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BURN CYCLE REQUIREMENTS COMPARISON OF PULSED AND STEADY-STATE TOKAMAK REACTORS*

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Burn cycle parameters and energy transfer system requirements were analyzed for an 8-m commercial tokamak reactor using four types of cycles: conventional, hybrid, internal transformer, and steady state. Not surprisingly, steady state is the best burn mode if it can be achieved. The hybrid cycle is a promising alternative to the conventional. In contrast, the internal transformer cycle does not appear attractive for the size tokamak in question.

1. Introduction

As part of an overall comparison study of tokamak operating cycles [1] the burn cycle parameters and the requirements and cost of the energy transfer system were analyzed for an 8-m commercial reactor. The energy transfer system (ETS) consists of the ohmic heating (OH) and equilibrium field (EF) power supplies, and the thermal storage system. In contrast to steady-state reactors such as STARFIRE [2], pulsed tokamaks will have large power supply requirements due to the need to transfer large amounts of magnetic energy (~10 GJ) in short times (~10 s). A thermal storage system is also needed for pulsed reactors to maintain turbine power between burn pulses. These systems are expensive and therefore constitute a key difference between pulsed and steady-state tokamak reactors.

Energy transfer system requirements, and burn cycle parameters, were analyzed for three types of pulsed cycles, conventional, hybrid [3-5], and internal transformer [3-5]. The cycles were further subdivided into those having a water coolant or a liquid metal coolant. The reference reactor used in the analysis is described in Ref. 1.

The following trends were noted in this analysis. For all operating cycles, the energy transfer system costs are highly dependent on cycle parameters — it is important to choose these parameters carefully to minimize cost. No pulsed cycle is as good as steady state. For a water-cooled conventional cycle, the cost of the ETS is ~425 M$. A liquid-metal based system is cheaper by ~150 M$. The ETS cost for a hybrid cycle is potentially less than for a conventional one. In addition, the hybrid cycle eliminates the plasma breakdown period and may reduce the number of plasma disruptions. Although these are not fundamental differences, the hybrid cycle appears to be promising and warrants further study. In contrast, the internal transformer cycle appears to be a poor choice of operating mode due to a combination of short burn time and high ETS cost.

2. Conventional Cycle

The burn cycle and the energy transfer system of the reference 8-m reactor were analyzed for a conventional cycle, i.e. one using an OH coil to supply volt-seconds for startup and burn. The analysis used the CTRAN, profile-averaged, time-dependent code to develop the general features of the burn cycle. Based on these results, a parametric model was used for a trade-off study of cost versus cycle parameters. The analysis also made use of results found in an earlier study of power supply requirements for commercial fusion reactors [6].

A power supply system developed for the conventional cycle is shown in Fig. 1. A typical burn cycle using this system is shown in Figs. 2-4. The power supply system and the burn cycle operation were chosen to minimize power supply requirements. The emphasis of the analysis is on the startup period since it was found [2] that shutdown imposes no additional requirements except if skin current formation in the then hot plasma proves to be a problem.

As shown in Fig. 1 the OH coil is driven by two types of energy transfer devices. (The OH current, over a complete burn cycle, is shown in Fig. 2.) A dump resistor/SCR switch system is used for startup to ramp down the initially charged OH coil in a time defined as the "ohmic heating time", t_{OH}. For the cycle shown, t_{OH} = 15 s. This resistor could probably be of the nonlinear type, e.g. zinc oxide, or silicon carbide as proposed for the TFTR- OH system [7]. The resistor was modeled as having an ideal, i.e. constant, voltage drop, when connected. The same resistor is also used for the shutdown. (The OH current waveform during shutdown is almost the reverse of the startup except that somewhat less ramp down of I_{OH} is needed.) During the burn period the OH current is slowly ramped up to make up for resistive losses in the plasma. The power needed to do this is relatively small, ~15 MVA. Finally, after shutdown, the OH coil must be recocked to the full 10-T value for the next burn pulse. This is done in a "dwell period" with duration t_{DWELL}. During the dwell period the plasma chamber is evacuated and then filled with fresh deuterium-tritium gas for the next burn pulse. The recocking OH power supply is a rectifier/invertor SCR-type supply operating out of an MGF set. The OH coil, for the reference reactor design, has a stored energy content of ~19 GJ at 10-T field. The cheapest way to recock the coil is alternate the direction of induced plasma current every pulse. Thus, in the example shown, I_{OH} is driven from ~80 MA turns to 163 MA turns in the dwell period rather than from ~80 MA turns to −163 MA turns if this strategy were not employed. We note, however, that this alternative current mode aggravates the toroidal magnet fatigue; thus, the power supply cost saving might be offset by the possible need for a more expensive TFC system. Another cost savings technique is to use the same OH recocking SCR supply to drive the EF coil during startup and shutdown and the OH coil during the burn phase. This useage requires that the OH and EF coils have compatible voltage and current requirements, which appears possible. The SCR power supply requirements are then set by whatever system, EF or OH, has the maximum power needs.

A low density startup, together with initial rf heating, is used in the cycle shown to minimize resistive volt-second losses. Thus the plasma is kept fairly hot throughout the "ohmic heating" portion of the cycle. For the cycle shown, the resistive volt-second loss during startup is only 5 V-s.

The second phase of the startup is defined as the "EF ramp". During this period the plasma is heated to ignition and the EF current brought to its full value. Throughout the startup the EF current is raised to maintain the plasma in MHD equilibrium. The EF power requirement is given by the product of the maximum EF voltage and the maximum current. In order to minimize the EF voltage during startup, the rf power is modulated to maintain a fixed rate of net heating power during different portions of the cycle. In addition, xenon is added towards the end of the startup to establish plasma thermal stability.

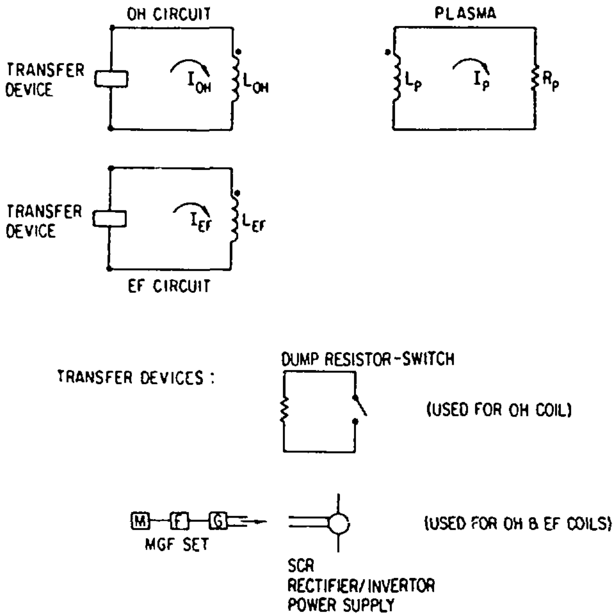

Fig. 1. Power supply system for a conventional cycle.

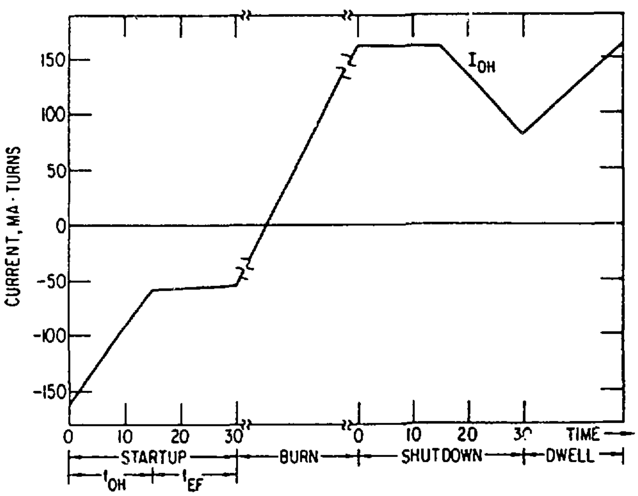

Fig. 2. Ohmic heating coil current waveform for a conventional burn cycle.

For the cycle shown, a burn time of ~51 min could be obtained, based on the OH flux swing of 307 V-s available for the burn period and on a plasma loop voltage of ~0.10 V. This loop voltage is based on neoclassical Spitzer resistivity, using an anomaly factor of 2.5 to account for trapped electrons.

A key parameter in comparing burn cycles is the rf power needed for heating to ignition. A feasible steady-state reactor requires on the order of 100 MW input into the plasma for current drive (i.e. much more than this would not be economically feasible). A pulsed reactor requires no current drive power but still needs auxiliary power to reach ignition. In a steady-state reactor the same rf system could hopefully be used for both purposes, i.e. heating and current drive. A study was made, using the CTRAN code, to

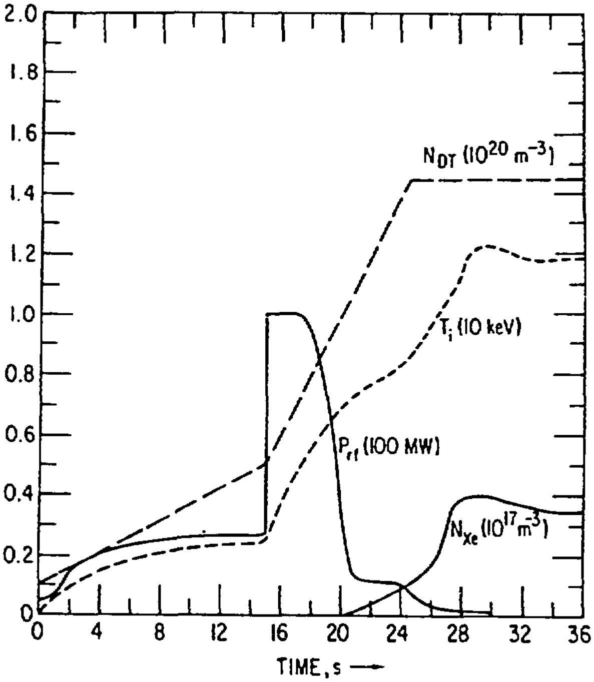

Fig. 3. Plasma parameters during startup of a conventional cycle

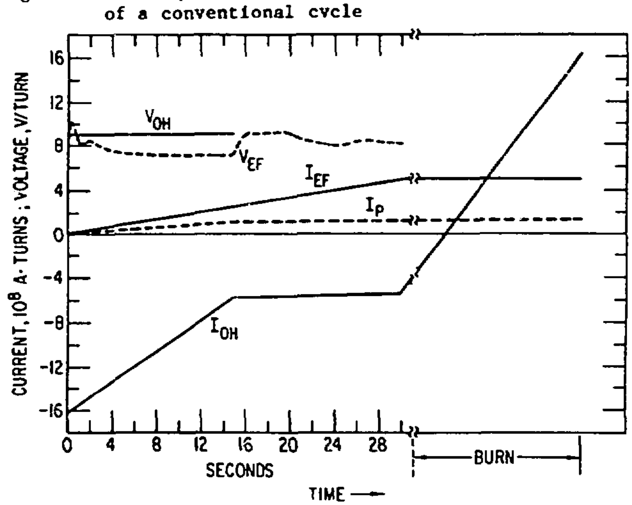

Fig. 4. Voltage and current waveforms during startup and burn of a conventional cycle.

identify the minimum rf power needed to reach ignition. For the reference reactor this value was found to be ~75 MW. Thus the rf heating power needed for ignition is similar to that needed for current drive, for feasible values of current drive efficiency.

Of course, the power required for current drive is a central issue for the feasibility of steady-state tokamaks. In comparing pulsed to steady-state tokamaks, a heating-only rf system might be cheaper due to relaxed antenna, frequency, and other requirements. For the present purposes, however, such differences were not assessed.

Parameteric Analysis

A trade-off study of energy transfer system cost versus burn cycle parameters was performed for a conventional cycle scaled from the above results. The burn cycle parameters were the OH ramp time, t_{OH}, the

EF ramp time, t_{EF}, and the dwell time, t_{DWELL}, as defined in the previous section. The power supply requirements were modeled as follows:

$$P_{OH} = \frac{\Delta\phi_{OH} \times I_{OH}^{max}}{t_{OH}} \tag{1}$$

$$P_{OH}^* = \frac{0.75\ \Delta\phi_{OH} \times I_{OH}^{max}}{t_{DWELL}} \tag{2}$$

$$P_{EF} = \frac{U_{EF}}{t_{EF}} \tag{3}$$

$$P_{max} = \max(P_{OH}^*, P_{EF}) \ , \tag{4}$$

where P_{OH} is the reactive power isolation requirement of the dump resistor/switch, P_{OH}^* is the OH recocking requirement, P_{EF} is the EF reactive power requirement (for $t_{EF} < t_{OH}$, and P_{max} is the reactive power requirement of the SCR supply used for both OH recocking and EF drive. P_{max} is also the requirement of the generator portion of the MGF set. The other parameters are $I_{OH}^{max} = 163 \times 10^6$ A, $\Delta\phi_{OH} = 163$ V-s, and $U_{EF} = 6.36$ GJ. The stored energy requirement of the MGF set is approximately constant, at ~30 GJ. Finally, the thermal storage system time requirement is given by:

$$t_{down} = 2\ t_{OH} + t_{EF} + t_{DWELL} \ . \tag{5}$$

This "downtime" is approximately equal to the time over one burn cycle when no fusion power is produced, considering the fact that there is some fusion power during the EF ramp-up and ramp-down periods.

The cost algorithms used for the power supplies were obtained by multiplying those used in Ref. 6 by a factor of 2 to approximately escalate them to 1983 dollars. (The original cost estimates were based, in part, on the TFTR experience.) The resulting cost algorithms are as follows:

$$C_{OH} = \$0.016 \times P_{OH} \tag{6}$$

$$C_{max} = \$0.1 \times P_{max} + 70\ M\$ \ , \tag{7}$$

where C_{OH} is the cost of the dump resistor/switch and C_{max} is the combined cost of the SCR supply and the MGF set. The thermal storage system cost [8] is given by:

$$C_{ST} = \begin{cases} 70\ M\$ + 3.70\ M\$\ (t_{down} - 10), & H_2O\ \text{system} \\ 30\ M\$ + 2.0\ M\$ \times (t_{down} - 10), & \text{lithium-sodium system} \end{cases} \tag{8}$$

where a minimum downtime of 10 s is used in either case. The total energy transfer system cost is then:

$$C_{ETS} = C_{OH} + C_{max} + C_{ST} \ . \tag{9}$$

A wide range of cycle parameters was examined. It was found that a choice of $t_{OH} = t_{EF}$ is about optimum for a fixed value of t_{DWELL}. The resulting ETS cost for this parameterization is shown in Fig. 5 for the H_2O system and in Fig. 6 for the lithium-sodium system. The results show an interesting tradeoff between the power supplies and the thermal storage system. At short dwell times, <10 s, the recocking supply requirements become very high and dominate the cost. At longer times the increase in thermal storage costs offsets any savings in the power supply. For a given

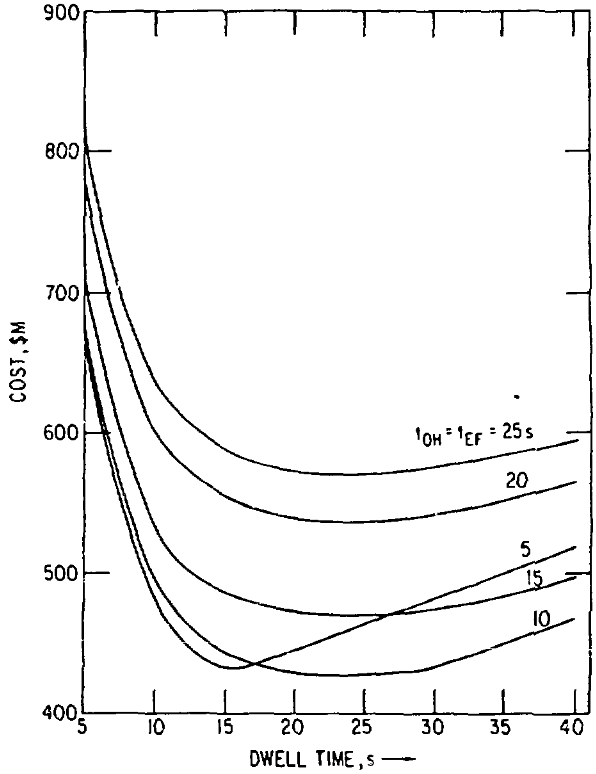

Fig. 5. Energy transfer system cost as a function of cycle parameters for a conventional system using water storage.

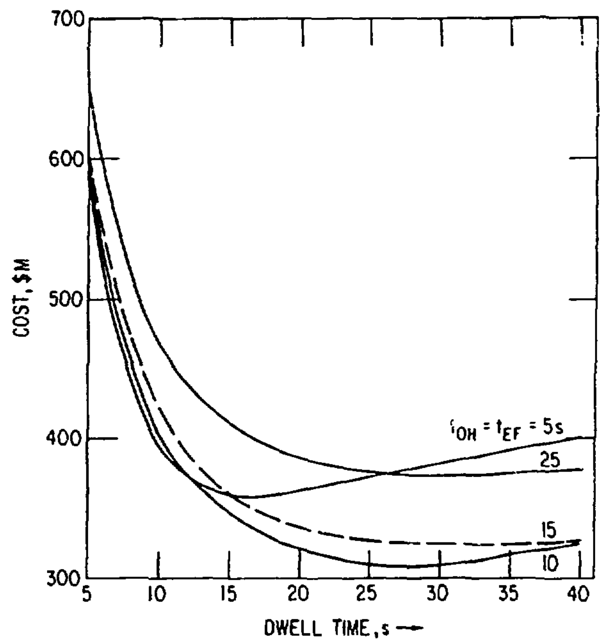

Fig. 6. Energy transfer system cost as a function of cycle parameters for a conventional system using metal thermal storage.

value of t_{OH} there is a broad minimum in cost for a 20- to 30-s dwell time.

For the values of $t_{OH} = t_{EF} = 15$ s and $t_{DWELL} = 25$ s the ETS cost is ~425 M$ for the H_2O system.

Thus the ETS cost is a substantial fraction of the total reactor capital cost. A liquid-metal-based system costs about 100 M$ less than a water-based system.

Hybrid Cycle

The hybrid cycle uses an OH coil to maintain plasma current during the burn, and a current drive system to maintain current during a period of time when the OH coil is recocked. The plasma density is reduced for the recocking period so that the current drive can function efficiently. After recocking, the density is ramped up and fusion power production resumes. Similar types of power supplies are needed for the hybrid cycle as the conventional system except that an OH dump resistor is not needed. The equivalent circuit of a system used for the hybrid cycle is shown in Fig. 7.

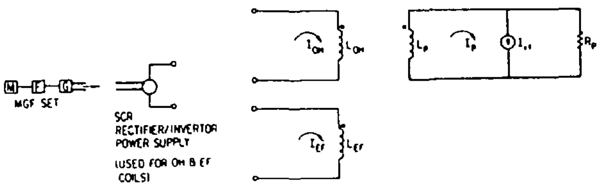

Fig. 7. Power supply system for a hybrid cycle.

As with the conventional system the same SCR supply can be used for both OH and EF coils since these coils are pulsed at different times. The current drive source, assumed to be rf, is shown as an equivalent current source in the plasma loop. From Fig. 7 the equations for the OH and plasma loop are given by:

$$L_{OH} \frac{dI_{OH}}{dt} - M_{OH,P} \frac{dI_P}{dt} = V_{OH} , \tag{10}$$

$$R_p\left(I_p - I_{rf}\right) + \frac{d}{dt}\left(L_p I_p\right) = M_{OH,p} \frac{dI_{OH}}{dt} + M_{EF,p} \frac{dI_{EF}}{dt} \tag{11}$$

where the M's denote the respective mutual inductances and where the fact that $M_{EF,OH} \approx 0$ has been used. During the OH recocking phase $dI_p/dt = 0$ and $dL_p/dt = 0$. Also during this phase $dI_{EF}/dt = 0$. The required value of voltage needed to recock the OH coil in a "dwell" time, t_{DWELL} is then given by:

$$V_{OH} = \frac{\Delta\phi_{OH}}{t_{DWELL}} , \tag{12}$$

where $\Delta\phi_{OH} = L_{OH}\Delta I_{OH}$ is the OH flux swing during the recocking phase.

The OH power required for recocking is given by:

$$P_{OH} = \frac{2U_{OH}^{max}}{\Delta t_{DWELL}} \tag{13}$$

where U_{OH}^{max} is the stored energy of the OH coil when fully charged.

From Eq. (11) the required value of I_{rf} needed to maintain a constant plasma current during the recocking phase is given by:

$$I_{rf} = I_p - \frac{V_{OH}}{R_p} , \tag{14}$$

where the relation $M_{OH,p} = L_{OH}$ has been used.

The rf power, corresponding to this current, is generally believed to have the following form:

$$P_{rf} = \frac{N_{e20} I_{rf}}{\gamma} , \tag{15}$$

where N_{e20} is the plasma density, in units of $10^{20}\ m^{-3}$, and γ is the current drive efficiency at $N_{e20} = 1$. Combining the above expressions then gives for the required rf power in terms of γ and the dwell time:

$$P_{rf} = \frac{N_{e20}}{\gamma}\left(I_p + \frac{\left|\Delta\phi_{OH}\right|}{R_p t_{DWELL}}\right). \tag{16}$$

Thus the required rf power depends linearly on the density during the recocking phase and also depends strongly on the plasma resistance during this phase. Obtainable values for these parameters as well as the value of γ are uncertain. A brief analysis of various hybrid burn cycles with the CTRAN code show that the following parameters may be obtainable: $N_{e20} = 0.02$ and $R_p = 10^{-7}\ \Omega$. [A technique is to keep the plasma temperature fairly low (several keV) during this phase in the injection of xenon.]

A value of $\gamma = 0.02$ A/W was assumed for reference purposes on this basis: if γ were ten times higher, then a steady-state cycle would be chosen, i.e. there would be no need for a hybrid cycle; and if γ were ten times lower, then no form of current drive cycle would work. The effect of different values of γ is discussed later.

The value of plasma current during the dwell period is lower than for the burn period. This is so because the reduction in EF current, necessary because of the reduction in plasma β, during the density ramp-down phase, reduces I_p. Conversely when the density is ramped back up, I_{EF} increases and ramps I_p up to its full value. From CTRAN results the value of plasma current during recocking was found to be $I_p = 10$ MA.

The hybrid cycle offers several options in regards to the OH coil design. One option is to design an OH coil to give the same burn time as a conventional cycle. Since the hybrid OH coil is only used to supply burn volt-seconds the OH field strength coil for this option would be lower than for the conventional cycle. This is the approach discussed first. As discussed later, another option is to use a different value of field to obtain a different burn time.

The value of OH field needed to obtain a burn time of 51 min, i.e. the same as for the conventional cycle is $B_{OH} = 6.53$ T. This gives a flux swing capability of $\left|\Delta\phi_{OH}\right| = 307$ V-s. The stored OH energy at full field is $U_{OH}^{max} = 8.2$ GJ, considerably less than the 19.2 GJ needed for the conventional cycle OH coil.

With the above parameters the required rf power is:

$$P_{rf} = 10^7 + \frac{3 \times 10^9}{t_{DWELL}} , \quad W \tag{17}$$

For a value of $t_{DWELL} = 30$ s, for example, $P_{rf} = 110$ MW.

An additional cycle parameter is the EF ramp time, t_{EF}, defined as the time in which the density is ramped down. The density ramp-up phase also takes a time t_{EF}. During the rampdown, the EF current is reduced from the full value to about one-half the full value, as β drops to nearly zero and the plasma current drops by 30%. If the plasma is controlled in an optimum manner. The EF reactive power requirement, is given by:

$$P_{EF} = \frac{U_{EF}}{t_{EF}} . \quad (18)$$

The thermal storage system time capacity required for the hybrid cycle is given by:

$$t_{DOWN} = t_{DWELL} + t_{EF} . \quad (19)$$

A parametric analysis was performed for the hybrid cycle by varying t_{EF} and t_{DWELL}. The ETS requirements and costs were computed in an analogous manner to the conventional system.

In addition, the incremental cost of the rf system, defined as the difference in cost between the rf system required and a 75-MW system was computed by:

$$\Delta C_{rf} = 1.5(P_{rf} - 75 \text{ MW}) , \text{ M\$} \quad (20)$$

where a minimum value of $P_{rf} = 75$ MW is used based on the need to heat the plasma to ignition.

The ETS cost of a hybrid system for various values of cycle parameters is shown in Fig. 8 for a water-based thermal storage system. A liquid metal system is about 75 M$ cheaper. The solid curves are C_{ETS} and the dashed curve is $C_{ETS} + \Delta C_{rf}$. The dashed curve indicates that one would expect to pay a high price for recocking in short times, because of the high rf power needed. At long dwell times the costs go up due to increases in the thermal storage system cost.

In addition to ETS differences the EF field swing over the hybrid cycle is reduced by about a factor of two for the conventional for the same number of cycles. This reduces stress on the TF and OH coils.

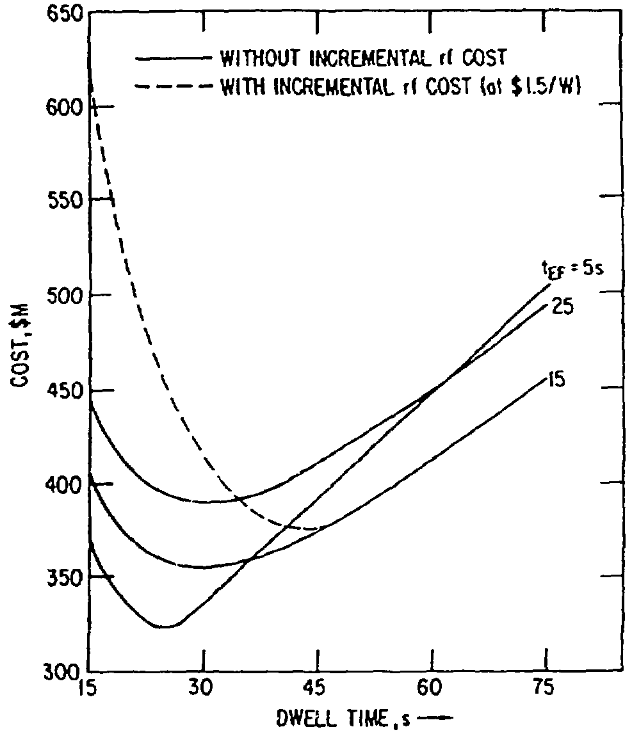

Fig. 8. Energy transfer system costs for a hybrid cycle, water system.

Internal Transformer Cycle

The internal transformer (IT) cycle does not use an OH coil at all but instead relies on overdriving the plasma current with a noninductive driver. This is done during a low density period. The plasma is then brought up to ignition and burns until the current decays to some minimum value. The density is then ramped down and the cycle is repeated.

The energy transfer system for the IT cycle consists of an EF power supply and a thermal storage system. A fundamental parameter for the IT cycle is the plasma current overdrive ratio defined as:

$$n = \frac{I_{p_1}}{I_{p_0}} , \quad (21)$$

where I_{p_1} is the maximum plasma current used, and I_{p_0} is the required minimum plasma current. For the IT cycle the plasma current is given by Eq. (11) with $M_{OH,p} = 0$. During the burn phase this has the solution

$$I_p = I_{p_1} e^{-t/\tau} ,$$

where τ is the plasma time constant during the burn phase. The burn time is given by the time it takes for I_p to decay to I_{p_0}:

$$t_{BURN} = \tau \log n . \quad (22)$$

During the current drive period the plasma current is given by:

$$I_p = I_{rf} + (I'_{p_0} - I_{rf}) e^{-t/\tau'} \quad (23)$$

where τ′ is the plasma time constant during the current drive period and I'_{p_0} is the plasma current at the start of the current drive period. I'_{p_0} is somewhat less than I_{p_0} due to the EF rampdown preceeding the current drive period. From the above equation the dwell time necessary to obtain a current I_{p_1} is given by:

$$t_{DWELL} = \tau' \log \left[\frac{1 - I_{rf}/I'_{p_0}}{n - I_{rf}/I'_{p_0}} \right] \quad (23)$$

The EF ramp period for the IT cycle is similar to that for the hybrid. However, the EF stored energy is higher because of the higher plasma current. The EF power requirement scales approximately as follows:

$$P_{EF} = \frac{n^2 U_{EF_0}}{t_{EF}} , \quad (24)$$

where U_{EF_0} is the EF energy corresponding to I_{p_0} and where the scaling $B_{EF} \sim I_p$ is employed. (EF power is also needed during the burn phase as I_p decays and where β is assumed constant, but this can be shown to be smaller than given by Eq. (24). A clearly unfavorable scaling of the IT cycle is that while burn time increases only logarithmically with overdrive ratio, the EF power increases as η^2. Also, a higher EF field B_{EF} is required which tends to result in a higher cyclic stress on the TF system. The EF coil system also needs to be bigger although this may be offset by the elimination of the OH coil. Neither the EF coil design, nor the plasma MHD equilibrium characteristics at higher values of plasma current were assessed for this study but these may be serious issues for the IT cycle.

The final parameter for the IT cycle is the thermal storage requirement, given by $t_{DOWN} = t_{DWELL} + t_{EF}$. The cost algorithms for the EF supply and thermal storage systems used previously were applied to the IT system. Similar parameters to the hybrid cycle were used, where applicable. The parameters used were: $I_{p_0} = 13$ MA, $I'_{p_0} = 10$ MA, $\tau' = 171$ s, and $\tau = 2236$ s.

A parametric analysis of the IT cycle using a range of overdrive ratios from $\eta = 1$ to 2 was performed. Note that a value of $\eta = 2$ corresponds to twice the plasma current and four times the plasma magnetic energy needed for the other cycles and this was intuitively felt to be a feasible upper limit. For each value of η a range of t_{EF} from 5-30 s was used.

The results of the parametric study of the IT system are discussed in the following section.

6. Burn Cycle Comparison

Using the models described previously, the cost of the energy transfer system was computed as a function of burn time for a conventional, hybrid, and internal transformer cycle. The costs shown include incremental rf costs at 1.5 \$/W where applicable. The results are shown in Fig. 9 for the water-cooled system. The trends are similar for a liquid metal system with all costs reduced. For the conventional and hybrid cycles the obtainable burn time is varied by varying the OH design field, B_{OH}. For a conventional cycle, B_{OH} varies from ~4 T to 10 T, the minimum value is needed to supply inductive volt-seconds for startup. For the hybrid cycle B_{OH} varies from 0 to 10 T. For both cycles the burn time varies linearly with B_{OH}. For the IT cycle the overdrive ratio, η, is varied from one to two. For the hybrid and IT cycles a broad range of current drive parameter $\gamma/N_{e_{20}}$ was used. Each point on the curves of Fig. 9 represents the cheapest ETS cost identified by the parametric analysis. In general, the duty factor and net power produced are about the same for the conventional and hybrid cycles at longer burn times, but are lower for all cycles at short burn times.

For the conventional cycle, the ETS cost increases fairly slowly with burn time. There is probably no point in using less than the maximum burn time of 51 min, corresponding to $B_{OH} = 10$ T.

As shown, the internal transformer cycle is limited to a ~25-min burn time. This corresponds to an overdrive ratio of two. The cost of the ETS system, for the IT cycle, depends on the current drive parameter. For a value of $\gamma/N_{e_{20}} = 1.0$ which is probably attainable, the ETS cost for the IT cycle is comparable to the conventional, at a 25-min burn time. For any given value of $\gamma/N_{e_{20}}$, the ETS cost for the IT cycle is significantly more than the ETS cost for the hybrid cycle.

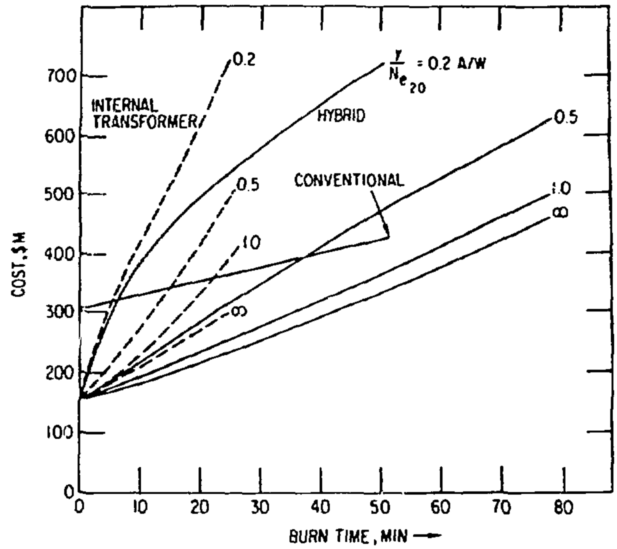

Fig. 9. Energy transfer system cost as a function of burn time and cycle type. (Includes incremental rf cost = 1.5\$ × $(P_{rf} - 75$ MW) where applicable).

The hybrid cycle has the potential of burning about 50% longer than the conventional. For a burn time of ~51 min the ETS cost for the hybrid cycle is less than or comparable to the conventional for values of $\gamma/N_{e_{20}} \geq 0.5$. For values of $\gamma/N_{e_{20}} < 0.5$, the hybrid cycle is probably unacceptable.

The burn time of all the cycles is linearly dependent on plasma resistivity during the burn phase. Therefore, uncertainties in the resistivity affect the burn time of all cycles equally.

Table 1 summarizes the net electrical power and several other parameters, for the various types of cycles including a steady-state cycle. A value of $\gamma/N_{e20} = 1.0$ is assumed. The number of cycles, N_c, is shown for a 40-yr plant lifetime at 75% availability. Data for the steady-state mode is based on extrapolation from the STARFIRE burn cycle. The ETS system for the steady-state mode is very modest. The net electrical power produced for each cycle type depends on the respective duty factor and the expended current drive energy. For the IT cycle with $\eta = 1.1$, the net power is 10% lower than for the 51-min conventional cycle, a serious deficiency. An overdrive ratio of $\eta = 2$ is necess y to produce about the same power as the conventional. The hybrid cycles of 51 and 77 min produce essentially the same net electrical power as the conventional, since the duty factors approach unity. Calculations for the steady-state cycle were based on a value of 100 MW of input current drive power to the plasma. This results in the net power of 1360 MWe based on STARFIRE values of current generation efficiency, and thermal-to-electrical efficiency.

7. Discussion

The results shown in this paper represent a first cut at comparing cycle types, as regards the ETS requirements, and general burn cycle parameters. There are clearly uncertainties in some of the critical physics issues such as obtainable densities, current requirements, etc. In addition, the cost algorithms used are fairly general ones intended for broad comparison purposes only. In spite of these qualifications, several conclusions can be made. The internal transformer cycle is not an attractive approach because

TABLE 1

Burn Cycle Parameter and Cost Summary

Cycle Type	Burn Time (min)	Duty Factor	No. of Cycles (N_c)	Energy Transfer System Cost (M$)	Net Electrical Power, P_{net} (MWe)
Internal transformer					
$\eta = 1.1$	3.5	0.87	3.9×10^6	178	1280
Internal transformer					
$\eta = 2.0$	26	0.95	5.6×10^5	404	1400
Conventional (alternating plasma current)					
$B_{OH} = 10$ T	51	0.97	3.0×10^5	425	1430
Hybrid					
$B_{OH} = 6.5$ T	51	0.97	3.0×10^5	355	1430
Hybrid					
$B_{OH} = 10$T	78	0.98	2.0×10^5	493	1445
Steady state					
$P_{rf} = 100$ MW	6 mo	1.0	~100	~10	1360

of limited burn time and high ETS cost, to say nothing of possible difficulties with operating the plasma at up to twice the nominal plasma current. However, the IT cycle would look better, in relative terms, for smaller tokamaks than the 8-m design. In contrast, the hybrid approach looks promising although differences between the hybrid and conventional cycles are much less than the difference between both these and a steady-state cycle.

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