Burning Simulation and Life-Cycle Assessment of Fusion Reactors

Kozo YAMAZAKI

Nagoya University, Nagoya 464-8603, Japan

(with the help of T. Oishi, K. Mori, Y. Hori and K. Ban)
OUTLINE

1. Introduction

2. Burning Simulation using “TOTAL”
   (Toroidal Transport Analysis Linkage)
   ITB, D/T ratio, Impurity

3. Life-Cycle Assessment using “PEC”
   (Plasma, Engineering and Cost)
   Cost, CO2, Energy Payback etc.

4. Summary
1. Introduction

Searching for Attractive Fusion Reactor
In our small Laboratory

Small Experiment
Burning Simulation
Reactor Assessment

TOKASTAR

Toroidal Transport Analysis Linkage

Physics, Engineering, Cost
2. Burning Plasma Simulation: “TOTAL” Code History

Start (~1980)
Tokamak (2\textsuperscript{nd} stability)


Helical Analysis


Burning Simulation (Tokamak & Helical)


Based on JT-60U ITB operation and LHD e-ITB data.
### Core Plasma
- **Equilibrium**
  - Tokamak: 2D APOLLO
  - Helical: 3D VMEC, DESCUR, NEWBOZ
- **Transport**
  - Tokamak: TRANS, GLF23, NCLASS
  - Helical: HTRANS, GIOTA
- **Stability** NTM, Sawtooth, Ballooning mode

### Edge Transport
- H-mode edge transport

### Impurity
- IMPDYN (rate equation) Tungsstein
- ADPAC (various cross-section)

### Fueling
- NGS (neutral gas shielding) model
- mass relocation model
- NBI HFREYA, FIFPC
- Puffing AURORA

### Divertor
- density control, two-point divertor

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**Main Feature of “TOTAL” is to perform both Tokamak and Helical Analyses**

**TOTAL**

- World Integrated Modeling
  - TOTAL-T,-H(J)
  - TOPICS(J)
  - TASK(J)
  - CRONOS(EU)
  - TRANSP(US)
  - ASTRA(RU)
Present Research Issues Using “TOTAL” Code

- Advance Reactor Operation Scenario with ITB assisted by Pellet Injection
- D/T fuel ratio adjustment for burn control
- High-Z impurity (Tungsten) Effect and Diverter Analysis
- NTM Effects on Burning Properties
- BS Current Fraction in ST reactor Stable against Ballooning Mode
Time evolution of reversed-shear-mode operation with continuous HFS pellet injection

1GWe Tokamak Reactor TR-1

(a) Power (MW)
- $P_\alpha$
- $P_{RF}$
- $P_{\text{radiation}}$

(b) Temperature & density
- $<T>$
- $<T_\text{e}>$
- $<n_\text{e}>$

(c) Electron density [$10^{19} \text{ m}^{-3}$]
- 0sec
- 10sec
- 20sec
- 60sec
- 80sec
- 100sec

(d) Electron temperature [kV]
- 0.4sec
- 0.8sec
- 2sec
- 4sec
- 20sec
- 40sec
- 100sec

Ignition **Tokamak** Design (~1980, PPPL)
Helical Design Assessment

Helical & **Tokamak** Assessment
  *IAEA-Lyon* (2002)

Cost/CO$_2$/EPR Analysis in MFE reactors

Cost/CO$_2$/EPR Analysis in MFE & IFE reactors
  *IAEA-Daejeon* (2010)
Main Feature is Comparative Assessment of Various Reactors

Thanks to US data (ARIES Group)

**MFE**

- Plasma beta value $\beta$
- Ignition margin
- Target Electric Output (MWe)

**Assumption of**

1. Thickness of Blanket (m)
2. Plasma major radius $R_p$ (m)

**Plasma Parameters**

**Power Balance**

**Check** $P_{\text{target}}, t_{\text{blanket}}, igm$

**Final Radial Build**

**Output**

- Cost & CO2 emission amounts

**IFE**

- Driver Energy (MJ)
- Driver Efficiency (%)
- Target Electric Output (MWe)

**Assumption of**

- Repetition Ratio $f_{\text{rep}}$ (Hz)

**Fuel Mass (g)**

**Fusion Energy (MJ)**

**Power Balance**

**Check $P_{\text{target}}$**

**Final Radial Build**

**Output**

- Cost & CO2 emission amounts
International Comparisons of Present Commercial COE

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<th>Country</th>
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<tr>
<td>Korea</td>
<td>0.09</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Data from OECD/IAE Energy Prices and Taxes (2009)
Multiple Approaches Have Similar COE

Tokamak Reactor 9.8¢/kWh
Spherical Torus 10.4¢/kWh
Helical Reactor 11.1¢/kWh
Inertial Reactor 10.7¢/kWh

1GWe Plant
Power Dependence on COE, CO₂ rate

Capital Cost ~ $P^{0.5}$
C.O.E. ~ $P^{-0.5}$
CO₂ Rate ~ $P^{-0.3}$
Power Dependence of IFE is similar to that of MFE

- IFE
- COE
- CO₂
- Capital Cost
- f_{rep}\ (Hz)
- CO₂ (g/kWh)

Capital Cost (B$)

p_{target} (MW)
New Scaling Laws are derived

\[
COE^{TR} [\text{mil/kWh}] = 10^{2.09} \frac{1}{P_e^{0.48} f_{\text{avail}}^{0.90} \beta_N^{0.40} B_{\text{max}}^{0.12} f_{\text{th}}^{0.32} t_{\text{oper}}^{0.78}}
\]

\[
COE^{HR} [\text{mil/kWh}] = 10^{3.96} \frac{1}{P_e^{0.50} f_{\text{avail}}^{0.93} <\beta>^{0.31} B_{\text{max}}^{0.60} f_{\text{th}}^{0.26} t_{\text{oper}}^{0.84}}
\]

\[
COE^{IR} [\text{mil/kWh}] = 10^{3.23} \frac{1}{P_e^{0.51} f_{\text{th}}^{0.33} f_{\text{avail}}^{0.90} t_{\text{oper}}^{0.75} \left(\frac{1}{\alpha_F}\right)^{0.23}}
\]

\[
CO_2^{TR} [\text{g – CO}_2/\text{kWh}] = 10^{1.60} \frac{1}{P_e^{0.26} f_{\text{avail}}^{0.43} \beta_N^{0.21} B_{\text{max}}^{0.05} f_{\text{th}}^{0.25} t_{\text{oper}}^{0.043}}
\]

\[
CO_2^{HR} [\text{g – CO}_2/\text{kWh}] = 10^{2.57} \frac{1}{P_e^{0.26} f_{\text{avail}}^{0.53} <\beta>^{0.33} B_{\text{max}}^{0.63} f_{\text{th}}^{0.35} t_{\text{oper}}^{0.54}}
\]

\[
CO_2^{IR} [\text{g – CO}_2/\text{kWh}] = 10^{2.34} \frac{1}{P_e^{0.31} f_{\text{th}}^{0.25} f_{\text{avail}}^{0.37} t_{\text{oper}}^{0.39} \left(\frac{1}{\alpha_F}\right)^{0.18}}
\]
Comparisons with Other Power Plants

- Wind *
  - $/kWh: 13.2
  - g-CO2/kWh: 29.5

- Solar *
  - $/kWh: 62.3
  - g-CO2/kWh: 53.4

- Water *
  - $/kWh: 11.2
  - g-CO2/kWh: 11.3

- Coal *
  - $/kWh: 5.4
  - g-CO2/kWh: 21.6

- Oil *
  - $/kWh: 10.1

- Fission *
  - $/kWh: 5

- IR
  - $/kWh: 10.7
  - g-CO2/kWh: 12.9

- TR (D-3He)
  - $/kWh: 9.4
  - g-CO2/kWh: 12.4

- TR (F-F)
  - $/kWh: 8.7
  - g-CO2/kWh: 10.4

- HR
  - $/kWh: 11.1
  - g-CO2/kWh: 9.9

- ST
  - $/kWh: 10.4
  - g-CO2/kWh: 9

- TR
  - $/kWh: 9.8
  - g-CO2/kWh: 9.2

Hondo et al., Socio-economic Research Center (2000)

* 1¢~1\"
CO$_2$ Tax combines Cost and CO$_2$
4. Summary

- Comparative system studies have been done for several magnetic fusion energy (MFE) reactors and inertial fusion energy (IFE) reactor.
- We clarified new scaling formulas for cost of electricity (COE) and GHG emission rate with respect to key design parameters.
- The comparisons with other conventional electric power generation systems are carried out taking care of the GHG taxes and the CCS (carbon dioxide capture and storage) system to fossil power generators.