SiC Tokamak Reactor in JAERI

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2. Material Performance Comparison
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Japan Atomic Energy Research Institute
Naka Fusion Establishment
Fusion Material Development

- LA Ferritic Steel (1st Candi. for DEMO)
- V-alloy (Candi. for Comm.)
- SiC/SiC Comp. (Candi. for Comm.)

R&D Target Diagram

Setup of Power Core Components

Neutron Fluence (MWa/m², ~10dpa)

Max. Temperature (°C)
### Tokamak Reactor Design in JAERI

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>DEMO</td>
<td>Commercial</td>
<td>Commercial</td>
<td>Commercial</td>
</tr>
<tr>
<td>Plasma current</td>
<td>12MA</td>
<td>12MA</td>
<td>9.2MA</td>
<td>12MA</td>
</tr>
<tr>
<td>Major radius</td>
<td>7m</td>
<td>6m</td>
<td>16m</td>
<td>6.2m</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Toroidal field</td>
<td>9T</td>
<td>11T</td>
<td>14.5T</td>
<td>11T</td>
</tr>
<tr>
<td>Max. neutron load</td>
<td>5MW/m²</td>
<td>10MW/m²</td>
<td>4MW/m²</td>
<td>8MW/m²</td>
</tr>
<tr>
<td>Blanket heat flux</td>
<td>1MW/m²</td>
<td>2MW/m²</td>
<td>0.5MW/m²</td>
<td>2MW/m²</td>
</tr>
<tr>
<td>Div. heat flux</td>
<td>7MW/m²</td>
<td>4MW/m²</td>
<td>7MW/m²</td>
<td>4MW/m²</td>
</tr>
<tr>
<td>Neutron fluence</td>
<td>7MW/a/m²</td>
<td>14MW/a/m²</td>
<td>10MW/a/m²</td>
<td>12MW/a/m²</td>
</tr>
<tr>
<td>Max. coolant temp.</td>
<td>550°C</td>
<td>650°C</td>
<td>900°C</td>
<td>900°C</td>
</tr>
<tr>
<td>Fusion power</td>
<td>3GW</td>
<td>4.5GW</td>
<td>5.5GW</td>
<td>4.5GW</td>
</tr>
<tr>
<td>Current drive</td>
<td>60MW</td>
<td>60MW</td>
<td>50MW</td>
<td>60MW</td>
</tr>
<tr>
<td>Blanket Mat.</td>
<td>F82H</td>
<td>F82H</td>
<td>SiC/SiC</td>
<td>SiC/SiC</td>
</tr>
<tr>
<td>Coolant</td>
<td>P. Water</td>
<td>P. Water</td>
<td>He</td>
<td>He</td>
</tr>
<tr>
<td>Bulk Shield Mat.</td>
<td>F82H</td>
<td>F82H</td>
<td>SiC/SiC, TiH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>TiH&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Remote radiative cooling is fully expected.

Diagram: Needs Pull Sketch

Diagram: Needs Pull Sketch

Diagram: Needs Pull Sketch

Diagram: Needs Pull Sketch

Commercial

12MA

6m

4

11T

10MW/m²

2MW/m²

4MW/m²

14MW/a/m²

550°C

3GW

60MW

F82H

P. Water

F82H

SiC/SiC

He

SiC/SiC, TiH<sub>2</sub>

He

TiH<sub>2</sub>
Major Milestones on Road to Fusion Power Reactor

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone</th>
<th>Reactor</th>
<th>Technology</th>
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<tbody>
<tr>
<td>1985</td>
<td>Scientific Inspection</td>
<td>JT-60(JPN)</td>
<td>TFTR(US)</td>
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<tr>
<td></td>
<td>Demonstration of Burning and Reactor Technology</td>
<td>Exp. Reactor (ITER)</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Demonstration of Electric Power Plant</td>
<td>Proto Type Reactor</td>
<td>DREAM SSTR</td>
</tr>
<tr>
<td>~2030</td>
<td>Utilization</td>
<td>Acceptable COE</td>
<td>DREAM D-SSTR</td>
</tr>
<tr>
<td>~2050</td>
<td>Maturity</td>
<td>Matured Reactor</td>
<td></td>
</tr>
<tr>
<td>~2100</td>
<td></td>
<td></td>
<td></td>
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</table>
Cost Competitiveness of Fusion is not Promising.
Total Radwaste is 1900 Ton.

- $7.5 \times 10^{20}$ Bq (2.0 $\times 10^{10}$ Ci) for F82H
- $1.5 \times 10^{18}$ Bq (4.0 $\times 10^{7}$ Ci) for SiC/SiC

After Irradiation of 10MWA/m$^2$
- Induced Activity $10^{18}$ Bq/ton for SS, F82H
- $5 \times 10^{15}$ Bq/ton for SiC/SiC

D-SSTR
- SiC/SiC Weight of Replaceable Blanket is 125 Ton.
- Every 2 years Replacement and 30 years Life time.

Total Radio Activity
- F82H : $7.5 \times 10^{20}$ Bq (2.0 $\times 10^{10}$ Ci)
- SiC/SiC : $1.5 \times 10^{18}$ Bq (4.0 $\times 10^{7}$ Ci)

Dose Rate Rapid Decline of Pure SiC/SiC : < 1mSv/h for 1 month cooling
Even the F82H fusion plant can catch up with the coal plant within 15 years. BHP of a SiC/SiC fusion plant may be negligible.
### Radwaste Weight of Tokamak Reactor

**Classification Criteria**: JAERI Clearance Level

<table>
<thead>
<tr>
<th>Material</th>
<th>Low Level Waste</th>
<th>Medium Level Waste</th>
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<tbody>
<tr>
<td>SSTR (F82H)</td>
<td>3 MW/m²</td>
<td>2.5 MW/m²</td>
</tr>
<tr>
<td>DREAM (SiC/SiC)</td>
<td>2.5 MW/m²</td>
<td></td>
</tr>
<tr>
<td>ARIES-RS (V-alloy)</td>
<td>4 MW/m²</td>
<td></td>
</tr>
<tr>
<td>SEAFP2 (Martensite)</td>
<td>3 MW/m²</td>
<td></td>
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</table>

Medium level waste requires 30 years care before the burial.

- **is derived from impurities, hence can be replaced** by \( \square \).
Material Comparison from Neutronics Viewpoint

<table>
<thead>
<tr>
<th>Material</th>
<th>Activation Intensity for Maintenance (for replacement)</th>
<th>Neutron Shielding Effectiveness (for thickness)</th>
<th>Radwaste Quantity after Plant Life Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC/SiC</td>
<td>$\sim 10^{-7}$</td>
<td>0.2~0.3</td>
<td>Total: $1 \times 10^4$ Ton</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low Level: 60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Medium Level: 40% (N and Cl)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100%※</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0%※</td>
</tr>
<tr>
<td>F82H</td>
<td>1 ($3 \times 10^4$ Sv/h)</td>
<td>$\sim 0.7$</td>
<td>$\sim 0.8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15% (Impurity)</td>
</tr>
<tr>
<td>V-alloy</td>
<td>$\sim 10^{-1}$</td>
<td>$\sim 0.8$</td>
<td>$\sim 0.65$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>78% (Impurity)</td>
</tr>
<tr>
<td>TiH$_2$</td>
<td>$10^{-3} \sim 10^{-4}$</td>
<td>1</td>
<td>$\sim 0.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt; 90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 10%</td>
</tr>
</tbody>
</table>

※without impurity (N and Cl)

For power core components, the combination of SiC & TiH$_2$ is preferable. For conducting material, V-alloy is desirable.
Artist's Conception of DREAM Blanket Module

**Parameters**
- Structural Mat. : SiC/SiC Comp.
- Therm. Cond. : 15W/m/K
- Vessel Size : 500x500 mm
- Coolant : Helium
- Coolant Pres. : 10 MPa
- Coolant Temp. : 600/900 °C
- Coolant Vel. : 100 m/s
- Wall Load : 3 MW/m²

**Components**
- High Temp. Cooling Channel
- Low Temp. Cooling Channel
- Thermal Insulator
- Shield Pebble
- Tritium Breeder
- Neutron Multiplier
- First Wall
- Partition Wall
- Branch Pipe
Blanket & Divertor Modules of DREAM

**First Wall (SiC with 15 w/m/K)**

**Blanket Vessel Wall (SiC)**

**Partition Wall (Porous SiC)**

**Bolt (SiC)**

**Low Temp. Wall (SiC)**

**Helium**

**Breeder (Li2O)**

**Neutron Multiplier (Be)**

**Thermal Insulator**

**Helium Flow**

**MUSHROOM BLANKET MODULE**

*(Solution)*

\[ P_{FW} = 0.5 \text{ MW/m}^2 \]

**DIVERTOR MODULE**

*(No Solution)*

\[ P_{DIV} = 7 \text{ MW/m}^2 \]
Manufacturing Process of Blanket Module

第1壁  
First Wall

容器  
Vessl

繊維織込まれ程  
Textile Preform

含浸と高密度化  
Densification

機械加工と最終仕上  
Machining & Finishing

Chemical species:
- CH₄
- H₂
- He
- SiCl₄

Exhaust

Neutron Irradiation Degradation of SiC/SiC

Divertor Plate of Future Reactor Requires Unrealistically high Performance to SiC/SiC Composite.

2mm W / 10mm SiC

12mm W

Inevitable?
Thermal Stress on SiC/SiC

( High Heat Flux Component )

Blanket First Wall

- Design Stress of 200 MPa
- He Pressure: 10 MPa
- Heat Flux on FW: 0.5 MW/m²
- 2D Numerical (FEM)

Tresca Stress (MPa) vs. Thermal Conductivity (W/m/K)

Tresca Stress (MPa) vs. Thermal Conductivity (W/m/K)

Divertor Plate

- Design Stress
- 5 MW/m² (guess)
- 3 MW/m²
- 1 MW/m² (guess)
- Design Condition
- 2D Numerical (FEM)

SOLUTION OPTION

- Full W Use for Divertor Plate
- Full Remote Radiative Cooling in Divertor Region
- Development of Excellent SiC/SiC
Radial Build of D-SSTR

TiH$_2$ as Bulk Shield
Blanket Module of D-SSTR

Structure Material: SiC/SiC Comp. (Therm. Cond. of 15W/m/K)
Vessel Contents: 1φ Pebble Be and 1φ Pebble Li$_2$TiO$_3$
Coolant and T Purge Gas: He (10MPa & 600°C$_\text{IN}$/900°C$_\text{OUT}$)

Small Blanket (221.69kg)
- Be = 0.02875m$^3$ = 53.59kg
- Li$_2$TiO$_3$ = 0.05509m$^3$ = 121.6kg
- SiC/SiC = 0.01485m$^3$ = 46.5kg

Large Blanket (301.57kg)
- Be = 0.03625m$^3$ = 67.57kg
- Li$_2$TiO$_3$ = 0.07509m$^3$ = 165.7kg
- SiC/SiC = 0.02182m$^3$ = 68.3kg

1950 modules S(675), L(1275)
Bulk Shield Structure Filled with TiH$_2$

Vessel Material : SiC/SiC Comp.

Inboard Shield
( Permanent & Lifetime Use )

\[ \phi_{n^{IN}} = \begin{cases} 9 \times 10^{17} \text{ m}^{-2}\text{s}^{-1} (> 0.1 \text{MeV}) \\ 2 \times 10^{16} \text{ m}^{-2}\text{s}^{-1} (14 \text{MeV}) \end{cases} \]

Outboard Shield
( Replaceable but Lifetime Use )

\[ \phi_{n^{OUT}} = \begin{cases} 5 \times 10^{17} \text{ m}^{-2}\text{s}^{-1} (> 0.1 \text{MeV}) \\ 1 \times 10^{16} \text{ m}^{-2}\text{s}^{-1} (14 \text{MeV}) \end{cases} \]

Shielding effectiveness of TiH$_2$ is more superior than SiC/SiC by several times.
Neutron Wall Load in D-SSTR

D-SSTR: Compact and high power reactor
- Very high neutron wall load

Max. Flux = 8MW/m²
Average Flux = 6MW/m²

2 years Replacement
75% Availability

Max. Fluence 12MWa/m²
Radiation Shielding of SiC & TiH$_2$ Power Core
(D-SSTR Power Core Structure)

Neutron flux (E>0.1MeV)
- $0.9 \times 10^{13}$ n/m$^2$/s (inside)
- $1.0 \times 10^{13}$ n/m$^2$/s (outside)
after 22.5FPY

Neutron fluence (E>0.1MeV)
- $0.64 \times 10^{22}$ n/m$^2$ (inside)
- $0.71 \times 10^{22}$ n/m$^2$ (outside)

Max. Nuclear Heating
- $0.06$ mW/cm$^3$ (inside)
- $0.04$ mW/cm$^3$ (outside)

Enough Shielding can be expected in compact and high power reactor.
Shell Structure for Vertical Stability
5 cm thickness of V-alloy Saddle Loop

Growth rate: 40 Hz
- controllable by normal conductors outside vessel
- No vessel

Stabilizing Effect N(s)

Plasma elongation 1.8 can be accepted.
Shell Structure for High $\beta$ Stability

V-alloy with 46cm x 46cm x 2cm and Hole for He Gas Coolant

Neutron Flux: $2 \times 10^{16} \text{m}^{-2}\text{s}^{-1}$ (14MeV), $1 \times 10^{18} \text{m}^{-2}\text{s}^{-1}$ (>0.1MeV) $4 \times 10^{18} \text{m}^{-2}\text{s}^{-1}$ (Total)
Summary

Material use optimization for fusion power core components has been attempted in D-SSTR.

- SiC/SiC for Replaceable Blanket Structure Material
- TiH2 for Bulk Shielding material
- V-alloy for Conducting Material
- W for Divertor Plate