *relative* cost differences of alternative burn cycles, calculated using a consistent set of cost algorithms.

Our comparison of burn cycle options concentrates on several subsystems which are sensitive to pulsed operation:

1. Thermal storage appears necessary for pulsed tokamaks. Utility preference is for steady electric power production, or at least for periods approaching a day-long burn. Moreover, for reasonable plasma parameters, tokamak dimensions, and transformer field, it appears that inductive burns in excess of three hours are highly unlikely.

2. Structural fatigue in pulsed magnets may be life-limiting. Whenever poloidal beta varies, the equilibrium field coils (EFC) impose a time-varying overturning force on the toroidal field coils (TFC), and substantial intercoil structure must be provided to resist the associated bending fatigue. Tokamaks like ITER are insensitive to this effect as, for only $\sim 10^4$ full power cycles, the stress calculation is dominated by the S_m limit.* However, commercial power plants, approaching $\sim 10^5$ cycles are affected by fatigue and may require additional TFC structure exceeding \$100M in cost. Of course the poloidal coils themselves will also need additional costly structure to survive the

*steady state limit (typically 1/3 of the ultimate or 2/3 of the yield stress).

repetitive hoop stresses accompanying highly cyclic operation.

3. Pulsed operation becomes expensive if short dwells ($\lesssim 100$ s) are attempted between fusion burns, because the electric power supplies must handle large reactive power in charging and discharging the poloidal coils. Optimized dwells typically have power supplies rated at more than 1000 MVA, and the associated costs of the whole electric power transfer system, based on SCR technology, is estimated to be $\gtrsim$ \$300M for pulsed commercial tokamaks. This is in contrast to the $\sim$ \$10M cost of power supplies needed for a steady state power plant.

4. The ohmic heating (OHC) transformer itself is an expensive item, storing ~ 25 GJ and costing over \$100M for pulsed tokamaks. This subsystem may be essentially eliminated with steady state operation.

5. Auxiliary power for heating to ignition and RFCD is a key issue. Short ignition times ($\lesssim 20$ s) cause increases in the power, P_{aux} , needed to ignite, with commensurate cost increases. Moreover, especially for RFCD, the electric-to-rf power conversion efficiency η_d is crucial. For RFCD the circulating power is minimized by maximizing the product ($\gamma \eta_d$).

6. Although difficult to quantify, thermal fatigue and disruption-related erosion of plasma facing surfaces, such as the divertor or limiter, will strongly influence performance. Indeed, advanced low-activation materials, such as SiC composites, may be entirely unusable beyond $\sim 10^2$ cycles due to thermal-mechanical fatigue. The thermal and electromagnetic loads associated with major disruptions are likely to be more frequent with pulsed operation, which is an additional motivation to pursue steady state operation.

A. Steady State (CW) Operation

This mode was postulated for STARFIRE and ARIES. This technique is only practical if noninductive current drive is so efficient during high density fusion operation that the CD power, P_{aux} , is a small fraction of the fusion power. With this proviso, however, reactor operation is possible in principle for very long periods (months), until reactor maintenance forces shutdown. Fatigue is expected to be of minor concern since only a few hundred thermal and magnetic cycles occur in the reactor lifetime. Thermal storage is eliminated, slow current and power ramps minimize the cost of startup power supplies, disruptions may be very infrequent, and additional design latitude (e.g., low aspect ratio) derives from eliminating the external transformer. The main drawbacks are circulating power and the capital cost of the noninductive driver hardware.

Figure 3, modified from Ref. 1, quantifies the effect of CD parameters on the performance of a CW reactor. The abscissa is a measure of noninductive CD efficiency ($\gamma \equiv \bar{n}_e I_{CD} R_o / P_{aux} \cdot 10^{20} \text{ A} \cdot \text{m}^{-2} \cdot \text{W}^{-1}$), which is significantly amplified when the naturally-occurring bootstrap current, I_B , is present ($f_B \equiv I_B/I_o$, $I_o = I_B + I_{CD}$). As an illustration, we note that JET and JT60 have already achieved $\gamma \approx 0.35$ at $T_e = 2$ keV, and experiments and theory predict γ will increase somewhat at higher T_e . Experiments have also achieved $f_B > 0.5$, and calculations² lead us to expect such large f_B values are attainable for stable equilibria at reactor-attractive values of beta. Reference to Fig. 3 shows that net electric power of $P_{net} = 1200$ MW (the same power as for CW operation of the idealized STARFIRE design³) is achievable with $\eta_d \gamma / (1 - f_B) \gtrsim 0.4$. If we take $\gamma = 0.35$ and $f_B = 0.5$ this goal is attainable with $\eta_d \gtrsim 0.57$. At low frequencies (ICRF) the JET RF system already operates in excess of $\eta_d = 0.60$, and class C/D operation of the tetrodes should permit $\eta_d \gtrsim 0.75$. Note also these γ and f_B values would

Fig. 3. Steady-state burn cycle for a 7-m major radius with $\bar{T}_e = 12$ keV, $n_{20} = 1.9$, and $I_o = 14.8$ MA: (A) Direct capital cost (normalized to STARFIRE) for two values of current-drive-system cost and (B) Net electric power.

Fig. 4 Current wave forms for ohmic burn cycles.

result in a plant capital cost about 13% higher than "free" CD ($\gamma \gg 1$) for typical ICRF system costs of \$1.50/W.

B. Ohmic (Inductive) Operation

1. Conventional ohmically driven (DCOH) cycle.

This cycle is shown schematically in Fig. 4. The toroidal current is driven by a transformer, and once the volt-seconds are consumed the current decays and the fusion burn is extinguished. Both the current pulse and fusion power period are nearly the same, $\sim 10^3$ - 10^4 s. Thermal loads and magnetic fields (ohmic heating and equilibrium) oscillate with the same periodicity. The top schematic illustrates single swing transformer action (plasma current and equilibrium field always in one direction), which we denote as DCOH operation. Neutron power and fusion thermal power are zero when the plasma density and temperature drop; during this down period thermal power must be extracted from auxiliary storage units to supply the steam generators.

2. Double-swing (ACOH) ohmic cycle without resetting transformer. The short-dotted I_{OH} curve on the bottom of Fig. 4 is the transformer current waveform utilized on JET to achieve AC operation.⁴ The plasma current is induced twice, once in each toroidal direction, as

the OHC current goes through one cycle. Note the I_{OH} magnitude is reduced to reverse loop voltage at the end of the burn as the toroidal current ramps down. This makes an inefficient use of the OHC as the next burn commences with the OHC only half charged.

3. Double swing (ACOH) cycle with resetting transformer. The dashed I_{OH} curve at the bottom of Fig. 4 shows a more efficient use of the OHC. In this case after plasma current ramp down the OHC is recharged to the same polarity for commencement of the next fusion burn. This is the preferred method of ACOH operation. Relative to DCOH, the ACOH cycle has two-way bending of the TFC legs by the vertical field, which exacerbates mechanical fatigue (by a factor of $\sim 30\%$).⁵ However, the energy transfer in/out of the OHC is much smaller than for the DCOH cycle, roughly reducing power supply ratings and cost by a factor of (0.75/1.25).

Figure 5 shows power supply and thermal storage costs for a typical ($P_{net} = 1000$ MW) tokamak operating in the preferred ACOH mode. It assumes optimal operation with symmetric current ramps, $\tau_R = 40$ s, and symmetric plasma heating and cooling periods (τ_I), and considers two different periods, τ_C , to reset the OHC. Shorter

Fig. 5 Cost of power supplies and thermal storage for ACOH cycle.

ignition ramps, $\tau_I \lesssim 10$ s, require more expensive high voltage power supplies to (de) energize the EFC system, whereas longer ramps, $\tau_I \gtrsim 30$ s, extend the dwell period and the cost of thermal storage. In addition this tokamak power plant requires an OHC costing ~\$121M. At the optimum τ_I these total costs represent a capital investment of \$456M, which should be compared to only ~\$35M of equivalent systems that would be needed if a CW-operated power plant had negligible CD power costs.

Pulsed operation imposes additional costs in order to accommodate mechanical fatigue in the magnets. Forty-year plant operation at 80% availability implies fusion production for a total of 1×10^9 s, so the number of fusion pulses is inversely proportional to the length of the fusion burn: $N_f = 10^9/t_f$. Figure 6, from Ref. 5, shows the total capital cost, normalized to STARFIRE, of OH operation. For advanced external liquid metal thermal storage with the preferred ACOH operation, a one-hour burn period results in capital costs about 30% larger than STARFIRE. Note this burn length corresponds to an OHC field of 10 T, with plasma neoclassical resistance just twice the Spitzer value and takes no credit for a bootstrap current. Two factors may reduce capital costs. If $f_B \gtrsim 0.5$ the burn length may be extended. Also, it may be possible

Fig. 6 OH cycle; $B_{OH} = 10$ T. Fusion burn period, t_f , assumes $Z_{eff} = 1.7$, $T_e = 10$ keV, $I_0 = 13$ MA, no bootstrap. Cost is normalized to STARFIRE. The one-turn plasma electrical resistance is normalized to the Spitzer value; long fusion burns, $t_f > 2$ h, require unrealistic resistivity, $R \lesssim R_{sp}$, for this 7-m reactor.

to store thermal energy in the tokamak shield (for a dwell period as long as ~200 s), which could reduce capital costs by ~8%.⁶ Nevertheless, under the most optimistic assumptions it still appears that OH operation will require 15-20% higher capital cost than the idealized STARFIRE (with CW operation and negligible CD cost).

C. Hybrid Transformer Operation

This cycle (see Fig. 7) would use an external transformer to maintain I_0 during the fusion burn and then keep I_0 at full value with low density noninductive current drive while the transformer is quickly recharged.^{7,8} Both thermal and magnetic fluctuations occur, and the fusion period is somewhat shorter than for the OH cycle. Compared to the OH cycle this mode benefits from keeping I_0 constant: equilibrium field power, P_{EF} , may be smaller, downtime (t_{off}) may be shorter, periodic purging and plasma breakdown is avoided, and disruptive regimes might be circumvented. Of course, an external transformer is a necessary system for this reactor cycle and represents additional cost and complexity relative to CW operation. Yet the low density during transformer recharge could

Fig. 7 Schematic time variations with hybrid cycle. During dwell (t_{off}) current is maintained near full value by noninductive current drive at low density as the emf is reversed by resetting the transformer.

compensate for low γ values if CD turns out to be too inefficient to achieve economical CW operation. Figure 8 from Ref. 5, shows the hybrid cycle may only cost 10-15% more than ideal CW operation (with negligible current drive cost); this assumes $\gamma = 0.35$ is possible, with recharge at a low density, $n_e' \leq 0.1 \times 10^{20} \text{ m}^{-3}$. [The figure assumes no bootstrap current but assumes an overly optimistic, Spitzer, resistance; these assumptions offset each other, so the figure remains approximately valid for realistic tokamaks.]

Additional cost savings would also result if the shield thermal storage concept were employed instead of the external liquid metal system assumed for Fig. 8. An explicit comparison of ACOH and hybrid cycles was performed as part of the Pulsar study to illustrate the differences in cycle cost/performance. For simplicity we dictated quite arbitrarily that the hybrid cycle should have the same burn length and same P_{aux} as for the ACOH cycle:

$$\begin{cases} \tau_B = 12652 \text{ s} \\ P_{aux} = 39.5 \text{ MW} \end{cases}$$

Fig. 8 Hybrid cycle: advanced external thermal storage; no bootstrap. Cost is normalized to STARFIRE. Abscissas indicate OHC field and flux and the fusion burn length and lifetime cycles, assuming Spitzer resistivity.

Additional degrees freedom are T_e' , n_e' , and Z' during τ_c . Again without detailed optimization, we simply selected

$$\begin{aligned} T_{e0}' &= 3.0 \text{ keV} \\ n_{e0}' &= 0.068 \times 10^{20} \text{ m}^{-3} \\ \bar{n}_e' &= 0.052 \times 10^{20} \text{ m}^{-3} \\ Z_{eff}' &= Z_{eff} = 1.59. \end{aligned}$$

The Table summarizes these non-optimized designs. The hybrid cycle has nearly identical performance with ~8% savings in direct costs (\$194 M out of a total of \$2400 M for the ACOH design).

Additional cost savings arise in TFC structure due to the smaller stress variation (in a single direction) with the hybrid cycle overturning forces. Also, fewer disruptions may occur with the hybrid cycle.

Table

Variable	Units	ACOH	Hybrid
current ramp time	s	39.8	0.
β_p ramp time	s	27.1	27.1
time to reset OHC	s	20.0	109.6
thermal storage period	s	127.0	136.7
flat top fusion period	h	3.5	3.5
N_f	10^4	7.4	7.4
OHC field	T	11.9	7.4
OHC flux	V·s	547.	340.
OHC energy	GJ	27.9	10.8
OHC/dump resistor power	MVA	1120.	0.
EFC/reset OHC power	MVA	1670.	590.
auxiliary heating to ignition	MW	39.5	39.5
OHC cost	\$M	120.6	46.5
OHC switch/dump resistor	\$M	17.9	0.
MGF set/SCR power supplies	\$M	236.5	105.0
auxiliary heating system	\$M	45.4 (ICRH)	79.0 (LHCD)
ECRH for startup	\$M	3.9	0.
shield thermal storage	\$M	32.0	32.0
total cycle-sensitive costs	\$M	456.3	262.5

III. CONCLUSIONS

Regarding the economic prospects for these cycles:

- The ACOH cycle will at best cost ~15% more than ideal (approximately "free CD") CW operation as embodied in the STARFIRE design. This is in remarkable agreement with cost analysis presented in Ref. 3.

- In principle, hybrid operation is more attractive than the best ACOH performance; e.g., even modest CD efficiencies of $\gamma = 0.18$ will result in lower capital costs than ACOH if recharging is done at $n_e' = 0.05 \times 10^{20} \text{ m}^{-3}$.

- Assuming $f_B \gtrsim 0.5$, $\eta_d \gtrsim 0.6$, and $\gamma \gtrsim 0.35$ the CW mode will be most economical for commercial power stations.

Two other issues strongly motivate the CW operation goal:

- CD will provide active control of the plasma current profile, which should provide higher stable beta (and higher mass power density) than is possible with pulsed, inductive operation.

- CW operation should provide more reliable fusion-electric power than pulsed operation, due to myriad factors which cannot be adequately quantified at present.

ACKNOWLEDGMENT

Interactions with C. Bathke and the Pulsar design team have helped in formulating this work. Work supported by the U.S. Department of Energy, Office of Fusion Energy, under contract W-31-109-Eng-38.

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