Economic Analysis of Advanced Fuel Fusion Reactors and Derivation of Scaling Law for COE*)

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Social acceptance of fusion reactors depends largely on their economic viability. To investigate this issue, we estimate and compare the cost of electricity (COE) among D-T, D-^{3}He, and D-D fusion reactors. Three types of confinement systems are evaluated: the tokamak reactor (TR), the spherical tokamak reactor (STR), and helical reactor (HR). For each reactor type, COE parameter surveys are performed and new scaling laws for COE are derived. The COE for D-^{3}He and D-D is high and depends more strongly on plasma beta value and maximum magnetic field strength than that of D-T.

Keywords: cost of electricity, economic, D-^{3}He, D-D, tokamak reactor, spherical tokamak, scaling law, helical reactor

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1. Introduction

Research and development of fusion reactors has primarily focused on the D-T reaction. However, the 14 MeV neutrons produced by this reaction present engineering and safety problems. Therefore, an ultimate future target is to realize an advanced fuel fusion reactor based on the D-^{3}He or D-D reaction.

Commercial fusion reactors must not only resolve the technical problems but be socially accepted as well. The latter is largely dependent on reactor fusion economics. In previous studies, we have investigated the economics of D-T, D-^{3}He and D-D fuel fusion reactors in Tokamak and spherical Tokamak confinement systems [1]. In the present study, we newly evaluate the economics of helical reactors, and perform an extensive parameter survey that clarifies the factors predominantly affecting the economics of advanced fuel fusion reactors.

The economics of D-T fusion reactors has been found to follow a scaling law [2, 3]. In this paper, we derive new scaling laws for the economics of D-T, D-^{3}He and D-D fusion reactors.

2. Analysis Procedures

The cost of electricity (COE) for fusion reactors is calculated from the physics–engineering–cost (PEC) system code (Fig. 1) [4]. The radial build of fusion-island (FI) components such as blanket and shield is mainly determined from the major radius of the plasma R_p and the component thickness. The volume and weight of each FI component is calculated from the radial build, and is multiplied by its unit cost to obtain the cost of the component. The cost of balance of plant (BOP), such as the turbine and the main heat transport system, is estimated from scaling formulas of net electrical and thermal outputs.

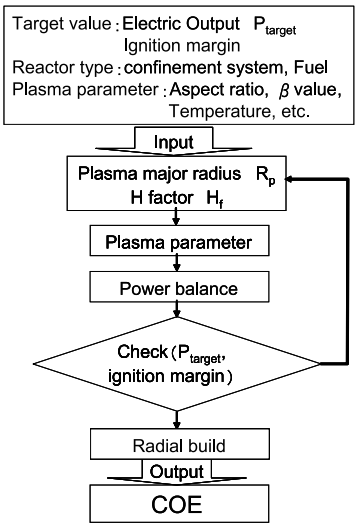

Fig. 1 Flowchart of the PEC code.

3. Reactor Model

We considered three types of confinement system and three types of fuel cycles (a total of nine reactor types), whose input and calculated parameters are listed in Table 1. The following input parameters were fixed: target net electric power of 1000 MW, plant availability of 75%, operating period 30 years, and target ignition margin of 1.01. Here, the ignition margin is refined by the ratio of the heating power of charged particles (produced by the

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Table 1 Main input and calculated parameters for reference reactor types.

Confinement system	TR			STR			HR		
Fuel cycle	D-T	D-^{3}He	D-D	D-T	D-^{3}He	D-D	D-T	D-^{3}He	D-D
Net electric power P_{enet} (GW)	1	1	1	1	1	1	1	1	1
Normalized beta β_N[a]	4	8	8	8	8	8	(7)	(16)	(16)
Average beta value $\langle\beta\rangle$ (%)	5.27	10.55	10.55	30.19	30.19	30.19	5.00	12.00	12.00
Aspect ratio A[a]	3.54	3.54	3.54	1.62	1.62	1.62	7.81	7.81	7.81
Ellipticity κ[a]	2.00	2.00	2.00	3.50	3.50	3.50	2.00	2.00	2.00
Maximum field B_{max} (T)[a]	13	13	13	8.75	13	13	13	13	13
Central ion temperature T_i (0) (KeV)[a]	30	70	70	30	70	70	20	70	70
Maximum coil current density J_{max} (MA/m^2)[a]	30	30	30	13	30	30	30	30	30
Plasma major radius R_p (m)	6.33	11.52	10.90	3.98	8.23	7.94	14.31	16.03	17.62
Toroidal field B_t (T)	6.13	8.08	8.07	2.34	3.62	3.57	4.35	8.05	7.31
Fusion power (GW)	3.35	3.09	2.79	4.56	2.96	2.69	2.36	2.40	2.32
Neutron power (GW)	2.68	0.07	0.55	3.65	0.07	0.53	1.88	0.06	0.46
Ohmic loss (GW)				0.96					
Power density (MW/m^3)	4.61	0.71	0.75	3.18	0.23	0.24	1.24	0.90	0.65
Plasma current (MA)	14.49	34.72	32.81	21.64	69.40	66.00	0.00	0.00	0.00
Current drive power (MW)	138.82	87.86	78.32	10.55	72.01	64.21	0.00	0.00	0.00
HH factor (H_{ITER}, H_{ISS})	1.21	3.27	4.13	1.74	2.97	3.41	4.63	18.94	21.04
Density limit $\overline{n}/n_{GW}$	1.12	2.31	2.18	1.17	1.61	1.53	(2.05)	(2.93)	(2.94)
Density limit $\overline{n}/n_{LHD}$	(0.66)	(0.97)	(1.04)	(1.08)	(1.49)	(1.60)	0.88	0.80	0.89
COE (cent/kWh)	10.89	13.09	13.33	10.26	14.40	14.69	11.55	17.12	20.10
Neutron wall load (MW/m^2)	3.54	0.03	0.25	4.99	0.02	0.18	1.08	0.03	0.17

[a] Input parameters

fusion reaction) to the loss power (including power lost by radiation).

3.1 Confinement systems

The confinement systems adopted here are the tokamak reactor (TR), spherical tokamak reactor (STR) and Helical Reactor (HR). The aspect ratio (A) and normalized beta value (β_N) of the TR reactor were set as 3.54 and 4 (D-T), respectively. D-^{3}He and D-D ($\beta_N = 8$) are assigned a high β_N. In the STR, we can omit the inner blanket and use a normal conducting coil system for the center post coil, permitting a low aspect ratio ($A = 1.62$). Because a high beta value is expected in the ST, we again assume $\beta_N = 8$. However, the use of a normal conducting coil (maximum field strength $B_{max} = 8.75$) requires that some of the electricity output by the STR compensates for power lost by ohmic heating in the coil system. In the TR and STR, the current drive power P_{CD} depends on the average electron density $\langle n\rangle$, R_P, the plasma current I_P, and the bootstrap current I_{BS}; more specifically, $P_{CD} = 2.0\langle n\rangle R_P(I_P - I_{BS})$. Since the HR confinement system does not use plasma current, this system requires no external current drive power. The reference blanket model of TR and STR is Li_2O/FS, as in the Steady-State Tokamak reactor (SSTR) [5], while that of HR is Flibe/FS, as in the Force-Free Helical Reactor (FFHR) [6]. The electron and ion temperatures are assumed equal. Plasma density and temperature radial profiles are assumed parabolic: $n(r) = n_0(1 - r^2)^{0.25}$ and $T(r) = T_0(1 - r^2)^1$, where T_0 and n_0 are the central temperature and density, respectively, and r is the normalized small radius.

3.2 Fuel cycle

We evaluated three types of fuel cycles: D-T, D-^{3}He and D-D. Since D-^{3}He reactors generate very few neutrons and do not breed tritium, these reactors are not supplied with a breeding blanket. The shield thickness of a D-^{3}He TR is assumed as 0.7 m, as in ARIES-3 [7]. Since ^{3}He gas is a very rare terrestrial resource, we assumed a scenario in which ^{3}He is transported from the lunar surface and estimated its cost as 200 US$/g [8]. The D-D reactor system recycles T and ^{3}He produced by the D-D reaction and extracts energy from D-T and D-^{3}He reactions (catalyzed D-D). The respective inboard and outboard blanket thicknesses of D-D TR are 0.21 and 0.41 m, whereas the inboard and outboard shield thicknesses are 0.44 and 1.00 m, as seen in WILDcat [9]. In STR, because of low neutron wall load for the D-^{3}He and catalyzed D-D reactors, we set the inboard shield thickness as 0.56 m for both D-^{3}He [10] and D-D, and suppose that STR uses a superconducting coil ($B_{max} = 13$ T). The ratio of ion to electron density (n_i/n_e) is assumed as 1.00 (D-T), 0.66, (D-^{3}He), 0.90 (D-D).

4. Assessment Results

4.1 Parameter dependence

For each type of reactor, we calculated the dependence of COE on beta value (β), maximum magnetic field (B_{max}), net electric power (P_{enet}), and thermal efficiency (f_{th}), using the parameters from Table 1. The results for TR, STR, and HR are shown in Figs. 2, 3, and 4, respectively. Since higher β and B_{max} characterize higher plasma density, they are also associated with higher power density. Consequently, the plasma volume that satisfies P_{enet} is re-

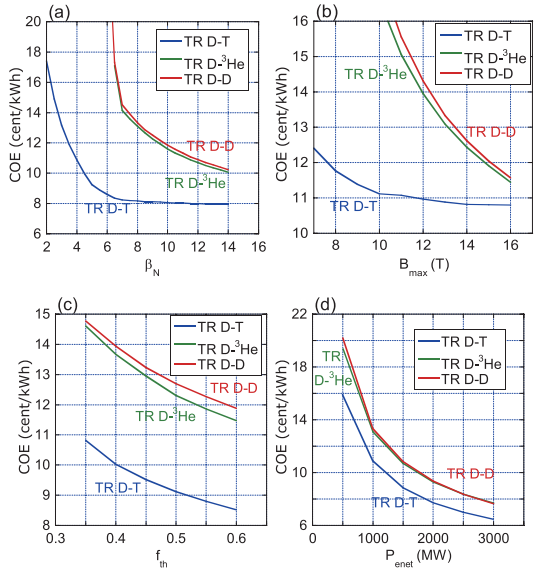

Fig. 2 Dependence of COE on (a) β_N, (b) B_{max}, (c) f_{th} and (d) P_{enet} of TR.

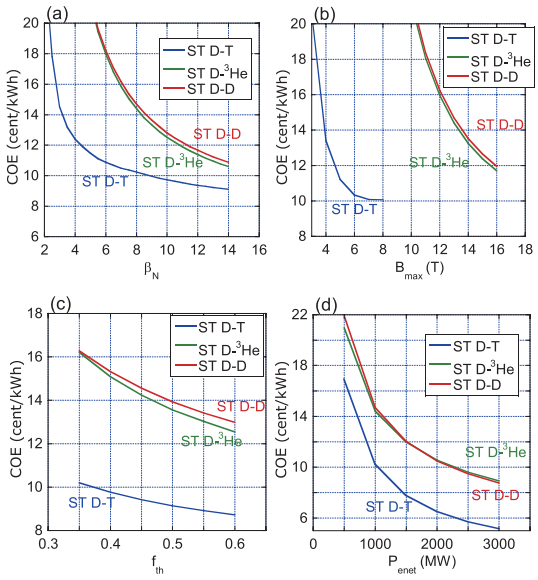

Fig. 3 Dependence of COE on (a) β_N, (b) B_{max}, (c) f_{th} and (d) P_{enet} of STR.

duced and a smaller reactor is required, reducing both the construction cost and COE. Since the reaction rate of an advanced fuel fusion reactor is very low, the COE for such a reactor is higher than that of D-T.

In TR, the bootstrap current ratio is assumed to be a function of poloidal beta value. At $\beta_N < 7$, the bootstrap current ratio is < 95%. Because a low bootstrap current ratio requires high current drive power, the power of the circulating electricity increases, along with the required fusion power. As a result, the COE in advanced fuel reactors is also increased by low bootstrap current ratio.

Since the STR D-T reactor uses a normal conducting coil system, we assume a small value of B_{max} in this reactor. Moreover, the power of the circulating electricity must be increased to compensate for ohmic heating loss in the coil.

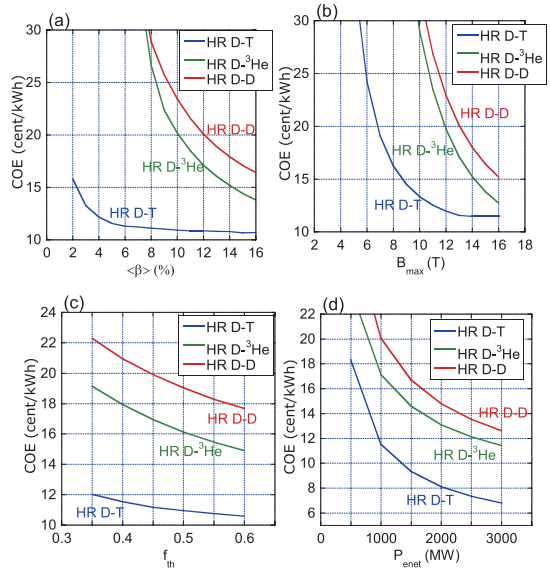

Fig. 4 Dependence of COE on (a) $\langle\beta\rangle$, (b) B_{max}, (c) f_{th} and (d) P_{enet} of HR.

Table 2 Design parameters for scaling laws.

		β_N, $\langle\beta\rangle$ (%)	B_{max} (T)
TR	D-T	2–5	10–16
	D-^{3}He,D-D	6–14	10–16
STR	D-T	6–12	4–10
	D-^{3}He,D-D	6–14	10–16
HR	D-T	2–6	10–16
	D-^{3}He,D-D	6–14	10–16

In the advanced fuel reactor of HR, the COE strongly depends on beta value and magnetic field strength, and the ISS confinement scaling law specifies an extremely high H factor. Thus, the confinement requires much improvement in the high temperature regime of HR.

In all reactors types, the COE is reduced by high f_{th} and P_{enet}. In particular, high-powered reactors incur small COE.

4.2 COE scaling laws

In addition to the survey parameters, the design parameters were the plant availability (f_{avail}) and operating period (t_{oper}). The COE scaling laws were derived from multiple regression analysis. The ranges of β and B_{max} are listed in Table 2; P_{enet} covers 0.5 - 3.0 GW, f_{avail} is 0.65 - 0.8, t_{oper} is 20 - 40 year and f_{th} is 0.35 - 0.60. The new scaling laws are derived as follows.

$$COE^{\mathrm{TRD-T}}[\mathrm{cent/kWh}] = 10^{2.36}\frac{1}{\beta_N^{0.54}B_{max}^{0.11}P_{enet}^{0.53}f_{avail}^{0.91}t_{oper}^{0.79}f_{th}^{0.48}}, \quad (1)$$

$$COE^{\mathrm{TRD-^3He}}[\mathrm{cent/kWh}] = 10^{3.49}\frac{1}{\beta_{\mathrm{N}}^{0.83}B_{\mathrm{max}}^{0.52}P_{\mathrm{enrt}}^{0.56}f_{\mathrm{avail}}^{0.92}t_{\mathrm{oper.}}^{0.82}f_{\mathrm{th}}^{0.39}}, \quad (2)$$

$$COE^{\mathrm{TRD-D}}[\mathrm{cent/kWh}] = 10^{3.67}\frac{1}{\beta_{\mathrm{N}}^{0.86}B_{\mathrm{max}}^{0.60}P_{\mathrm{enet}}^{0.58}f_{\mathrm{avail}}^{0.95}t_{\mathrm{oper.}}^{0.85}f_{\mathrm{th}}^{0.37}}, \quad (3)$$

$$COE^{\mathrm{STD-T}}[\mathrm{cent/kWh}] = 10^{2.53}\frac{1}{\beta_{\mathrm{N}}^{0.33}B_{\mathrm{max}}^{0.30}P_{\mathrm{enet}}^{0.62}f_{\mathrm{avail}}^{0.95}t_{\mathrm{oper.}}^{0.82}f_{\mathrm{th}}^{0.33}}, \quad (4)$$

$$COE^{\mathrm{STD-^3He}}[\mathrm{cent/kWh}] = 10^{4.05}\frac{1}{\beta_{\mathrm{N}}^{0.67}B_{\mathrm{max}}^{1.14}P_{\mathrm{enet}}^{0.48}f_{\mathrm{avail}}^{0.94}t_{\mathrm{oper.}}^{0.85}f_{\mathrm{th}}^{0.48}}, \quad (5)$$

$$COE^{\mathrm{STD-D}}[\mathrm{cent/kWh}] = 10^{4.01}\frac{1}{\beta_{\mathrm{N}}^{0.62}B_{\mathrm{max}}^{1.09}P_{\mathrm{enet}}^{0.55}f_{\mathrm{avail}}^{0.96}t_{\mathrm{oper.}}^{0.87}f_{\mathrm{th}}^{0.40}}, \quad (6)$$

$$COE^{\mathrm{HRD-T}}[\mathrm{cent/kWh}] = 10^{2.97}\frac{1}{\langle\beta\rangle^{0.33}B_{\mathrm{max}}^{0.60}P_{\mathrm{enet}}^{0.54}f_{\mathrm{avail}}^{0.92}t_{\mathrm{oper.}}^{0.84}f_{\mathrm{th}}^{0.34}}, \quad (7)$$

$$COE^{\mathrm{HRD-^3He}}[\mathrm{cent/kWh}] = 10^{6.13}\frac{1}{\langle\beta\rangle^{1.35}B_{\mathrm{max}}^{2.11}P_{\mathrm{enet}}^{0.46}f_{\mathrm{avail}}^{0.96}t_{\mathrm{oper.}}^{0.91}f_{\mathrm{th}}^{0.52}}, \quad (8)$$

$$COE^{\mathrm{HRD-D}}[\mathrm{cent/kwh}] = 10^{5.85}\frac{1}{\langle\beta\rangle^{1.16}B_{\mathrm{max}}^{1.98}P_{\mathrm{enet}}^{0.46}f_{\mathrm{avail}}^{0.96}t_{\mathrm{oper.}}^{0.92}f_{\mathrm{th}}^{0.50}}. \quad (9)$$

In D-^{3}He and D-D, the β and B_{max} exponents exceed those of D-T, and the COE of these advanced fusion reactors strongly depends on β and B_{max}.

5. Summary

We have calculated the COE of advanced fuel fusion reactors in three types of confinement systems and derived new scaling laws for the COE of advanced fuel reactors.

Since the reaction rate in advanced fuel fusion reactors is very low, more plasma volume is required than in the D-T reactor to produce the same target net electric power. Therefore the plant construction cost, and consequently the COE, is increased. To achieve COE similar to that of the D-T Tokamak reactor TR ($\beta_{\mathrm{N}} = 4$), the β_{N} should be raised in the D-^{3}He and D-D TR reactors ($\beta_{\mathrm{N}} > 10$). However, high β_{N} (> 5) is not readily attained in a conventional TR. If high β_{N} could be realized in spherical tokamak confinement systems, together with high magnetic field generated by the superconducting coil, the COE of D-^{3}He would become comparable to that of D-T.

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