Introduction condition of a tokamak fusion power plant as an advanced technology in world energy scenario

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°R. Hiwatari, K. Tokimatsu, Y. Asaoka, K. Okano, S. Konishi and Y. Ogawa

Central Research Institute of Electric Power Industry (CRIEPI), Tokyo, Japan
Research Institute for Innovative Technology for the Earth (RITE), Tokyo, Japan
Institute of Advanced Energy, Kyoto Univ., Kyoto, Japan
High Temperature Plasma Center, the Univ. of Tokyo, Tokyo, Japan
1. Introduction and objectives
   electric and economic break-even conditions in the fusion energy development
2. World energy scenario and break-even price of fusion energy
3. Analysis method of electric and economic break-even condition
4. Electric break-even condition
   Completion of this condition leads to recognize fusion energy as a suitable candidate of an alternative energy source in world energy scenario.
5. Economic break-even condition
   Completion of this condition leads for fusion energy to be selected as an alternative energy source
6. Summary
Introduction

Three Milestone of Fusion Energy Development

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**Electric breakeven condition**
- Gross electric power is larger than circulating power

**Breakeven condition**
- Discussed as an important issue

**Commercial Reactor**
- CREST, A-SSTR2, ARIES-AT etc
- Introduction into market

**Economic breakeven condition**
- Cost Competition with other energy sources

**Experimental Reactor**
- JT-60U, JET, TFTR
- Prospect for burning plasma

**3 major tokamak**
- JT-60U, JET, TFTR
- Prospect for burning plasma

**Development Path**
- Selected as an alternative energy in a long term energy scenario

**Demo. Reactor**
- Demo Reactor

**Proto. Reactor**
- Proto Reactor

**Demonstration Reactor**
- ITER
- Prospect for net electric power generation

**Recognized as a suitable candidate of an alternative energy in a long term energy scenario**
Objectives

The present study reveals the following two introduction conditions of a tokamak fusion power plant in a long term energy scenario.

(1) **Electric breakeven condition**, which is required for the fusion energy to be recognized as a suitable candidate of an alternative energy.

(2) **Economic breakeven condition**, which is required to be selected as an alternative energy source.
World Energy Scenario

Long term world energy and model (Linearized DNE21) is applied to the fusion energy. (This model is used for IPCC post SRES activity.)

Under the condition of 550 ppm CO₂ concentration in atmosphere, breakeven price and introduction year are analyzed.

If the COE for the fusion energy can achieve the 65mill/kWh, 20% share of the fusion energy in all produced electricity in 2100 is expected.

Break-even Price (BP) in 2050 is estimated at 65mill/kWh ~ 135mill/kWh

Economic Breakeven condition in this study.
Analysis Method

FUSAC (FUsion power plant System Analysis Code)
- 0D plasma model of ITER Physics Guidelines
- simple engineering model based on TRESCODE(JAERI)
- Generomak Model for economic analysis

Database of 10,000 operation points for a tokamak
Plasma size (major radius, aspect ratio), major physical parameters, shape and location of reactor component (TF, CS coil, radial build), weight of each component, construction cost, cost of electricity (COE)

Electric and economic break-even condition
$\beta_N$, $f$, $n_{GW}$, HH required to achieve electric and economic break-even condition
**Parameter Region**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R (m)</th>
<th>A</th>
<th>κ</th>
<th>δ</th>
<th>Te(=Ti) (keV)</th>
<th>qψ</th>
<th>Btmax (T)</th>
<th>ηe (%)</th>
<th>ηNBI (%)</th>
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<tbody>
<tr>
<td>Plasma size</td>
<td>5.5 ~ 8.5</td>
<td>2.6 ~ 4.0</td>
<td>1.8, 1.9, 2.0</td>
<td>0.35, 0.45</td>
<td>12 ~ 20</td>
<td>3.0 ~ 6.0</td>
<td>13, 16, 19</td>
<td>30, 40</td>
<td>30, 50, 70</td>
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Plasma Performance Required to Generate Net Electric Power \( \beta_N \)

\( \beta_N \) required for net electric power

- \( P_{e\text{net}} = 0 \text{ MW} \)
  
  \( 1.2 \leq \beta_N \leq 2.7 \)

- \( P_{e\text{net}} = 1000 \text{ MW} \)
  
  \( 3.0 \leq \beta_N \leq 5.8 \)

ITER inductive operation mode (\( \beta_N = 1.8 \)) corresponds to \( P_{e\text{net}} = 0 \text{MW} \) region

**Effect of restriction \( P_{\text{NBI}} \)**

The operational region is enlarged with the increasing the restriction PNBI

\( P_{e\text{net}} = 1000 \text{ MW} \) case

\( P_{\text{NBI}} \leq 100 \text{ MW} \) and \( 3.5 \leq \beta_N \)  \( \Rightarrow \)  \( P_{\text{NBI}} \leq 300 \text{ MW} \) and \( 2.7 \leq \beta_N \)
Plasma Performance Required to Generate Net Electric Power ---HH---

HH required for net electric power

- $P_{e_{\text{net}}} = 0 \text{ MW}$
  - $0.8 \leq HH \leq 2.2$

- $P_{e_{\text{net}}} = 1000 \text{ MW}$
  - $0.9 \leq HH \leq 1.6$

**ITER inductive operation mode (HH=1.0) is included in $P_{e_{\text{net}}} = 0 \text{ MW}$ region**

**Effect of restriction $P_{\text{NBI}}$**

The operational region is enlarged with the increasing the restriction $P_{\text{NBI}}$

- $P_{e_{\text{net}}} = 1000 \text{ MW}$ case
  - $P_{\text{NBI}} \leq 100 \text{ MW}$ and $1.1 \leq HH \Rightarrow P_{\text{NBI}} \leq 300 \text{ MW}$ and $0.8 \leq HH$
Plasma Performance Required to Generate Net Electric Power ---fn_{GW}---

\[ fn_{GW} \text{ required for net electric power} \]

- \( P_{e}^{\text{net}} = 0 \text{ MW} \)
  \[ 0.4 \leq f_{n_{GW}} \leq 1.1 \]

- \( P_{e}^{\text{net}} = 1000 \text{ MW} \)
  \[ 0.9 \leq f_{n_{GW}} \leq 2.0 \]

ITER inductive operation mode (\( fn_{GW} = 0.85 \)) corresponds to \( P_{e}^{\text{net}} = 0 \text{ MW} \) region.

Effect of restriction \( P_{\text{NBI}} \)

The effect of restriction \( P_{\text{NBI}} \) is not described in case of the required \( fn_{GW} \).
Correlation between Plasma Performances

Both $f_{n_{GW}}$ and $\beta_N$ have to be increased together so as to increase the net electric power.

No clear relationship between $f_{n_{GW}}$ and $H_H$.

No clear relationship between $\beta_N$ and $H_H$.

There is no operational point under $H_H \leq 0.8$, of course, which is depending on the restriction $P_{NBI}$.

Existence of inevitable $HH$ value.
Plasma Performance Diagram for the Net Electric Power Generation ---R=8.5m---

\[ P_{\text{net}} = 0 \text{ MW and } P_f = 1000 \text{ MW} \]
\[ \beta_N = 1.5, \text{ HH} = 1.0 \]

\[ P_{\text{net}} = 600 \text{ MW and } P_f = 3000 \text{ MW} \]
\[ \beta_N = 3.0, \text{ HH} = 1.15 \]

Requirement to increase \( P_{\text{net}} \)

\[ \beta_N \text{ and } f_{\text{GW}} \]
- Increase together

\[ \text{HH} \]
- Not necessary to increase
- Depending on the restriction \( P_{\text{NBI}} \)

In comparison with the present ITER experimental plan

The outlook of both \( P_{\text{net}} = 0 \text{MW} \) and \( P_{\text{net}} = 600 \text{ MW} \) will be obtained.
In comparison with the present ITER experimental plan

The outlook of both Penet =0MW and Penet=600 MW will be obtained.
In comparison with the present ITER experimental plan

The outlook of Penet =0MW will be obtained, but it is difficult to achieve Penet=600MW.
Typical electric break-even condition

Typical operation point for each major radius and each net electric power in the previous figures.

- HH \sim 1.0 \text{ for } P_{e}^{\text{net}}=0\text{MW operation points}
- HH \sim 1.2 \text{ for } P_{e}^{\text{net}}=600\text{MW operation points}

ITER experimental region covers wide range of operation point from $\beta_N=1.8$ to $\beta_N=3.6$.

How small device is feasible for Demo depends on how high plasma performance is achieved in ITER.

\[ \kappa = 1.9, \quad B_{t_{\text{max}}} = 16\text{ T}, \quad \eta_e = 30\%, \quad \eta_{\text{NBI}} = 50\% \]
Advancement of engineering condition

Engineering Conditions for economic break-even condition

- $B_{\text{tmax}} = 16T$, $\eta_e = 40\%$, $P_e^{\text{net}} = 1000$MWe, other condition are the same as the previous electric breakeven analysis.
- Plant availability 60%, an unexpected outage is considered
- Including **without CS coil case (CS-less case)**, Note that full non-inductive current ramp-up is required
Economic break-even condition $\beta_N$

$\beta_N$ required for breakeven price

Higher limit of breakeven price (135mil/kWh) $\beta_N \geq 2.5$ is required

Lower limit of breakeven price (60mil/kWh) $\beta_N \geq 5.0$ and $R_p < 5.5$ m is required.

◆ In the lower limit of $5.5m < R_p < 6.5m$, simplified radial build without CS coil is required.
◆ Upper limit of breakeven price is possible to be attained by $\beta_N \geq 2.5$, which is examined in the ITER advanced operation model.

$k = 1.9, B_{\text{tmax}} = 16$ T, $\eta_e = 40\%$, $\eta_{\text{NBI}} = 50\%$
HH required for breakeven price

- The higher HH is the lower COE is, because of reduction of the cost for the current drive system.
- In contrast with $\beta_N$, the required HH region is almost the same through the range of $5.5m < R_p < 8.5m$.
- The important suggestion is that there is no path with $HH < 0.9$ to introduction of the tokamak fusion reactor into the long term world energy scenario.
Dependence of COE on $B_{tmax}$

- The increase of $B_{tmax}$ is very effective for the mitigation of the required $\beta_N$ under the condition of including the simplified radial build without a CS coil.
- The increase of $B_{tmax}$ increases the lowest limit of COE under the condition of the same critical current density of TF coils, because the increase of the coil volume or the device size, and the lower limit of COE range of 19T increases up to 90mill/kWh.
- CREST ($R_p=5.4$, $\eta_e41\%$, $B_{tmax}=13T$) is near the breakeven price of 65mill/kWh.

To get the merit of high magnetic field, the current density of super conductor also has to be improved. When current density about 20MW/m$^2$ of TF coils is feasible with the same cost as a 10MA/m$^2$ coil, the merit of high field is clearly seen.
**Electric Breakeven condition**

$\beta_N \geq 2.0$, $HH \geq 1.0$, steady state operation technique, max. magnetic field $16T$, thermal efficiency $\eta_e = 30\%$ lead to achieve the electric breakeven condition.

The electric breakeven condition requires the simultaneous achievement of $1.2 < \beta_N < 2.7$, $0.8 < HH$, and $0.3 < fn_{GW} < 1.1$ under the condition of $B_{tmax} = 16T$, $\eta_e = 30\%$, and $P_{NBI} < 200MW$. It should be noted that the relatively moderate conditionns of $\beta_N \sim 1.8$, $HH = 1.0$, and $fn_{GW} \sim 0.9$, which correspond to the ITER reference operation parameters, have a strong potential to achieve the electric breakeven condition.

**Economic Breakeven condition**

$\beta_N \geq 3.0$, $HH \geq 1.0$, $\eta_e > 40\%$ leads to the upper limit of breakeven price and to the possibility for fusion energy to be introduced into the world energy scenario. To prepare for a severe breakeven price ($65\text{mill/kWh}$), $\beta_N > 5.0$ with $R_p < 5.5m$ should be aimed at.

The economic breakeven condition requires $\beta_N \sim 2.5$ for $135\text{mill/kWh}$ of higher breakeven price case and $\beta_N \sim 5.0$ for $65 \text{ mill/kWh}$ of lower breakeven price case under the conditions of $B_{tmax} = 16T$, $\eta_e = 40\%$, plant availability 60%, and feasibleness of a simplified radial build without CS coils. The demonstration of steady state operation with $\beta_N \sim 3.0$ in the ITER project leads to the prospect to achieve the upper region of breakeven price in the world energy scenario. This $\beta_N$ requirement will be somewhat mitigated with higher $B_{tmax}$. 
System Analysis Code (FUSAC)

Calculation Flow

Input and initial calculation
- $q_v$, $\beta_N$, $T_{ave}$, $R_p$, $a_p$, $B_{max}$, $B_i$

- plasma current $I_p$
- beta value $\beta_{th}$, $\beta_{th}$
- plasma density $n_e$, $n_i$

- total fusion power $P_f$

- driving and bootstrap current $I_{CD}$, $I_{BS}$

- confinement property $W_{th}$, $\tau_E$, $HH$, $f_{n_{GW}}$

- current driving power $P_{NBI}$

- total thermal output $P_{th}$
- neutron wall load $P_{nw}$

- circulating electric power $P_{circ}$

- gross electric power $P_{gross}$

- net electric power $P_{net}$

Output of Result

- elevation view
- plane view
- radial build
\( f_{GW} \) and Operation Temperature

- The required \( f_{GW} \) decreased with increasing operation temperature.
- \( \beta_N \) is almost constant.

The operation temperature will be optimized.
The effect of thermal efficiency

R=7.5 m and $\eta_e=40\%$ case

$P_{e\text{net}}=0$ MW and $P_f=1000$ MW
$\beta N=1.5$, HH=0.9

$P_{e\text{net}}=900$ MW and $P_f=3000$ MW
$\beta N=3.4$, HH=1.15

The $\eta_e$ progress will decrease the required plasma performances with the same $P_{e\text{net}}$, or increase the net electric power with the same plasma performance.

To get the economical outlook, the $\eta_e$ progress is inevitable.
The effect of NBI system efficiency

R=7.5 m and $\eta_{\text{NBI}}=30\%$ case

$P_{\text{e, net}}=0$ MW and $P_f=1000$ MW

$\beta_N=1.8$, HH=1.4

$P_{\text{e, net}}=450$ MW and $P_f=3000$ MW

$\beta_N=3.4$, HH=1.15

The $\eta_{\text{NBI}}$ is critical to the required HH, especially, in the low Penet region.

The $\eta_e$ progress should be almost completed by the demo reactor stage.
Increase of $B_{\text{tmax}}$ from 13T to 19T

- The required $\beta N$ decrease
- The operational region is shrank

In case of $B_{\text{tmax}}=19T$, the current ramp-up is not possible by CS coil, or 1.4m space for blanket and shield cannot be accommodated ($R<7.5$).