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Assessment for Economics and Energy Payback of Fusion Reactors
核融合炉の経済性及びエネルギー収支に関する評価研究

Kanae BAN, Kozo YAMAZAKI, Hideki ARIMOTO, Tetsutarou OISHI, Tatsuo SHOJI
伴佳奈恵，　山﨑耕造，有本英樹，大石鉄太郎，庄司多津男

Nagoya University
Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
名古屋大学　〒464-8601　名古屋市千種区不老町

To optimize fusion reactor designs, we used the system code and evaluated the cost of electricity (COE) and the energy payback ratio (EPR) of several fusion reactors; tokamak (TR), helical (HR), spherical tokamak (ST), and inertial confinement fusion reactor (IR). Also, we focus on three blanket designs including rare and valuable structural materials. After the evaluation of the EPR of three TR designs with different blanket and shield models, we found that the input energy of TR with ARIES-AT like blanket (SiC/LiPb blanket) and shield model is the lowest.

1. Introduction

In order to realize the fusion energy plant, high social acceptability is required. But, fusion reactors might require enormous amount of construction costs and rare and valuable materials. Then, we evaluated the cost of electricity (COE) and energy payback ratio (EPR) of fusion reactors. The COE is an index evaluating whether fusion reactor construction cost is appropriate or not. And, the EPR is an index evaluating how a power plant produces the energy effectively from the lower input energy.

In this study, we use some fusion reactor models; tokamak (TR), helical (HR), spherical tokamak (ST), and inertial confinement (IR). In addition, we compare several blanket and shield designs with rare and valuable materials; such as silicon carbide (SiC), vanadium alloy (V), and ferritic steel (FS). Finally we compare the EPRs of fusion reactors with those of other electric power plants.

2. Analysis method

Fusion reactors were designed using physics engineering, and cost (PEC) code [1]. The PEC code calculates the plasma major radius assuming the target electrical power (typically 1GWe) (P_{target}), normalized beta (β_N) and so on. And then, the fusion island weight and the total cost are evaluated. The COE is defined as the cost for the 1kWh energy production. In this study, we carried out the life cycle assessment (LCA) from resources supply to decommission.

2.1 Energy payback ratio (EPR) definition

The EPR means energy output efficiency. The EPR is defined as the ratio of electrical output energy to input energy. The definition of the EPR is as follows:

$$EPR = \frac{E_{output}}{E_{const.} + E_{operation} + E_{fuel} + E_{replace} + E_{Decon.\&Decom.}} \quad (1)$$

The denominator shows the total input energy; fusion power plant construction ($E_{counst.}$) including fusion island (FI) and balance of plant (BOP) which are more than 20 components, management and operation ($E_{operation}$), fuel production (E_{fuel}), replacement ($E_{replace}$) and decontamination and decommission of reactor equipment ($E_{Decon.\&Decom.}$).

2.2 Reactor parameters

The reactor parameters used in this study are shown in Table I. There are some input parameters, normalized beta (β_N), and maximum toroidal field (B_{max}). The toroidal field coils of ST use normal conducting coil. The parameters calculated from PEC code describe below the center line.

Table I. Typical reactor parameters

	TR	ST	HR
β_N,*< β>[%]	4.0	7.96	*4.0
B_{max}[T]	13	7.4	13
P_{th}[MW]	2220	3203	2065
R_p[m]	5.25	3.90	13.32
a_p[m]	1.72	2.44	2.34

2.3 Components of fusion island

The construction input energy is evaluated from the weight or the cost of components multiplied by energy intensity [2] [3]. Table II shows the blanket and shield models, ARIES-AT [4] shown as A, ARIES-RS [5] shown as B, SSTR [6] shown as C.

The B-blanket model is assumed to be high temperature structure and good heat transfer coolant. So the B-blanket has high thermal efficiency. The energy intensity is calculated from each original blanket and shield mass and volume fraction. Other fusion island components such as, magnet, vacuum vessel, and support structure are evaluated.

First, we evaluate the COE and the EPR of three typical reactor designs with B-blanket model. After then, we evaluate the COEs and the EPRs of TR with the three blanket models.

Table II. Three blanket models

	A	B	C
Structure/breeder/ coolant/multiplier	V/Li/Li/-	SiC/LiPb/ LiPb/-	FS/Li_2O/ H_2O/Be
Energy intensity [TJ/t]	0.804	0.222	0.526
Thermal efficiency [%]	46	50	34.5

3. Results

First, the COEs and the EPRs of three typical reactor designs are shown in Table III. We found that the COE of TR is the lowest and the EPR of TR is the highest. As shown Fig.1, the FI construction input energy of TR is the lowest. In the case of ST, the more input energy of BOP construction is required so that ST needs thermal fusion power against power loss from ohmic-heating of normal conducting coils. As for HR, the major radius becomes large, and large input energy of FI construction is required. The EPRs of fusion reactors are as same as that of fission power plant [7]. In the conference, we will also present the assessment results of IR.

Table III. COEs and EPRs of three typical fusion reactor designs compared with fission.

	TR	ST	HR	Fission[7]
COE [mil/kWh]	8.8	11.0	12.2	5.9
EPR	32	26	22	24

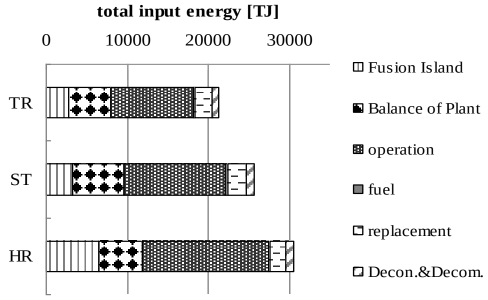

Fig.1. Input energy breakdown of each reactor, TR, ST, and HR.

Table IV shows the COEs and the EPRs of TR with three blanket and shield models. We assumed that these tokamak reactors have same input parameters shown in Table I of TR. The COEs of three models are slightly different. In the case of EPR, that of TR with B-blanket model is the highest. As shown Fig.2, the total input energy of TR with B-blanket is the lowest. Because B-blanket model has high thermal efficiency and lowest blanket energy intensity. The A-blanket has also high thermal efficiency, but the total input energy is high. Because of the usage of vanadium alloy and liquid lithium materials, the energy intensity of A-models might be high.

Table IV. COEs and EPRs of three TR designs with different blanket model

	A	B	C
R_p[m]	5.37	5.25	5.79
blanket and shield weight [t]	3999	2032	3914
COE [mil/kWh]	8.4	8.8	9.3
EPR	26	32	27

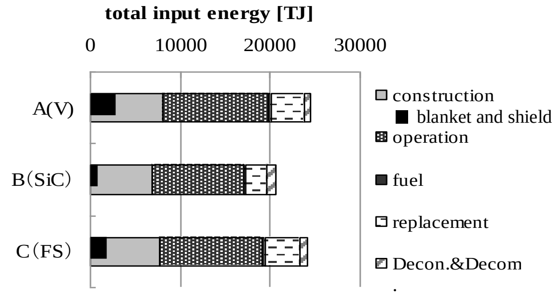

Fig.2. Input energy breakdown for three blanket models, A, B, and C.

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