Development Scenario of Tokamak Reactor for Early Demonstration of Electric Power Generation

US/Japan Workshop on Power Plant Studies and Related Advanced Technologies With EU Participation

24-25 January 2006, 584 EBUII (Engineering Building Unit II), UC San Diego, La Jolla, CA

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\textsuperscript{c)} The University of Tokyo, Kashiwa, Japan
Outline

1. **Background and Objectives**
   Why is a development scenario required and what is its objectives?

2. **A development scenario of ITER, Demo-CREST and CREST**
   Characteristics of this development scenario, ITER, Demo-CREST, and CREST

3. **Development issues on plasma performance**
   What is the critical issue on the core plasma performance and to what extent it has to be developed in each step?

4. **Development issues on reactor technology**
   What is the critical issue on the reactor technology and to what extent it has to be developed in each step?

5. **Role of each development program**
   Specification of the role of each development program (ITER, IFMIF, DEMO, inevitable support program) in this development scenario

6. **Summary**
Development scenario of tokamak fusion power plant

Tokamak devices
JT-60U, JET etc
Feasibility of burning plasma
From 1980’s to present

Experimental Reactor
ITER
Feasibility of net electric power generation
From 2015 to 2035

Demonstration Reactor
Demonstration of net electric power generation
In 2030~2040

Commercial Plant
Introduction into market
In 2050~

How about the development scenario after the ITER?

In this study
Development Scenario
Development Goal
Development Time Schedule
Technological and physical Issue to be completed
Development Priority
Specification of the role of each development program

Effective Development Road Map to Realize the Fusion Energy
Objectives

Key issues of development scenario
1. Development Goal
   Reactor type (Plasma Physics)
   Tokamak → variation of aspect ratio, Max.Bt
   (Helical → variation of plasma configuration)
   (Laser → central spark ignition)
   Engineering
   Blanket → Coolant, Breeder
   Maintenance scheme → sector type, module type

2. Development time schedule and the role of Demo
   When is the commercial plant?
   → 2050’s is assumed
   When is the demo?
   → available plasma performance and technology
   → the role of demo toward the commercial plant

Now, the role of development scenario is to show several development path to fusion energy and its critical issues. (If possible, select the master plan and feed back to ITER and other R&D project).

Those help us to propose the appropriate next project when the ITER is completed.
Overall Feature of Development Scenario

- The demonstration of electric power generation in the 2030’s is focused on. That means Demo-CREST has to be constructed just after or during the ITER project.
- Testing by ITER is an important policy in this development scenario of Demo-CREST and CREST. This leads to the selection of $A=3.4$.
- This development scenario is characterized by an **advanced tokamak plasma reactor** with a **water cooled RAF (Reduced Activated Ferritic Steel) blanket system**.
Principles for the Demo-CREST Design

1. to demonstrate electric power generation as soon as possible in a plant scale, with moderate plasma performance which will be achieved in the early stage of the ITER operation, and with foreseeable technologies and materials (Demonstration Phase OP1~OP4)

2. to show a possibility of an economical competitiveness with advanced plasma performance and high performance blanket systems, by means of replacing breeding blanket from the basic one to the advanced one (Development Phase OP4, OPRS)

<table>
<thead>
<tr>
<th>OP</th>
<th>OP2</th>
<th>OP3</th>
<th>OP4</th>
<th>OPRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m) / A</td>
<td>7.25 / 3.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>κ/δ</td>
<td>1.85 / 0.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>qmin/q95</td>
<td>-/5.0</td>
<td>-/5.2</td>
<td>3.6 / 6.5</td>
<td></td>
</tr>
<tr>
<td>βN</td>
<td>1.9</td>
<td>2.5</td>
<td>3.0</td>
<td>3.4</td>
</tr>
<tr>
<td>HH</td>
<td>0.96</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>fnGW</td>
<td>0.56</td>
<td>0.73</td>
<td>0.80</td>
<td>1.02</td>
</tr>
<tr>
<td>Pb (MW)</td>
<td>188</td>
<td>190</td>
<td>185</td>
<td>191</td>
</tr>
<tr>
<td>Pf (MW)</td>
<td>1260</td>
<td>1940</td>
<td>2460</td>
<td>2840</td>
</tr>
<tr>
<td>Penet (MWe)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic Blanket</td>
<td>30</td>
<td>230</td>
<td>390</td>
<td>490</td>
</tr>
<tr>
<td>Advanced Blanket</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>850</td>
</tr>
</tbody>
</table>
The aim of CREST design is to show the typical development goal to get the economic competitiveness.

<table>
<thead>
<tr>
<th>High beta $\beta_N \approx 5.5$</th>
<th>Reversed Shear Profile control and high speed plasma rotation</th>
<th>High efficiency $\eta_{th} &gt; 40%$</th>
<th>High thermal efficiency $\eta_{th} \approx 41%$ Advanced ferritic steel component with water cooled system</th>
</tr>
</thead>
<tbody>
<tr>
<td>High $\kappa$ and $\delta$ $\kappa \approx 2.0, \delta \approx 0.5$</td>
<td>Active and passive feedback coils</td>
<td>Quick Maintenance</td>
<td>Full sector removal design for blanket (14 sectors) High availability (&gt;80%)</td>
</tr>
</tbody>
</table>

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R (m) / A$</td>
<td>5.4 / 3.4</td>
</tr>
<tr>
<td>$\kappa / \delta$</td>
<td>2.0 / 0.5</td>
</tr>
<tr>
<td>$B_t (T) / I_p (MA)$</td>
<td>5.6 / 12</td>
</tr>
<tr>
<td>$q_o / q_{min} / q_{95}$</td>
<td>2.9 / 2.4 / 4.3</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>5.5</td>
</tr>
<tr>
<td>$HH$</td>
<td>1.5</td>
</tr>
<tr>
<td>$f_{GW}$</td>
<td>1.3</td>
</tr>
<tr>
<td>$f_{bs}$</td>
<td>0.83</td>
</tr>
<tr>
<td>$P_b (MW) / E_b (MeV)$</td>
<td>97 / 2.5</td>
</tr>
<tr>
<td>$P_f (MW)$</td>
<td>2970</td>
</tr>
<tr>
<td>$P_e / P_{enet} (MWe)$</td>
<td>1385 / 1163</td>
</tr>
</tbody>
</table>

**Figure:** Bird’s-eye of CREST
• In the demonstration phase of Demo-CREST, the plasma performance parameters ($\beta_N$, HH, $f_{nGW}$) completed in ITER are applied to the Demo-CREST operation, step by step

• In the development phase, the advanced blanket system for higher thermal efficiency enable to increase the net electric power, and conducting walls installed in this blanket system break the road to the more advanced plasma performance such as $\beta_N > 4.0$.

**Table: Electric power and technology advancement in Development scenario by CRIEPI**

<table>
<thead>
<tr>
<th>Reactor technology advancement</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>ITER</strong></td>
<td><strong>Demo-CREST</strong></td>
<td><strong>CREST</strong></td>
</tr>
<tr>
<td>R= 6.2m, a=2.0m</td>
<td>R=7.3m, a=2.13m</td>
<td>R= 5.4m, a=1.59m</td>
</tr>
<tr>
<td>$B_{t_{\text{max}}}$=13 T</td>
<td>$B_{t_{\text{max}}}$=16 T</td>
<td>$B_{t_{\text{max}}}$=13T</td>
</tr>
<tr>
<td><strong>Demonstration Phase</strong></td>
<td><strong>Development Phase</strong></td>
<td></td>
</tr>
<tr>
<td>$\eta_{\text{th}}&gt;30%$</td>
<td>$\eta_{\text{th}}&gt; 40%$</td>
<td></td>
</tr>
<tr>
<td><strong>ITER Reference Plasma</strong></td>
<td><strong>30MWe</strong></td>
<td><strong>850MWe</strong></td>
</tr>
<tr>
<td>$\beta_N=2.0$</td>
<td><em>(Electric break-even)</em></td>
<td></td>
</tr>
<tr>
<td>To get the Outlook for the DEMO</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ITER Advanced Plasma</strong></td>
<td><strong>490MWe</strong></td>
<td></td>
</tr>
<tr>
<td>$\beta_N=3.4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>To become the promising candidate of alternative energy source</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CREST-like Advanced Plasma</strong></td>
<td><strong>1090MWe</strong></td>
<td><strong>1163MWe</strong></td>
</tr>
<tr>
<td>$\beta_N=4.0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Development Phase</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_{\text{th}}&gt; 40%$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• In the development phase of Demo-CREST, the plasma performance parameters ($\beta_N$, HH, $f_{nGW}$) completed in ITER are applied to the Demo-CREST operation, step by step

• In the development phase, the advanced blanket system for higher thermal efficiency enable to increase the net electric power, and conducting walls installed in this blanket system break the road to the more advanced plasma performance such as $\beta_N > 4.0$.
As for $\beta_N$ and HH, the Demo-CREST parameters are possible in this HPSS ITER scenario, but \textbf{fn$_{GW}$ of OP4 for Demo-CREST is a little larger than that of ITER}. Hence, the physics of density limit and its attainable region should be examined in the ITER program.

In the development phase of Demo-CREST, \textbf{the $\beta_N$ value is larger than the ideal wall limit of the present ITER design ($\beta_N\sim3.8$)}. Hence, this advanced plasma region should be explored, by other support devices and by itself, and this is why we think \textbf{Support device is required}. In case that ITER would be improved to achieve $\beta_N>4.0$, of course, such high performance plasma should be demonstrated in the ITER burning plasma.

Finally, \textbf{the increase of plasma shape parameters from (k$\sim1.85$, $\delta\sim0.35$) to (k$\sim2.0$, $\delta\sim0.5$) is required to achieve $\beta_N\sim5.0$}, however, several improvement for positional instability is supposed to be required in the present design of Demo-CREST.

<table>
<thead>
<tr>
<th></th>
<th>ITER Ref.</th>
<th>HPSS</th>
<th>Demo-CREST OP1</th>
<th>OP4</th>
<th>OPRS</th>
<th>CREST</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_N$</td>
<td>1.9</td>
<td>3.6</td>
<td>1.9</td>
<td>3.4</td>
<td>4.0</td>
<td>5.5</td>
</tr>
<tr>
<td>HH</td>
<td>1.0</td>
<td>1.53</td>
<td>0.96</td>
<td>1.2</td>
<td>1.40</td>
<td>1.5</td>
</tr>
<tr>
<td>fn$_{GW}$</td>
<td>0.85</td>
<td>0.86</td>
<td>0.56</td>
<td>1.02</td>
<td>1.31</td>
<td>1.3</td>
</tr>
</tbody>
</table>
In the demonstration phase, plasma performance is improved from OP1 to OP4, assisted by the conducting wall at $r_{\text{wall}}=1.3a$ just behind the blanket modules. NTM probably appears even in the low $\beta_N$ region corresponding to OP1 and OP2.
Development Issue on Heat and Particle Control

• Peak power load on the targets is limited to $q_{\text{div}} < 10 \text{MW/m}^2$
• One of the key parameters is the upstream SOL density $n_s$
• One of the control issues is increase of $n_s$ without the degradation of core plasma performance.
• The radiation power required for $q_{\text{div}} < 10 \text{MW/m}^2$ and its fraction to total heating power gradually increase from ITER, Demo-CREST (from OP1 to OP4), to CREST.

Design condition, $n_s \sim 2/3 < n_e$ enables to keep $q_{\text{div}} < 10 \text{MW/m}^2$ by using impurity seeding in the SOL region in the design of Demo-CREST, CREST

The ITER design is carried out with the conventional case of $n_s \sim 1/3 < n_e$

Controllability of $n_s$ and impurity seeding level consistent with core plasma performance has to be precisely examined in ITER, and its operational window should be mapped out for the next step devises.
In the Demo-CREST design, maximum performance of superconducting coil is 16T 10MA/m² for TF coils (15MA/m² for CS coils), which is higher maximum magnetic field strength ($B_{\text{tmax}}$) with the same coil current density (Jsc) as the ITER design.

In the CREST design, $B_{\text{tmax}}$≈13T, but higher Jcs (twice of the ITER design) is required.

$\text{Nb}_3\text{Al}$ has a good potential.

Figure Operating points of superconducting coils constructed so far and the target for fusion demo plant[N.Koizumi, et al., 20th IAEA Fusion Energy Conf. IAEA-CN116-FT/P1-7]
Development Issue on Blanket Concept

• The same outlet coolant condition (15MPa, 603K) as proposed in ITER TBM is applied, and this condition accepts the large breeding zone and the small cooling channel one in the blanket, because of relatively low temperature. In this blanket concept, the local TBR is estimated at 1.48, which allows the net TBR larger than 1.1.

• In the development phase of Demo-CREST, an advanced coolant condition (25MPa, 773K) with supercritical water, which is also proposed in ITER TBM, is applied. The local TBR of this advanced blanket system is TBR~1.34. Whether this local TBR is enough or not should be conformed in the previous demonstration phase.

<table>
<thead>
<tr>
<th></th>
<th>Demo-CREST Blanket</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic</strong></td>
<td>Advanced</td>
</tr>
<tr>
<td>Structure material</td>
<td>RAF</td>
</tr>
<tr>
<td>Breeding material</td>
<td>Li$_2$TiO$_3$</td>
</tr>
<tr>
<td>Neutron multiplier</td>
<td>Be(&lt;773K)</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water (603K, 15MPa)</td>
</tr>
<tr>
<td>Local TBR</td>
<td>1.48</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>&gt;30%</td>
</tr>
<tr>
<td>Note</td>
<td>Conducting wall</td>
</tr>
</tbody>
</table>

Basic blanket

Advanced blanket
Development Issue on Plasma Control Device

ITER

• Beam energy $E_b \sim 1.0$ MeV
• System efficiency $\eta_{\text{NBI}} = 30\sim40\%$
• Gyrotron frequency $f \sim 170$ Mz for ECCD

Demo-CREST

• Steady state operation of the NBI system and the EC one
• Beam energy $E_b \sim 1.5$ MeV for feasible current control.
• System efficiency $\eta_{\text{NBI}} > 50\%$ by developing a plasma neutralizer
• Gyrotron frequency $f \sim 300$ Mz for ECCD

CREST

• Beam energy $E_b \sim 2.5$ MeV
Development Issue on Maintenance Method

The handling device for shielding plugs in ITER can handle the weight of 40 tons.

The handling device is considered as a device scaled up form the one for the ITER shielding plug. The maximum weight to be handled in Demo-CREST is 130 tons of the outer shield.

- A larger TF coil
- A heavier full sector

The full sector removal scheme for blanket and divertor systems is applied to the CREST design. The weight of the one sector (1/14 of the torus) is estimated at about 250 tons.

The full sector removal scheme is very effective to the plant availability. In the CREST design, the plant availability achievable to more than 80% including an unexpected outage period. However, a system for extraction and attachment of the full sector with precise alignment has to be developed and demonstrated like the ITER maintenance system.
Development Issue on Structure Material

• For the demonstration phase of Demo-CREST, the reduced activation ferritic steel (RAF) has a good potential, however, it should be noted that the neutron fluence experienced in ITER is not enough for Demo-CREST, because of neutron fluence 6~9 MWa/m² (2.25FPY) more than that of ITER. Hence, the IFMIF program is indispensable.

• In the development phase of Demo-CREST, the oxide dispersion strengthened reduced activation ferritic steel (ODS-RAF) is probably required as the structure material for higher thermal efficiency. The advanced blanket system made of ODS-RAF also should be demonstrated in the ITER TBM program.

• In the CREST design, the design condition becomes more severe. More advancement up to 10~15 MWa/m² (2.25FPY) is required.

Figure Design windows for the structural materials for the DEMO reactor blanket. [M.Seki, et al., Fusion Science and Technology 42(2002)50]
## Role of Each Development Program for Demo-CREST Demonstration Phase (1)

### Plasma Physics Issues

<table>
<thead>
<tr>
<th>Development Issues for Demo-CREST demonstration phase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ITER</strong></td>
</tr>
<tr>
<td>• NTM stabilization in a burning plasma</td>
</tr>
<tr>
<td>• RWM n=1 mode stabilization by both of the plasma rotation and control coils</td>
</tr>
<tr>
<td>• Demonstration of a steady state burning plasma operation</td>
</tr>
<tr>
<td>• $f_{GW} \sim 1.0$ with advanced plasma</td>
</tr>
<tr>
<td>• Small non-inductive current ramp up of $f_{nonramp} \sim 0.2$</td>
</tr>
<tr>
<td>• Accessibility for high $n_s \sim 0.67 \langle n_e \rangle$ with the radiated SOL-divertor plasma</td>
</tr>
<tr>
<td><strong>Support Device</strong></td>
</tr>
<tr>
<td>• Steady state operation technique applicable to demonstrate electric power generation</td>
</tr>
<tr>
<td><strong>Demo-CREST</strong></td>
</tr>
</tbody>
</table>
## Role of Each Development Program for Demo-CREST Demonstration Phase (2)

### Engineering Issues

<table>
<thead>
<tr>
<th>Development Issues for Demo-CREST demonstration phase</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ITER</strong></td>
</tr>
<tr>
<td>• Outlet coolant condition (15MPa, 600K) of TBM for $\eta_{th}=30%$</td>
</tr>
<tr>
<td>• Assured prospect for self-sustainment of tritium</td>
</tr>
<tr>
<td><strong>IFMIF</strong></td>
</tr>
<tr>
<td>• Demonstration of RAF for neutron fluence up to 6~9 MWa/m² region</td>
</tr>
<tr>
<td><strong>Other R&amp;D</strong></td>
</tr>
<tr>
<td>• 16T 15MA/m² Nb₃Al coil for CS coil (16T 10MA/m² for TF coil)</td>
</tr>
<tr>
<td>• Development of RAF</td>
</tr>
<tr>
<td>• 1.5MeV beam energy of NBI</td>
</tr>
<tr>
<td>• High frequency gyrotron f&gt;300MHz for ECCD</td>
</tr>
<tr>
<td>• Scale up of handing device up to 130ton weight and maintenance scheme</td>
</tr>
<tr>
<td>• Effective tritium handling technique</td>
</tr>
<tr>
<td>• Waste management technique</td>
</tr>
<tr>
<td><strong>Demo-CREST</strong></td>
</tr>
</tbody>
</table>
# Role of Each Development Program for Demo-CREST Development Phase (1)

## Plasma Physics Issues

<table>
<thead>
<tr>
<th></th>
<th>Development Issues for Demo-CREST demonstration phase</th>
</tr>
</thead>
</table>
| **ITER**       | •Control technique for precise current alignment of reversed shear plasmas  
                 | •$f_{nGW} >1.0$ with the advanced plasma performance |
| **Support Device** | •RWM $n>1.0$ stabilization by both of the plasma rotation and control coils for $\beta_n>3.5$ |
| **Demo-CREST** |                                                        |
## Role of Each Development Program for Demo-CREST Development Phase (2)

### Engineering Issues

<table>
<thead>
<tr>
<th>Program</th>
<th>Development Issues for Demo-CREST demonstration phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER</td>
<td>• Outlet coolant condition (25MPa, 780K) of TBM for $\eta_{th}=40%$</td>
</tr>
<tr>
<td>IFMIF</td>
<td>• Demonstration of ODS-RAF for neutron fluence up to 6~9 MWa/m² region</td>
</tr>
<tr>
<td>Other R&amp;D</td>
<td>• Development of ODS-RAF with handling technique of supercritical water</td>
</tr>
<tr>
<td>Demo-CREST</td>
<td>• Assured margin of local TBR for net TBR $TBR_{net}&gt;1.1$</td>
</tr>
</tbody>
</table>
## Role of Each Development Program for CREST (1)

### Plasma Physics Issues

<table>
<thead>
<tr>
<th>Development Issues for Demo-CREST demonstration phase</th>
</tr>
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<tbody>
<tr>
<td><strong>ITER</strong></td>
</tr>
<tr>
<td>• Substantial non-inductive current ramp-up of ( f_{\text{nonramp}} \sim 0.5 )</td>
</tr>
<tr>
<td><strong>Support Device</strong></td>
</tr>
<tr>
<td>• RWM ( n&gt;1.0 ) stabilization only by the plasma rotation for ( \beta_N &gt; 4.0 )</td>
</tr>
<tr>
<td>• Control technique for positional instability close to ( \kappa \sim 2.0 ) and ( \delta \sim 0.5 )</td>
</tr>
<tr>
<td><strong>Demo-CREST</strong></td>
</tr>
<tr>
<td>• Accessibility for ( \beta_N \sim 5.0 ) of steady state burning operation</td>
</tr>
</tbody>
</table>
## Engineering Issues

<table>
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<th>Development Issues for Demo-CREST demonstration phase</th>
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<td><strong>ITER</strong></td>
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<td>• Demonstration of ODS-RAF for neutron fluence up to 10~15MWe/m² region</td>
</tr>
<tr>
<td><strong>Other R&amp;D</strong></td>
</tr>
<tr>
<td>• 13T 20MA/m² Nb₃Al coils</td>
</tr>
<tr>
<td>• 2.5MeV beam energy of NBI</td>
</tr>
<tr>
<td>• Sector removal maintenance scheme (sector weight is 250ton)</td>
</tr>
<tr>
<td><strong>Demo-CREST</strong></td>
</tr>
<tr>
<td>• Demonstration of the advanced blanket system for $\eta_{th}&gt;40%$ and $TBR_{net}&gt;1.1$</td>
</tr>
</tbody>
</table>
Summary

• We proposed the development scenario of ITER, Demo-CREST, and CREST aiming at the early realization of net electric power generation.
• This development scenario is characterized by a highly advanced tokamak plasma reactor with a water cooled RAF blanket system.
• As for plasma performance, MHD control for high plasma performance and heat and particle control are mainly discussed, and the role of each device (ITER, Demo-CREST, Support device) is specified, respectively.
• The typical development issue on the reactor technology (SC coils, blanket systems, plasma control devices, maintenance systems, structure materials) for Demo-CREST and CREST is also picked up, respectively.
• Such specification of each development role in the development scenario is the starting point to structure the effective development strategy of fusion energy, and this is very helpful to understand the development priority.