

Critical Issues of Burning Plasma, Engineering, Economic and Environmental Assessments on Steady-State Fusion Reactors^{*)}

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For burning plasma simulation and reactor system analysis on steady-state high beta fusion reactors, TOTAL physics code and PEC engineering code have been developed. From TOTAL analysis, it is clarified that by choosing appropriate external current drive profile, high bootstrap-current fraction is achieved in steady-state. From PEC analysis, it is found that the current drive efficiency should be raised for cost of electricity (COE) and CO₂ reductions in rather low-beta reactors. Newly derived scaling formulas on COE and life-cycle CO₂ emission rate might contribute to the future reactor design projection.

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1. Introduction

In order to search for attractive steady-state tokamak fusion reactors, burning plasma studies and engineering system design analyses were carried out focusing on advanced plasma operations with internal transport barrier (ITB) and high bootstrap current (BSC) fraction, high magnetic field and high neutron wall load limits, high economic efficiency without frequent blanket exchanges and environmental assessments related to global warming gas emission.

In this paper, we check critical physics and engineering issues for the development of steady-state reactor, and especially focus on the bootstrap current fraction, current drive efficiency and neutron wall load fluence relevant to equipment replacement.

2. Requirements of Steady-State High-Beta Tokamak

Previous reactor system analysis [1] clarified physics, engineering and economics requirements of attractive steady-state reactors. For the attainment of compact reactors, high normalized beta value ($\beta_N > 4$) and high BSC fraction ($> 80\%$) are needed as physics requirements, and tight radial-build, high field superconducting magnet technology and compact/high efficient blanket design should be realized as engineering requirements.

As for physics issues, we developed toroidal transport linkage analysis code TOTAL [2] to simulate good confinement operation with ITB in tokamak and helical systems. Especially, physics issues to be treated with TOTAL code are as follows:

- (1) Simulation modelling and transport benchmark test,
- (2) ITB operation with high bootstrap current,
- (3) pellet injection and ITB control,
- (4) impurity injection and edge control,
- (5) sawtooth simulation and impurity exhaust,
- (6) neoclassical tearing mode (NTM) evolution and external current-drive control, and
- (7) helical field application for plasma improvement.

After the benchmark test with JT-60U and LHD experimental results and other integrated code results, we analyzed ITB operation scenario with high bootstrap current [3], ITB control by pellet injection [4], edge control by Krypton impurity injection [5], impurity exhaust by sawteeth oscillation [6], NTM evolution/control by electron cyclotron current drive/non-resonant helical field (ECCD/NRHF) application [7], and rather strong helical field application for plasma configuration improvement [8,9].

As for engineering issues, we developed reactor physics-engineering-cost system code PEC [10]. In this code, we can clarify the following issues:

- (1) physics requirement check,
- (2) magnet requirement evaluation,
- (3) blanket design evaluation,
- (4) evaluation of reactor scale for target power,
- (5) construction cost, cost of electricity (COE),
- (6) life-cycle carbon dioxide (CO₂) emission, and
- (7) energy payback ratio (EPR).

The system analysis was extended to include inertial confinement fusion reactors [11] in addition to magnetic confinement fusion reactors.

When the target net output power is assumed, the required reactor scale strongly depends on plasma beta value as physics criteria. After averaged plasma temperature is

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optimized for each DT reactor system (~ 30 keV for tokamak, ~ 20 keV for helical system), the confinement improvement factor and the plasma density limit are obtained as output parameters.

The weight and cost of each component are evaluated, and COE, CO_2 emission rate and EPR are finally evaluated based on unit cost, unit emission and unit energy in the PEC code.

The COE and EPR depend on the plant availability. As a standard case, the assumed availability is 75% (9 month operation per year). The annual maintenance of plant facilities and the annual replacement of the divertor plate should be done within the operation interval. The replacement frequency of blanket is determined by the calculated neutron wall load and the permissible neutron fluence as described in Section 4.

3. Internal Transport Barrier Operation with High Bootstrap Current

For steady-state operation of tokamak reactors, high bootstrap current (BSC) utilization is important. Physics assessments have been done using integrated toroidal transport linkage analysis code (TOTAL) with ITB, high BSC profile focusing on steady-state operations of D-T tokamak fusion reactors. Especially to sustain ITB profile in steady-state manner, external current drive control or plasma confinement control/external heating control is required. This depends critically on the transport models which determined relationship among transport coefficient, the magnetic shear, ITB formation and bootstrap current. In the TOTAL analysis we found that in the current diffusive ballooning mode (CDBM) model the ITB location gradually shifted into plasma center, and the external current drive near the half-radius is required to sustain steady-state ITB operation.

4. System Design Analysis of Steady-State Tokamak Reactors

Engineering assessment shows the relationship among the maximum magnetic field strength, neutron wall load, blanket thickness, thermal efficiency, operational period and reactor system availability.

Economic and environmental system analysis has been carried out [1, 11], and comparative studies among other conventional electric power plants are done, such as oil, coal, water, solar, wind, fission power plants, with respect to cost of electricity (COE), CO_2 emission amounts and energy payback ratio (EPR). The assessment shows that fusion power plants have an advantage in energy payback ratio (EPR), but have disadvantages in COE and CO_2 emission, in comparison with fission reactors [1].

4.1 Scaling formula

Recently we derived some scaling formula for COE

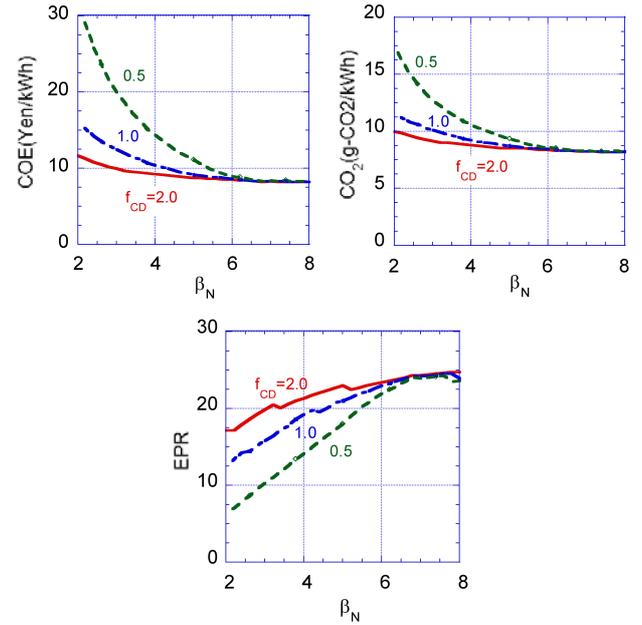


Fig. 1 Effect of current drive efficiency f_{CD} on COE, CO_2 emission rate and EPR as a function of normalized beta.

and CO_2 emission rate in tokamaks:

$$\begin{aligned} \text{CO}_2^{\text{TR}}[\text{g} - \text{CO}_2/\text{kWh}] \\ = 10^{1.60} \frac{1}{P_e^{0.26} f_{\text{avail}}^{0.43} \beta_N^{0.21} B_{\text{max}}^{0.05} f_{\text{th}}^{0.25} t_{\text{oper}}^{0.43}}, \end{aligned} \quad (1)$$

$$\begin{aligned} \text{COE}^{\text{TR}}[\text{mil}/\text{kWh}] \\ = 10^{2.09} \frac{1}{P_e^{0.48} f_{\text{avail}}^{0.90} \beta_N^{0.40} B_{\text{max}}^{0.12} f_{\text{th}}^{0.32} t_{\text{oper}}^{0.78}}, \end{aligned} \quad (2)$$

These scaling laws defines dependences of net electric power P_e (MW), plant availability f_{avail} , normalized beta value β_N , thermal efficiency f_{th} and operation period t_{oper} (Yr). This is determined by the assumption of current drive model and total neutron fluence limit.

4.2 CD efficiency effects

In this paper focusing on the steady-state operation of tokamak reactors, we checked effect of current drive efficiency on the reactor design. The required CD power with assumed efficiency f_{CD} in the PEC code is given by

$$P_{CD}[\text{MW}] = 2n_e[10^{20} \text{m}^{-3}] R_p[\text{m}] (I_p - I_{RS}[\text{MA}]) / f_{CD}, \quad (3)$$

where standard f_{CD} value is one. As shown in Fig. 1, the change in CD efficiency contributes to the change in low beta reactor designs. In the case of 50% efficiency, COE increases 50% beyond standard $\beta_N = 4$ case.

4.3 Wall load effects

Figure 2 shows the effect of neutron wall fluence limit on COE, CO_2 and EPR. If the wall load is 5 MW/m^2 in the case of fluence limitation of 40 MWYr/m^2 , the blanket exchange should be performed every 8 years. This exchange

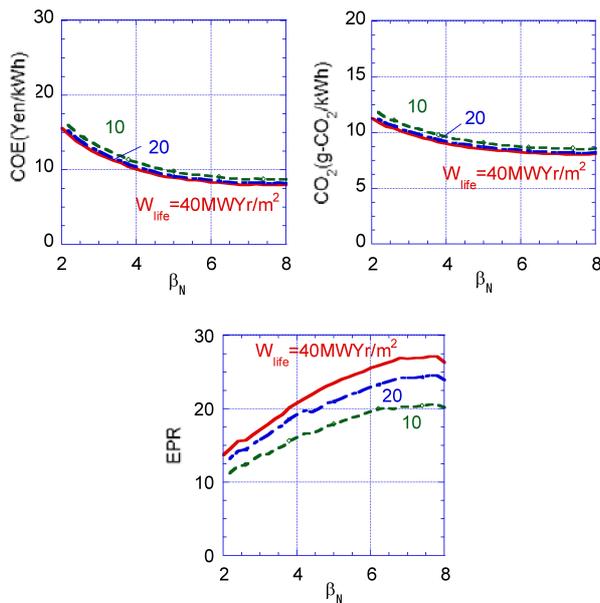


Fig. 2 Effect of neutron wall life fluence W_{life} on COE, CO₂ emission rate and EPR as a function of normalized beta.

rate might determine the assessment results. However, this effect on COE and CO₂ is not so large as shown in Fig. 2.

5. Summary

For the realization of steady-state high-beta fusion reactors, physics code TOTAL and engineering code PEC have been developed for burning plasma simulation and

reactor system analysis. The following conclusions are obtained from TOTAL and PEC analyses.

- (1) By choosing proper external current drive profile, high bootstrap current fraction is achieved in steady state.
- (2) Advantage of high-beta reactors is clarified in COE and CO₂ reduction.
- (3) Newly derived COE and CO₂ scaling formulas might contribute to the future design projection.

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