Economic Evaluation of D-T, D-^{3}He, and Catalyzed D-D Fusion Reactors*)

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Because the D-^{3}He reaction generates no neutrons and the D-D reaction can use abundant fuel resources, these reactions are expected to be used in advanced fuel fusion reactors. Economic considerations and engineering problems are important for realizing such reactors as commercial plants. Therefore, we estimate and compare the cost of electricity (COE) from D-T, D-^{3}He, and catalyzed D-D (cat D-D) fusion reactors. D-^{3}He and cat D-D reactors have a low neutron wall load. Therefore, the D-^{3}He reactor has no wall replacement cost. In addition, no tritium breeding system is needed for the D-^{3}He reactor, but ^{3}He gas is rare. Because the reaction rates of the D-^{3}He and D-D reactions are less, D-^{3}He and D-D reactors require highly efficient confinement properties and operation at high ion temperatures. Furthermore, the power densities of D-^{3}He and D-D reactors are smaller than that of the D-T reactor; thus, D-^{3}He and D-D reactors require a large plasma volume. Assuming a high ion temperature (= 60 keV) and high normalized beta (= 7–8), the COE of a D-^{3}He reactor is expected to be similar to that of a D-T reactor. In terms of cost, cat D-D is disadvantageous in comparison with D-^{3}He and D-T reactors.

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

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1. Introduction

A D-T fusion reactor system can be realized at low plasma temperatures; approximately 80% of the power of the D-T reactor is from 14.1 MeV neutrons. These neutrons activate the reactor wall, and the walls and other components must be replaced every few years. In addition, the D-T reactor requires a breeding and storage system for a radioactive substance (tritium). Because the D-^{3}He reaction generates no neutrons and the D-D reaction can use abundant fuel resources, these reactions are expected to be used as advanced fuel fusion reactors. Economic considerations and engineering problems are important for realizing advanced fuel fusion reactors as commercial plants. Our group has focused on economic assessments of the D-T fuel system. In this study, we evaluate the economics of D-^{3}He and D-D fuel fusion reactors in more detail than in our previous studies [1]. We estimate the costs of D-T and advanced fuel fusion plants and compare them with each other.

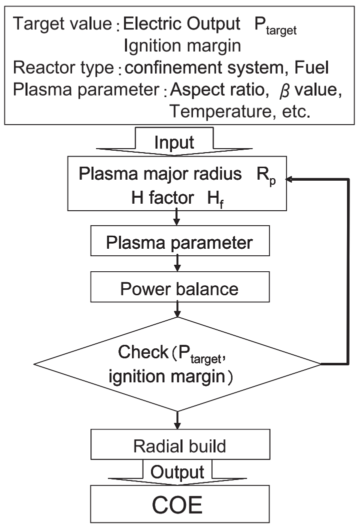

Fig. 1 Flowchart of the PEC code.

2. Analysis Procedures

We calculate the cost of electricity (COE) of fusion reactors using the Physics-Engineering-Cost (PEC) system code [2]. A flowchart of the PEC code is shown in Fig. 1. The PEC code calculates the plasma parameters and engineering design parameters of fusion reactors using input parameters such as the target output electric power, target ignition margin, normalized beta value (β_N), and aspect ratio (A). Representative input parameters are shown in Table 1. The plasma major radius R_P and the HH factor are iteration parameters for satisfying the target output electric power and ignition margin. The current drive power P_{CD} is given in terms of the average electron density $\langle n \rangle$, R_P, the plasma current I_P, and the bootstrap current I_{BS}: $P_{CD} = 2.0\langle n \rangle R_P(I_P - I_{BS})$. The toroidal field coil radius and thickness are calculated according to an inboard ra-

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Table 1 Main input parameters and calculated parameters for reference cases.

Confinement system	TR			ST		
Fuel cycle	D-T	D-^{3}He	cat D-D	D-T	D-^{3}He	cat D-D
Net electric power P_{enet} (GW)	1	1	1	1	1	1
Normalized beta β_N [a]	4	8	8	8	8	8
Aspect ratio A [a]	3.53	3.53	3.53	1.62	1.62	1.62
Ellipticity κ [a]	2.0	2.0	2.0	3.5	3.5	3.5
Maximum field B_{max} (T)[a]	13	13	13	8.75	13	13
Central ion temperature T_i (0) (KeV)[a]	30	70	70	30	70	70
Maximum coil current density J_{max}(MA/m^2)[a]	30	30	30	13	30	30
Plasma major radius R_p (m)	6.33	8.57	10.53	3.99	6.66	7.83
Toroidal field B_t (T)	6.13	7.81	8.15	2.33	3.30	3.55
Fusion power (GW)	3.35	2.74	3.19	4.55	2.68	3.08
Neutron power (GW)	2.68	0.07	0.63	3.64	0.06	0.61
Ohmic loss (GW)				0.95		
Power density (MW/m^3)	4.61	1.52	0.96	3.18	0.40	0.28
Plasma current (MA)	14.49	24.95	32.00	21.64	51.15	64.69
HH factor	1.21	1.98	3.07	1.75	2.26	2.09
Current drive power (MW)	138.8	43.8	75.3	10.5	35.6	61.3
COE (cent/kWh)	10.97	9.69	11.74	10.29	10.41	12.84
Neutron wall load (MW/m^2)	3.54	0.05	0.31	4.94	0.03	0.21

[a] Input parameters

dial build determined using the input maximum field B_{max}, maximum coil current density J_{max}, among others.

3. Reactor Model

We estimated two types of confinement system: the tokamak reactor (TR) and spherical tokamak reactor (ST). In the ST, we can omit the inner blanket and use a normal conducting coil for the center post coil;thus, the ST can have a low aspect ratio. The ST is expected to have a high beta value. However, because a normal conducting coil is used, it is necessary for the ST to use some of the electric output to make up ohmic heating loss.

We estimate three types of fuel cycles: D-T, D-^{3}He, and catalyzed D-D (cat D-D). The D-T reactor has a relatively high reaction rate and requires tritium breeding by a blanket. The blanket model assumed here is Li_2O/FS, as in the Steady State Tokamak Reactor [3]. The estimated unit cost of this blanket is 0.34 M$/m^3. The D-^{3}He reactor does not have a blanket because tritium breeding is not needed. However, ^{3}He gas is a very rare resource on the earth. In this study, we assumed a scenario in which ^{3}He is taken from the moon's surface [4]; the cost of ^{3}He was calculated as 200 $/g. The cat D-D reactor system recycles T and ^{3}He produced by the D-D reaction and extracts energy from the D-T and D-^{3}He reactions. The cat D-D cycle does not require tritium breeding; thus, a cat D-D reactor has no breeding blanket. The shield thickness of a D-^{3}He TR is 0.7 m, as in ARIES-3 [5], and that of a cat D-D TR is 0.65 m inboard and 1.41 m outboard, as in WILDcat [6]. Because D-^{3}He and cat D-D reactors have a low neutron wall load, the shield thickness is 0.56 m for a D-^{3}He [7] or cat D-D ST.

The electron and ion temperatures are assumed to be

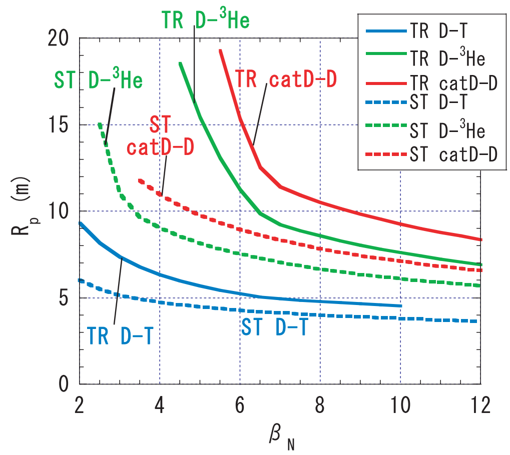

Fig. 2 Dependence of R_p on normalized beta.

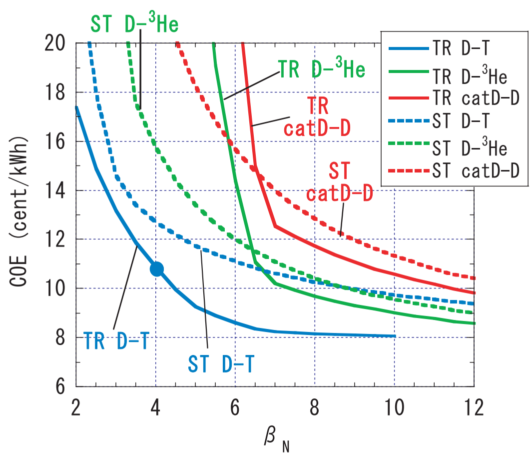

Fig. 3 Dependence of COE on normalized beta. Circle indicates the reference case of a D-T TR.

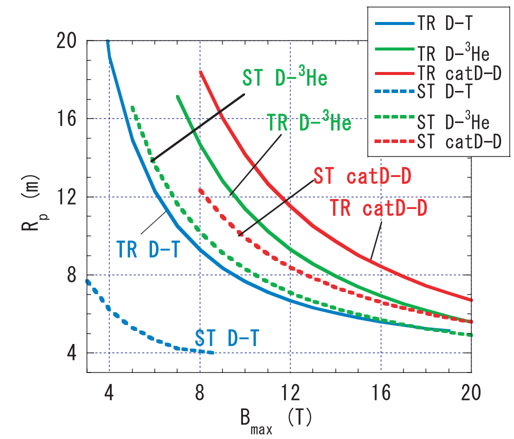

Fig. 4 Dependence of R_p on B_{max}.

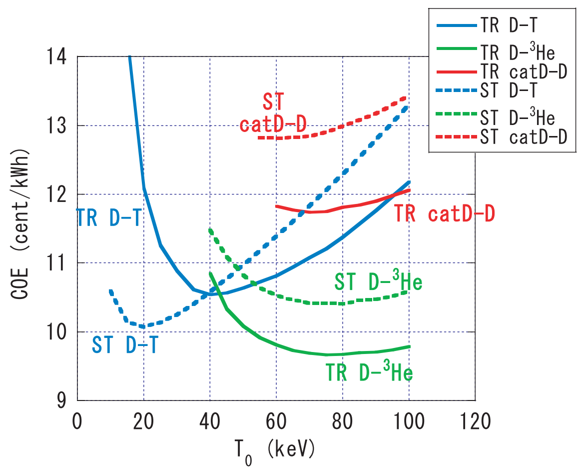

Fig. 6 Dependence of COE on central temperature.

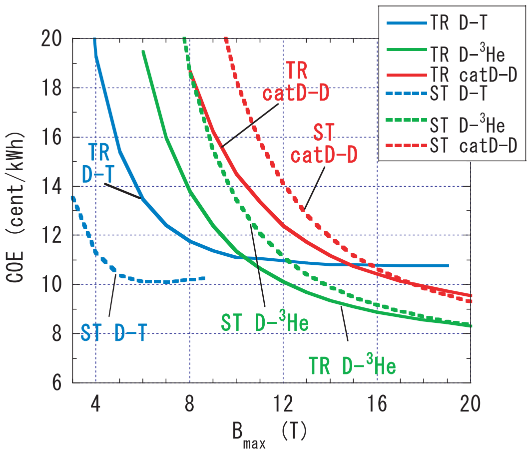

Fig. 5 Dependence of COE on B_{max}.

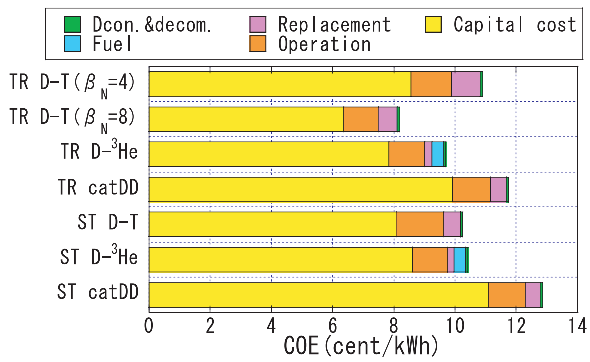

Fig. 7 COE breakdown for reference cases and D-T TR with $\beta_N = 8$.

equal. Parabolic plasma temperature and density profiles are assumed: $T(r) = T_0(1 - r^2)^1$, $n(r) = n_0(1 - r^2)^{0.25}$, where T_0 and n_0 are the central temperature and density, respectively, and r is the normalized small radius.

We fixed the following input parameters: target net electric power: 1000 MW, plant availability: 75%, operating period: 30 years, and target ignition margin: 1.01. The reactors used as reference cases are shown in Table 1.

4. Assessment Results

The dependence of R_p and the COE on the normalized beta value (β_N) is shown in Figs. 2 and 3, respectively. A high β_N improves the burning plasma performance, and the power density increases. As a result, the plasma volume required to satisfy the target output electric power is reduced. Therefore, the size of the reactor decreases, and the COE decreases. D-^{3}He and cat D-D reactors need a high β_N in order to obtain almost the same COE as that of a D-T TR (at $\beta_N = 4{\sim}5$) D-^{3}He and cat D-D have a lower output power density and require a larger plasma volume than D-T. In a D-^{3}He TR or cat D-D TR, the decrease in the COE is relaxed at around $\beta_N = 7$, because at $\beta_N > 7$, the bootstrap current ratio is 95%. When the bootstrap current ratio is low, the circulating electricity power used for the current drive increases, which in turn increases the required nuclear fusion output. In D-^{3}He and cat D-D reactors, it is important to increase the bootstrap current ratio. The maximum bootstrap current ratio of a ST was assumed to be fixed at 95%.

The dependence of R_p and the COE on the maximum field B_{max} is shown in Figs. 4 and 5, respectively. Because a high magnetic field improves the confinement performance, the COE decreases However, in a D-T TR at a maximum magnetic field of greater or equal to 12 T, the improvement of the magnetic field does not contribute significantly to COE reduction. When the system becomes compact, the first wall surface area becomes small, increasing the neutron wall load. Therefore, the activated wall must be replaced more often. Because a D-T ST uses a normal conducting coil, the maximum magnetic field permitted by the radial build is 8.7 T.

Figure 6 shows the dependence of the COE on the central temperature. Because β_N is given as an input parameter and the plasma pressure is constant in the PEC code, the ion density is high at low temperature. At high ion density, a large current drive power is needed, and the recirculating electric power in the plant is high. Therefore high fusion power is required to obtain 1 GW of output electric power. Thus, R_p increases and thus, the COE increases. In an advanced fuel reactor, in addition to the above, the reaction rate at low temperature can be too low to satisfy the target electric power.

Figure 7 shows a COE breakdown for the reference cases; data for a D-T TR with $\beta_N = 8$ are added for comparison Because D-^{3}He and cat D-D reactors require a large plasma major radius, the construction cost and capital cost increase. Because of neutron damage to the first walls, the D-T reactor requires frequent blanket replacement within the plant's lifetime. In contrast, advanced fuel reactors have a very low neutron wall load. The wall loading for cat D-D is one order smaller than that for D-T, and that for D-^{3}He is, in turn, one order smaller than that for cat D-D. Accordingly, blanket replacement is not needed in a D-^{3}He reactor. Therefore, the D-^{3}He reactor has almost no replacement costs, and the cat D-D reactor has a lower replacement cost. However, D-^{3}He reactors require ^{3}He gas, which is a rare resource. The operation cost of a D-T ST is higher than that of other reactors because of normal conducting ohmic heating loss.

5. Summary

We calculated the COE of advanced fuel fusion reactors. Because these reactors have low power density, they require high plasma temperature and high confinement performance. To obtain a COE similar to that of a D-T TR ($\beta_N = 4$), a D-^{3}He reactor requires $T > 60$ keV, $\beta_N > 7$~8, $B_{max} > 13$ T, and economical ^{3}He sources. A cat D-D reactor requires $T > 60$ keV, $\beta_N > 8$-9, $B_{max} > 14$ T, and an improved fuel cycle system. It seems difficult to achieve high β_N (> 5) in a conventional TR. Thus, because an ST can achieve high β_N, the ST is expected to be a confinement system suitable for D-^{3}He and cat D-D reactors.

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