FEASIBILITY STUDY OF SMALL SODIUM COOLED FAST EACTORS

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Japan Atomic Energy Agency
Previous Studies
JAEA has studied about small sodium cooled reactors in the Feasibility Study.

- Modular Reactor for base load power source
- Remote Place Power Source (<50MWe)
- Multi-purpose Reactor (Hydrogen Production)
Large Scale Reactor
- High economic performance with scale effect
- High R&D risk

Modular Reactor
- High economic performance with standardization & Common use between units
- Low R&D risk

- IRIS, IMR, small BWR

- IFR
Purpose

Energy Resource Sustainability, Low Environmental Burden with MA transmutation

Proposal of a commercialize fast reactor with low R&D risk (major requirement)
- Economical competitiveness with large scale reactors
- Demonstration of reactor technologies
- Demonstration of economical performance including a whole fuel cycle system

Important for Commercialization

- Further cost reduction of modular fast reactor
- Evaluation of construction cost of a first kind of plant (FOAK) (demonstration plant) considering a whole fuel cycle system
Major Design Conditions

- Electric Output: 300MW-electric
- Fuel Type: U-TRU-Zr
- Reactor Type: Loop Type
- Spent Fuel Storage: In-vessel Storage (IVS)
- Main Cooling System: One-Loop Main Cooling System
- Main Pump: Electro Magnetic Pump (EMP)

Potential of Cost Reduction

Simple ex-vessel fuel handling system

Cost Reduction

Technology for one-loop main cooling system

MA transmutation

Low construction cost in the small fuel cycle facility
Core Design

Single Pu enrichment plural Zr content Regions Core

- Output: 714MW (300MW-electric)
- Operation Cycle: 2 years (4 batches)
- Burnup: 80GWd/t
- Outlet Temp.: 550deg-C

Core Diameter: 2.63m  Pin Diameter: 8.5mm
Core Height: 1m      S/A pitch: 157.2mm

- Inner core fuel S/A 81
- Outer core fuel S/A 162
- S.S. shielding 60
- Zr-H shielding 66
- Primary control rod 7
- Backup control rod 3

Reactor Vessel

L shape piping with high chromium steel*

Compact Rotating Plug with Slit UIS*

IVS with capacity for 4 years storage

*: Same technologies from JSFR

Reactor Cooling System

One-Loop Main Cooling System with Dual EMPs

Annular Linear Induction Pump Experience
44 m³/min: W. Kwant et al., ICONE-5, No. 2553, (1997)

Operation: 2550h
Efficiency: 40%
**IHX with Internal EMP**

<table>
<thead>
<tr>
<th>Internal EMP</th>
<th>Items</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature</td>
<td>395deg-C</td>
</tr>
<tr>
<td></td>
<td>Flow Rate</td>
<td>255m³/min</td>
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<tr>
<td></td>
<td>Pump Head</td>
<td>0.4MPa</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>IHX</th>
<th>Items</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity</td>
<td>714MW</td>
</tr>
<tr>
<td></td>
<td>Tube Outer Diameter</td>
<td>25.4mm</td>
</tr>
<tr>
<td></td>
<td>Tube Thickness</td>
<td>1.1mm</td>
</tr>
<tr>
<td></td>
<td>Tube Length</td>
<td>5m</td>
</tr>
<tr>
<td></td>
<td>Tube Quantity</td>
<td>4412</td>
</tr>
<tr>
<td></td>
<td>Tube Arrangement</td>
<td>Triangle</td>
</tr>
<tr>
<td></td>
<td>Tube Pitch</td>
<td>32mm</td>
</tr>
<tr>
<td></td>
<td>Heat Transfer Area</td>
<td>1700m²</td>
</tr>
<tr>
<td></td>
<td>Material</td>
<td>12Cr</td>
</tr>
</tbody>
</table>

*Dual EMPs*
Decay Heat Removal System

Two DRACS and one IRACS with Natural Convection

Penetration between Low and High Plenum with Flow Diode (Water Experiment in 2005)
Total Volume $65,100\text{m}^3$ for 300MW-electric
(Reactor Building of MONJU $207,000\text{m}^3$ for 280MW-electric)
## Construction Cost Estimation

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Structure</td>
<td>107</td>
</tr>
<tr>
<td>IHX</td>
<td>125</td>
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<tr>
<td>Primary Circuit Pump</td>
<td>122</td>
</tr>
<tr>
<td>Primary Circuit Piping</td>
<td>72</td>
</tr>
<tr>
<td>SG</td>
<td>276</td>
</tr>
<tr>
<td>Secondary Circuit Pump</td>
<td>330</td>
</tr>
<tr>
<td>Total</td>
<td>1037</td>
</tr>
</tbody>
</table>

*Except EMP stator 154tonne

**FOAK** 190% of Target (2,000$/kW, 1USD=100JPY)

**NOAK** 115%
Economic Competitiveness

Target for Large Scale Reactor in Future Japan 4 cents/kWh

300 MWe SFR-SMR has a potential for economic competitiveness versus large scale plant.
- JNC has studied about small sodium cooled Reactors since FY2001.

**Design Condition in the present study**

- Electric power 50MW
- Core life time 30y
- Without Refueling

**Simple Compact Reactor Vessel**
Core design

- Thermal output: 120MWt
- Electric output: 50MWe
- Fuel type: U-Pu-Zr ternary metal
- Outlet temperature: 550°C
- Core life time: 30年
- Burnup reactivity: 1.2%Δk/kk'
- Core height: 1.18m
- Core equivalent diameter: 1.82m
- Average discharge burnup: 74GW/dt

<table>
<thead>
<tr>
<th></th>
<th>Inner</th>
<th>Middle</th>
<th>Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr content</td>
<td>10%</td>
<td>10%</td>
<td>6%</td>
</tr>
<tr>
<td>Smear density</td>
<td>70%</td>
<td>79%</td>
<td>85%</td>
</tr>
</tbody>
</table>
Simplified Compact Reactor Vessel

Ordinary Loop Type

Rotating Plug

Subassembly in fuel handling

Sodium level is given by the requirement in fuel handling

In-vessel Fuel Transfer Machine

- Sodium level is restricted only in operating condition
- Rotating plug and in-vessel Fuel Transfer Machine can be removed
Reactor Vessel

- Simplified upper structure without rotating plug
- DHX at cover gas (reduction of RV height)
- Direct subassembly support by RV (removing core barrel)
- Piping with nozzles (reduction of RV diameter)

Diameter 2.8m
Height 13.4m
Total system (1 loop)

- Reactor Vessel
- IHX with double EMP
- Helical coil SG
- EMP for 2nd circuit

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### Mass Evaluation

<table>
<thead>
<tr>
<th>Item</th>
<th>Previous Pool type design</th>
<th>Loop design</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV</td>
<td>70</td>
<td>38.5</td>
</tr>
<tr>
<td>In-vessel Structures</td>
<td>65</td>
<td>28</td>
</tr>
<tr>
<td>Roof Deck</td>
<td>40</td>
<td>18</td>
</tr>
<tr>
<td>GV</td>
<td>40</td>
<td>20.5</td>
</tr>
<tr>
<td>IHX</td>
<td>90</td>
<td>41.5</td>
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<tr>
<td>Primary Circuit Pump</td>
<td>40</td>
<td>13</td>
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<tr>
<td>Primary Circuit Piping</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>SG</td>
<td>90</td>
<td>97</td>
</tr>
<tr>
<td>Secondary Circuit Pump</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Secondary Circuit Pump</td>
<td>7</td>
<td>7.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>477</strong></td>
<td><strong>308.6</strong></td>
</tr>
</tbody>
</table>

Simplified Loop type design has a advantage in construction cost.
Present Study in JAEA
Innovative Energy System around 2050 and beyond

Innovation objectives:
- Co-existence with renewable energy
- 80% CO2 reduction in 2050

Current

Innovative energy system

- No fossil fuel use
- LWR → SFR/HTGR
- Load following to VRE

https://www.fepc.or.jp/index.html

https://www.enecho.meti.go.jp/
<table>
<thead>
<tr>
<th>JAEA's Nuclear Innovation Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1) Significant cost reduction</strong></td>
</tr>
<tr>
<td>✓ Reduce manufacturing cost</td>
</tr>
<tr>
<td>✓ Raise fuel performance w/ extended burnup</td>
</tr>
<tr>
<td>✓ Raising thermal efficiency to 50-60%</td>
</tr>
<tr>
<td>✓ Standardization and non-nuclearization</td>
</tr>
<tr>
<td><strong>2) Fuel cycle synergy</strong></td>
</tr>
<tr>
<td>✓ SFR + HTGR closed fuel cycle - reduce or eliminate U use</td>
</tr>
<tr>
<td>✓ Supply sufficient Pu required for zero emission grid</td>
</tr>
<tr>
<td>✓ MA burning, etc.</td>
</tr>
<tr>
<td><strong>3) Zero emission grid</strong></td>
</tr>
<tr>
<td>✓ Capability to follow variable renewables while operating reactor at baseload</td>
</tr>
<tr>
<td>✓ Capability to produce hydrogen and heat at low demand/price of electricity</td>
</tr>
<tr>
<td>✓ Smart grid system integrating requirements of environment, market, safety, maintenance, grid resilience, regulation, etc.</td>
</tr>
<tr>
<td><strong>4) Significant nuclear safety improvement</strong></td>
</tr>
<tr>
<td>✓ Order of magnitude reduction or elimination of risk of core melt, radioactive material release, combustion chemicals</td>
</tr>
</tbody>
</table>

- Set vision goals
- Evaluate R&D needs
- Implement R&D activities
Innovative Nuclear System for Grid

HTGR roles:
- Process heat and hydrogen supply
- Load following
- GF/LFC/EDC power adjustment

SFR roles:
- Pu burning and fuel supply
- Pu cleanup
- MA burning
- Hydrogen production for electricity storage
- BL and load follow
- EDC power adjustment

LWR role:
- Baseload (BL) electricity

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Nuclear production of hydrogen processes

- **Reactor temperature**
  - 950°C (HTGR)
  - 500°C (SFR)
  - 300°C (LWR)

- **Process temperature**
  - 100°C
  - 500°C
  - 800°C

- **Thermal efficiency**
  - 50%
  - 42%
  - 25-30%

- **Processes**
  - Thermal chemical
    - High temperature electrolysis
    - Methane reforming
  - Hybrid cycle
    - Thermal efficiency 42%
  - L-T methane reforming
  - Electrolysis
    - Thermal efficiency 25-30%

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Zero-emission energy by RE+NU

Japan 9 regional utilities’ average in 2018

Electricity [MW]

0:00 24 hours 24:00

2018/3/24

2018/7/17

Sector
Why SMR?

• Flexible introduction
  – SFR: Pu management flexibility (Pu burning/breeding, and Pu cleanup from LWRs)
  – HTGR: Flexibility of co-existence with renewable energy
  – SMR: Lower investment cost and lower R&D risks

• Safety enhancement
  – SFR: Lower void coefficient for Pu management core
  – HTGR: High passive safety ability with large heat capacity of the core

• Requirement from the society
  – Hydrogen energy...etc.