Comparative Study of Cost Models for Tokamak DEMO Fusion Reactors[*)]

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Cost evaluation analysis of the tokamak-type demonstration reactor DEMO using the PEC (physics-engineering-cost) system code is underway to establish a cost evaluation model for the DEMO reactor design. As a reference case, a DEMO reactor with reference to the SSTR (steady state tokamak reactor) was designed using PEC code. The calculated total capital cost was in the same order of that proposed previously in cost evaluation studies for the SSTR. Design parameter scanning analysis and multi regression analysis illustrated the effect of parameters on the total capital cost. The capital cost was predicted to be inside the range of several thousands of M$s in this study.

Keywords: reactor design, cost model, system code, demonstration reactor, tokamak, multiple regression analysis

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1. Inroduction

To prove the feasibility of nuclear fusion power plants, various designs of tokamak-type demonstration reactors (DEMOs) have been proposed [1, 2]. One of the tasks of a DEMO includes establishing an accurate economic perspective of its construction and operation. Therefore, an attractive design of DEMO requires the assessment of its cost under different parameters. The appropriate choice of a cost model in studies of the system codes for the economic optimization of the design of a DEMO or similar commercial reactor is not a trivial matter, and should be based on research.

In the present paper, the construction cost of a tokamak DEMO reactor (capital cost) is calculated using the PEC system code. The relationship between the capital cost and design parameters was investigated using a parameter scan calculation. The calculated cost was also compared with that of a previously proposed reactor design study, in order to clarify the critical issues for the establishment of a cost model applicable to a tokamak DEMO reactor.

2. Methods of Cost Calculation

The reactor designing system code PEC (Physics Engineering Cost) was used for the cost evaluation [3]. Firstly, the target electrical power (500-2000 MW_e in this study), normalized beta, maximum magnetic field, and parameters of plasma shapes or profiles were decided as input parameters. Plasma parameters such as fusion output power, current drive power, and plasma current were calculated using input parameters and considering energy flow with changing the major radius of the plasma. If the calculated net electrical power matches the target value, the major radius and associated radial build are decided. The amount of materials used in the fusion island was employed as fundamental data of cost evaluation. In the calculation of the cost of the balance of plant, cost-scaling formulas of the thermal output power were applied to the main heat transport system, auxiliary cooling system, radioactive waste management, and other systems of the reactor plant, and cost-scaling formulas of the gross electrical output power were applied to the turbine building, cooling structure, turbine plant equipment, electric plant equipment, and miscellaneous plant equipment, while the cost of some other components are given as fixed values.

3. Results of Cost Calculation

3.1 Reference design: SSTR-like tokamak

Table 1 shows the plasma parameters of a tokamak DEMO reactor designed by PEC code. It was designed so that the plasma parameters are similar to those of the SSTR (steady state tokamak reactor) DEMO reactor [1]. The parameters of the SSTR are shown together in this table. The net output electrical power is 1080 MW. Although there are small differences in the normalized beta and plasma current between two designs, the size of the torus can be

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Table 1 Plasma parameters of a DEMO reactor designed by PEC code and those of SSTR.

	PEC	SSTR [1]
Major Radius R_p	7.09 m	7.0 m
Aspect Ratio A_p[a]	4.1	4.1
Ellipticity κ[a]	1.85	1.85
Triangularity δ[a]	0.4	0.4
Maximum field B_{max}[a]	16.5 T	16.5 T
Toroidal field B_t	9.14 T	9.0 T
Normalized beta β_N[a]	3.0	3.3
Safety factor q_{95}[a]	5.0	5.0
Plasma current I_p	11.6 MA	12.0 MA
Central ion temperature $T_i(0)$[a]	34 keV	34 keV

[a]input parameters of PEC code.

Table 2 Capital cost and its breakdown of a SSTR-like DEMO reactor designed by PEC code.

Breakdown	Cost [M$]
Total direct cost	**2984.7**
Fusion island	**1271.4**
FW/blanket/reflector	128.2
Shield	315.5
Magnets	354.0
Current drive & heating	225.9
Primary structure & support	62.5
Vacuum systems	106.2
Power supply, switching	67.6
Impurity control & divertor	11.5
ECRH breakdown system	4.9
Balance of plant	**1713.3**
Land & land rights	12.7
Structures & site facilities	433.6
Main heat transport systems	473.9
Auxiliary cooling system	5.7
Radioactive waste management	10.1
Fuel handling and storage	108.2
Other reactor plant eqt.	9.2
Instrumentation and control	46.8
Turbine plant equipment	345.2
Electric plant equipment	170.0
Misc. plant equipment	83.0
Heat rejection system	0.0
Special materials	14.9
Total indirect cost	**2795.1**
Construction services & eqt.	358.2
Home office engr. & services	155.2
Field office engr. & services	179.1
Owners cost	551.6
Process contingency	0.0
Project contingency	731.6
Interest during construction	819.4
Total capital cost	**5779.7**

almost reproduced by the calculation of the PEC code. The cost for the construction of the reactor designed by PEC code is shown in Table 2. Dollar values in this table were priced in 2003. To compare this result to another cost evaluation study, an appropriate conversion rate from dollars to yen is needed. If the exchange rate of 116 yen/$ or the purchasing power parity calculated for GDP comparison of 140 yen/$ (both in 2003) is employed, the total capital cost of 5779.7 M$ in Table 2 is 670 billion yen or 809 billion yen, respectively. These are in the same order of the total capital cost shown in the previously proposed cost evaluation of SSTR, which was 720 billion yen in 1991 [4].

It is worth noting that we have to improve the validation of our cost model. More consideration will be needed to conclude that our model is appropriate when we investigate the ratio of each component to the total cost. For example, the cost of magnets calculated by PEC code of 354.0 M$ is 6% of the total capital cost of 5779.7 M$. However, the cost of magnets in the SSTR is 143 billion yen, which is up to 20% of the total capital cost of 720 billion yen. This kind of difference could be originated in the assumptions of the cost calculation. Several parts of our cost model are based on those proposed in the ARIES program [5]. Therefore, our cost model has several differences on account titles, employed scaling formulas, and definition of direct/indirect costs compared to that of SSTR. For example, the cost of "construction service and equipment" in "total indirect cost" in Fig. 2 is pre-included into the direct cost of each component in the SSTR cost model and is not counted as an indirect cost. It could also cause an unnaturalness that the total indirect cost in Table 2 of 2795.1 M$, or 48% of the total capital cost, seems large. Therefore, to compare the calculation results of the cost evaluation studies, we should investigate the difference between assumptions for the design and cost calculation, definitions of account titles, and parameter dependence of each cost model in the future.

3.2 Parameter dependence of the capital cost and its breakdown

In order to investigate the sensitivity of each parameter for reactor design, such as normalized beta β_N, maximum magnetic field B_{max}, conversion efficiency from heat to electricity f_{th}, and net output electrical power P_{trg}, in the capital cost, these parameters were scanned and the capital costs were evaluated. The reference case was the SSTR-like tokamak reactor as mentioned in the previous section.

Figure 1 shows the β_N dependence of (a) capital cost and the major radius R_p, and (b) the breakdown of capital cost of DEMO reactor designed using PEC code. A more detailed breakdowns of (c) the fusion island and (d) the balance of plant are shown together. "Shield", "magnets", and "current drive & heating" assume large fractions in the cost of the fusion island and have a negative correlation with β_N. In the case of a lower β_N, the cost of "current drive &

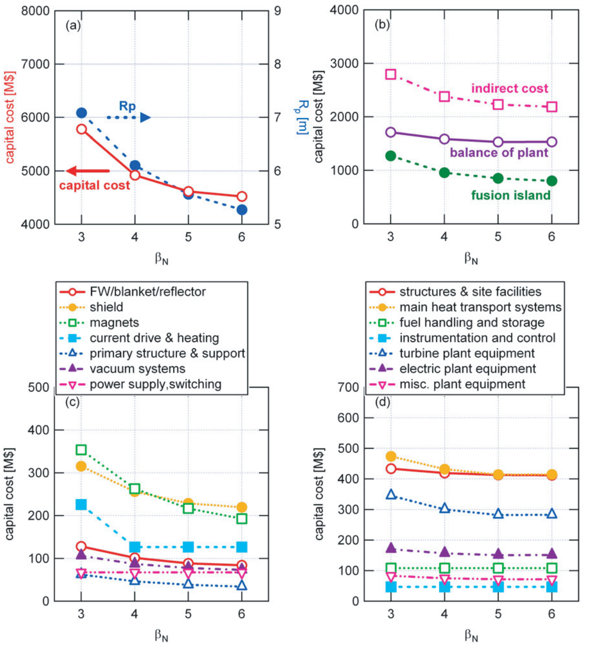

Fig. 1 Normalized beta β_N dependence of (a) capital cost and major radius R_p, and (b) breakdown of capital cost of DEMO reactor designed using PEC code. More detailed breakdown of (c) the fusion island and (d) the balance of plant are shown together.

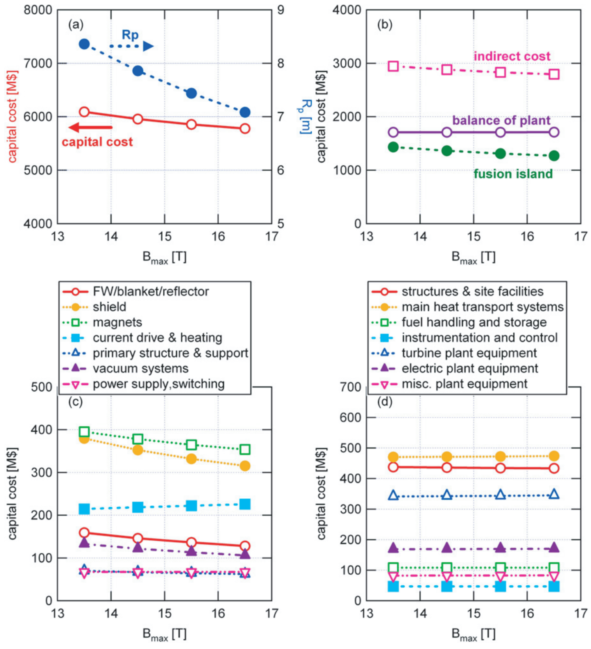

Fig. 2 Maximum field B_{max} dependence of (a) capital cost and major radius R_p, and (b) breakdown of capital cost of DEMO reactor designed using PEC code. More detailed breakdown of (c) the fusion island and (d) the balance of plant are shown together.

heating" increases significantly because of the small bootstrap current fraction. This increase of the cost of "current drive & heating" means that more gross electricity should be generated in a reactor to operate the current drive and heating equipment having larger power in the low-β_N case. This fact results in the increase of the costs of the "main heat transport systems" and "turbine plant equipment" in the cost of the balance of plant in the low-β_N case as shown in Fig. 1 (d). Figure 2 shows the B_{max} dependence of the capital cost and its breakdown. Dependence of the capital cost is not so large, while R_p clearly depends on B_{max}. "FW/blanket/reflector", "shield", "magnets", and "vacuum systems" decrease with decreasing R_p because they relate to the torus size. Figure 3 shows the f_{th} dependence of the capital cost and its breakdown. Almost all components in the fusion island decrease with increasing f_{th}. "Main heat transport systems" in the balance of plant can be also decreased because the gross electric power generated in a reactor is decreased in the case of a higher f_{th}.

Figure 4 shows the P_{trg} dependence of the capital cost and its breakdown. Capital cost has a large dependence on P_{trg}. The change in the cost of turbine plant equipment in the balance of plant is the largest. In addition, one can see that the capital cost is only doubled while P_{trg} is quadrupled, when P_{trg} changes from 500 MW to 2000 MW.

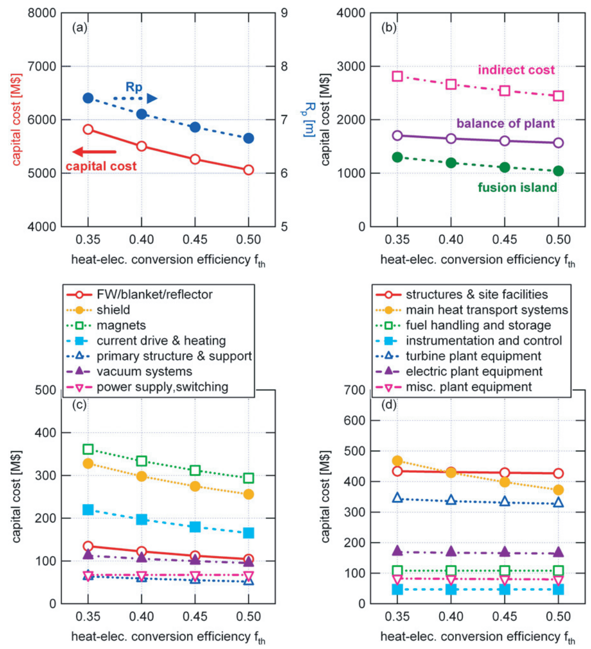

Fig. 3 Conversion efficiency from heat to electricity f_{th} dependence of (a) capital cost and major radius R_p, and (b) breakdown of capital cost of DEMO reactor designed using PEC code. More detailed breakdown of (c) the fusion island and (d) the balance of plant are shown together.

3.3 Scaling prediction of the capital cost and the cost of electricity

Multiple regression analysis clarifies the significance of each design parameter in the total capital cost. The scanning parameters and their ranges are the same as those investigated in the previous section. The cost of electricity

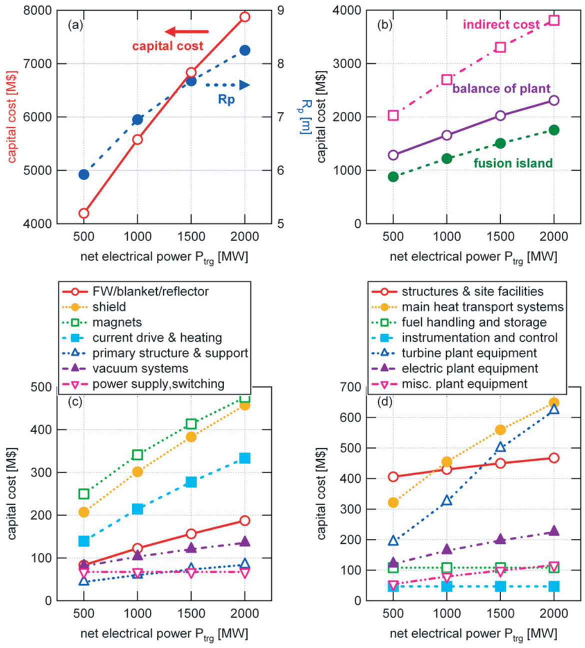

Fig. 4 Net output electrical power P_{trg} dependence of (a) capital cost and major radius R_p, and (b) breakdown of capital cost of DEMO reactor designed using PEC code. More detailed breakdown of (c) the fusion island and (d) the balance of plant are shown together.

(COE) can also be estimated as

$$COE \equiv \frac{CC + C_{OM} + C_F + C_R + C_{DD}}{P_{trg} \cdot T_O \cdot 8760 \cdot f_{av}}, \tag{1}$$

where CC is the total capital cost [\$], C_{OM} is the cost of operation and maintenance [\$], C_F is the cost of fuels [\$], C_R is the cost of replacement [\$], C_{DD} is the cost of deconstruction and decommission [\$], P_{trg} is the net output electrical power [W], T_O is the operational period [years], and f_{av} is the plant availability. C_{OM}, C_F, and C_R are costs integrated throughout the operation period. T_O = 30 years and f_{av} = 0.75 are assumed. As the results of the analysis, we obtained the scaling laws for the capital cost and COE as follows.

$$CC\ [\mathrm{M\$}] = 10^{2.727} \beta_N^{-0.3284} B_{max}^{-0.1896} f_{th}^{-0.2884} P_{trg}^{0.4227}, \tag{2}$$

$$COE\ [mil/kWh] = 10^{3.838} \beta_N^{-0.2996} B_{max}^{-0.1304} f_{th}^{-0.2876} P_{trg}^{-0.5542}. \tag{3}$$

Figure 5 shows (a) the capital cost and (b) the COE evaluated from designs using the PEC code plotted against those predicted by the scaling laws. Both PEC-designed findings are in good agreement with scaling-predicted values, with a root mean square error of about 1%. The net electrical power was the most significant among the parameters scanned in this study. The capital cost falls inside the range of several thousands of M$s. On the other hand, for more accurate evaluation of the COE, the parameters of

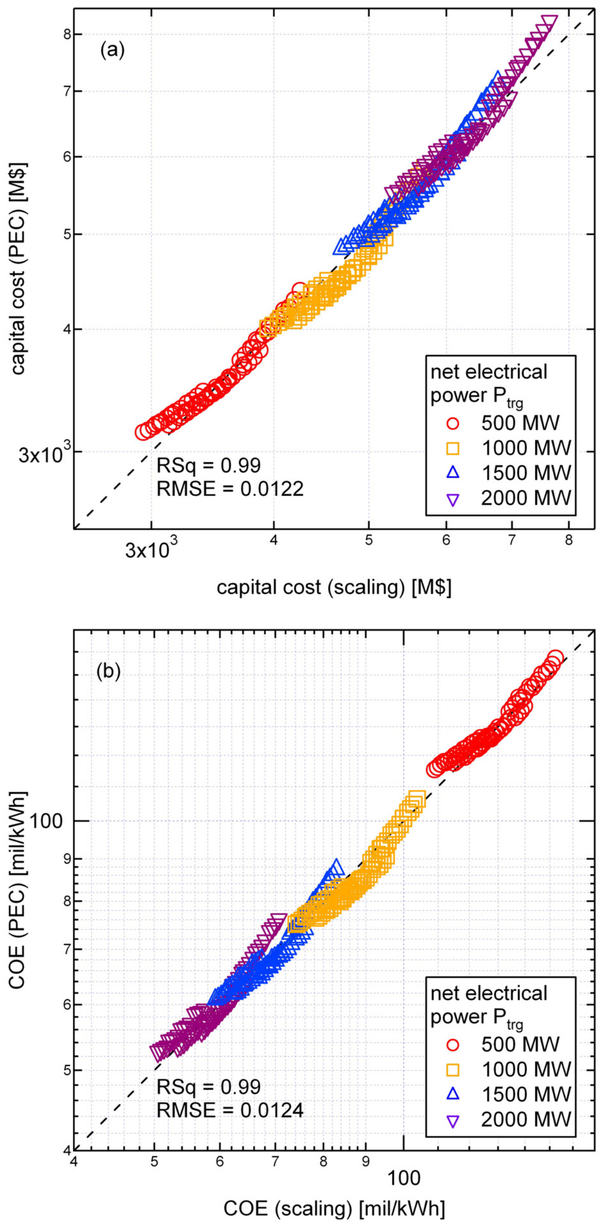

Fig. 5 (a) Capital cost and (b) COE evaluated from designs using PEC code plotted against those predicted by the scaling laws.

learning effect, effect of mass production, plant availability, and operation period should be taken into consideration.

4. Summary and Future Plans

Cost evaluation analysis of the fusion demonstration reactor DEMO using the PEC (physics-engineering-cost) system code is underway to establish the cost model to be included in the system code for DEMO reactor design. As a reference design, a tokamak DEMO reactor was designed with reference to the SSTR (steady-state tokamak reactor) using the PEC code. The calculated total capital cost was on the same order as that proposed previously in cost evaluation studies for the SSTR. We used design parameter scanning analysis and multi regression analysis to illustrate the effect of parameters on the total capital cost. The capital cost was predicted to be within the range of several thousands of M$s in this study. To compare the calculation results to those of other cost evaluation studies, we should investigate the differences between each study, such as assumptions for the design and cost calculation, parameter dependence of the calculated cost, and so on. These investigations remain as future studies.

Acknowledgments

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