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Potential of Commercial Tokamak Reactors with Improved Physics*

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ABSTRACT

The impact of improvements in plasma confinement and beta on commercial tokamak embodiments has been systematically investigated. Cases were investigated for both steady-state and pulsed reactors. A narrow range of useful confinement enhancement (H factors over the ITER-89 Power scaling) and Troyon beta limit coefficients g are found to be beneficial for reducing the cost of electricity (COE). Improvements in the beta limit (i.e., g) offer the greatest improvement in reactors. For g limited to about 4, H factors of only 2 are needed. If g of 6 is attainable, H factors up to 2.5 are useful. Pulsed reactors have slightly higher useful H factors, ranging from 2.5 for g near 4 to 3 for g near 6.

INTRODUCTION

A key element in planning the next-generation tokamak experiments [1, 2] is the impact these experiments will have on DEMO and future power reactors. Namely, can next-generation experiments identify regimes of operation that result in power reactors being built at a smaller unit size and cost and ultimately be more competitive with other power sources? To this end it is important to determine which physics improvements offer the most advantage to the tokamak reactor concept and the magnitude of these benefits. Is it better to push for beta improvements or confinement improvements? These questions are addressed here by showing the impact of these physics improvements on commercial tokamak power reactors. The following are some key results from this study:

- A surprisingly narrow range of plasma confinement and beta are found to be useful in minimizing the COE for a tokamak reactor. Improvements in only one of these quantities are not useful beyond some point.
- Improvements in beta have the greatest impact on reactor improvement. For the plasma beta limited by a Troyon coefficient g near 4.3 (%mT/MA), confinement levels characterized by ITER 89 Power law H factor enhancements of only 2 are useful for our nominal steady-state-driven tokamak. These confinement levels are similar to those observed in present-day experiments. If the permissible Troyon beta coefficient is near 6, the useful H factor

confinement range increases to 2.5, which is still close to present-day confinement levels.

- Inductively driven, pulsed reactors have somewhat increased useful ranges of confinement relative to the steady-state cases. For a Troyon beta limit coefficient g near 4.3, H factors up to 2.5 are useful, and for g near 6, H factors up to 3 are useful.
- The inductively driven pulsed reactor performance is sensitive to the required pulse length. With comparable H factors and g levels, pulsed reactors obtain COEs comparable to steady-state cases if burn times near 5 can be attained without significant penalty for energy storage and fatigue issues. Higher burn times tend to have a severe detrimental impact on the pulsed cases.

MODELING

We use the SUPERCODE systems code [3] as the vehicle for this study. This code is particularly useful for this type of study because of its flexible optimization package. This model permits all major device parameters (R , a , B , I_p , ...) to be treated as variables. A summary of the primary constraints considered in this paper is given in Table I. The models and assumptions used in this study are described in more detail in [4].

In general we follow the global physics models widely used in reactor analysis [5, 6] that follow the International Thermonuclear Experimental Reactor (ITER) Conceptual Design Activity (CDA) physics guidelines. For plasma power balance we calculate the energy confinement time (τ_E) using an inverse quadrature combination of the ITER-89 Power scaling [6] and neoclassical confinement. The plasma beta is constrained to be within the Troyon beta limit.

Many of the engineering models employed for this study were developed for, and calibrated to, the ITER CDA device. In this respect, we do not assume large extrapolations in the present-day technology base, as was done, for instance, in the ARIES reactor study [5]. The aim of this study is to address the impact of physics advances on reactors under the same set of conventional engineering constraints, rather than the impact of technology advances.

The models used in reactor power flow, and the COE calculations follow the generally accepted practice. More

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detailed descriptions of the terms used here may be found in the [5, 7]. The main reactor/COE assumptions are shown in Table II, and details of the modeling are described in [4]. Note that the method employed here for calculating the direct cost is based on the ITER-CDA costing [4] which was developed for a first-of-a-kind reactor cost. The direct costs from this model tend to be greater than cost estimates of comparable devices using tenth-of-a-kind discounting factors [5, 7, 8]. In any case, we wish to stress relative cost differences in this paper.

TABLE I

Summary of the plasma and device constraints applied in this study

Constraints	
Physics	
Plasma power balance (with ITER-89 L mode energy confinement)	
Troyon beta limit	
$q_{95} \geq 3$	
$q_0 = 1.05$	
$I_{\text{plasma}} = I_{\text{bootstrap}} + I_{\text{noninductive}}^a$	
(V-s)capability $\geq$ (V-s)requirement ^a	
$I_{\text{plasma}} \geq$ minimum to confine alphas	
Magnets	
TFC conduit stress ≤ 550 MPa	
TFC external case stress ≤ 550 MPa	
TFC dump voltage ≤ 20 kV	
TFC $I_{\text{operate}} / I_{\text{critical}} \leq 0.5$	
TFC hot spot temp ≤ 150 K	
TFC temperature margin ≥ 2 K	
OHC JBOP $\leq$ allowable	
OHC JEOF $\leq$ allowable	
Device	
Inner shield thickness $\geq$ allowable	
Inner divertor $\rightarrow$ TFC distance $\geq$ allowable	
TFC ripple $\leq$ allowable	
Average neutron wall load ≤ 20 MW/m ²	
Area for injection power $< 10\%$ wall area	
$P_{\text{net-electric}} =$ input requirement	

^aOnly for steady-state cases

^bOnly startup requirement for SS cases

RESULTS

The primary goal of this study is to identify the areas of physics improvements that have the largest impact on making a tokamak reactor more attractive. By "impact" we mean reducing the COE. The two primary physics considerations in reactor design are energy confinement and attainable beta. For the energy confinement consideration, we take the energy confinement enhancement factor (i.e., H factor) needed to maintain plasma power balance as a parameter indicative of the confinement requirements. As noted above, we use the ITER 89 Power scaling for calculating the energy confinement time. For the beta consideration, we use the coefficient in the Troyon beta scaling g as the measure for required beta level.

TABLE II

Assumptions used in the plant power balance and COE calculation

Plant power balance	
Thermal $\rightarrow$ electric efficiency ^a	0.4
Charged power $\rightarrow$ thermal power	70%
Blanket energy gain	1.30
Injector power efficiency, wall plug $\rightarrow$ plasma efficiency	72%
Costing assumptions	
Construction time, (year)	6
Plant life (year)	30
Average capacity factor	75%
Indirect + contingency cost factor	55%
Fixed charge rate ^b (FCR0)	0.0966
Effective cost of money (year ⁻¹)	0.0605
Inflation rate (year ⁻¹)	0.05
Direct cost	First-of-a-kind

^aAssumes a high-temperature Helium cooling system

^bConstant dollar

A. Steady-State Reactors

As a first example we consider a steady-state, non-inductively driven reactor at 1000 MWe. Fig. 1 shows contours of minimum COE in ($H_{\text{max}}, g_{\text{max}}$) space—henceforth referred to as H, g space. At each H, g grid point, we solve for the minimum COE steady-state reactor design at 1000 MWe. The "max" subscript on H and g refer to the fact that these are maximum values. That is, at each H_{max} point we require the actual H value to be less than or equal to H_{max} . It is apparent that the COE does not decrease for all increasing H_{max} and g_{max} levels. The thick solid line is the maximum useful Troyon coefficient. Above this line the COE contours turn vertical (i.e., the COE becomes independent of g_{max}). Similarly, the dotted line is the maximum useful energy confinement time enhancement factor, and to the right of it, the COE contours are independent of H_{max} . Thus the useful region of H, g space is the relatively narrow band between the thick solid line and dotted line in Fig. 1.

Fig. 2 shows the minimum COE vs the base electric power level for three different choices of physics performance: (1) present physics¹ ($H \leq 2, g \leq 2.5$), (2) modest physics improvements ($H \leq 3, g \leq 4$), and (3) advanced physics ($H \leq 4, g \leq 6$) all with a lower bound on the edge q_{95} of 3 (which is always hit). In this set of runs, the beta limit we chose was always hit and the H factor limit was never met. The usual reduction in COE for increased base loads is observed, most noticeably for the present-day physics level case, which has the highest capital cost. All cases have high recirculating power fractions due to the injection power required to maintain a steady-state plasma current. For the present-day physics case, the energy multiplication Q is always < 10 , the modest

¹That is presently achieved physics performance that would be sustainable in a nontransient manner in a conservatively designed system.

physics case has $Q < 15$, and to achieve $Q > 20$, the advanced physics scenario with high beta must be used. The increase in Q with the more advanced physics scenarios closely follows an increased bootstrap fraction, which is possible under the higher allowable betas.

Fig. 1 Minimum COE in the allowable H, g space for steady-state reactors.

Fig. 2 Minimum COE vs net electric power, for steady-state reactors under various physics assumptions.

The higher Q cases have lower plant recirculating power fractions, but even for the $Q = 20$ – 25 cases, the recirculating power fraction is 20 to 25%. The fraction of the direct costs related to tokamak specific items is high, ranging from 66 to 73% of the total costs. This is in contrast with predictions for advanced fission concepts, which have a fission core cost fraction of 32% [9]. Also the Mass Power Density (MPD) defined as the ratio (net electric power/mass of the reactor core) has more variation from case to case than does the COE. This is because the reactor core items with significant mass (magnets, shield, structure, etc.) account for only a fraction of the total costs. In addition to the balance of plant costs (which are fairly constant) much of the costs are in

tokamak related items, which have little mass (injection power, tritium and fueling systems, power supplies, cryogenics, vacuum systems, etc.).

B. Pulsed Reactors

An alternate to the steady-state tokamak reactor approach is to drive the current inductively for a finite pulse length. We investigate this possibility by dropping the non-inductive current drive constraint and requiring full inductive plasma current startup and maintenance throughout the entire pulse. We ignore any penalty associated with energy storage as well as associated load-leveling penalties and magnet fatigue issues. In this sense, these results should be viewed as being the best case. We use 10 h the nominal value for the pulse length of the plasma burn, which we suggest may be near the minimum desirable for a practical reactor.

Fig. 3 Minimum COE in the allowable H, g space for inductively pulsed reactors.

Fig. 3 shows the minimum COE contours for 1000-MWe reactors in the H, g space, produced using the method discussed in Sect. 3.1.1. There is an enlargement of the useful H, g space, with the maximum useful H boundary moving up by roughly 0.5 for a constant g level, relative to that in Fig. 1. In this case, energy confinement enhancement H factors of 2 are useful for g values near 2.5. While the pulsed reactors are larger and more expensive than the corresponding steady-state cases, they do not require any injection power at the maximum useful H level. This alleviates both the capital cost and recirculating power impacts on the COE. These pulsed reactors tend to have higher aspect ratios (near 5) and lower plasma currents than the steady-state reactors, both of which are consequences of the inductive pulse length requirement.

We show the sensitivity of the pulsed reactor results to burn time in Fig. 4, for the same three physics levels as used in the steady-state net electric scans discussed previously. All these cases are for a 1000-MWe power level. At the lower end of the burn time range, the pulsed reactor COE is lower than the corresponding steady-state cases (Fig. 2). These low burn time results are not realistic, however, due to our neglect

of energy storage and fatigue issues, which become important at low burn time. As the burn time increases, there is a strong increase in the COE at the point where inductive drive requirements begin to be the major driver in the design. This strong increase in COE occurs at a lower burn time for the present-day physics (near 10^4 s) than for the aggressive physics cases ($>10^5$ s). To mitigate the effect of increased burn time, the aspect ratio tends to increase to lower the neoclassical increase in loop voltage and to provide more space for the OH solenoid. Also the plasma temperature tends to increase (to lower the loop voltage) with increasing burn time.

Fig. 4 Pulsed reactor sensitivity to the required burn time for various physics levels.

SUMMARY

The impact of improvements in plasma confinement and beta on commercial tokamak embodiments has been systematically investigated. This study uses tokamak systems optimization code that couples physics with engineering/costing models. Cases were investigated for steady-state and pulsed reactors. A narrow range of useful confinement enhancement (H -factors over the ITER-89 Power scaling) and Troyon beta limit coefficients (g) are found to be beneficial for reducing the COE. For g limited to about 4, H factors of only 2 are needed. If a g of 6 is attainable, H factors up to 2.5 are useful. Pulsed reactors have slightly higher useful H factors, ranging from 2.5 for g near 4 to 3 for g near 6.

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