A conceptual design study of pool-type sodium-cooled fast reactor in Japan

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National status of SFR development in Japan
Points of Strategic Roadmap in Japan

- At the Ministerial Meeting for the Nuclear Energy Policy in December 2018, we decided “Strategic Roadmap” specifying the development work of fast reactor for approximately 10 years.

Significance of fast reactor development

- In the long term,
  1. Effective utilization of resources
- In the short term,
  2. Volume reduction and
  3. Mitigation of harmfulness of radioactive waste are important.
- It is necessary to pursue the function of plutonium management.

Schedule

- Present state of uranium: Identified resources are sufficient for over 135 years.
- Commercial use:
  - At some point in the latter half of the 21st century
- Start operation of the 1st fast reactor:
  - For example, at an appropriate timing around the middle of the 21st century
- How to spend 10 years for the time being
  - First half: Support diversified technologies
    - Shorten and prioritize technologies after 5 years
  - Latter half: Develop prioritized technologies

Target technology

- Pursuing the possibility of various fast reactor technologies while maximizing the technology and personnel cultivated to date
  - Sodium-cooled fast reactor
    - MOX fuel (France, Russia, etc.)
    - Metal fuel (USA, etc.)
  - Molten salt fast reactor
  - Water-cooled fast reactor, etc.

Role sharing / Development system

- Manufacturers utilize knowledge and ingenuity to promote technological development on their own initiative.
- Electric power companies as future users implement technology selection.
- The government presents the direction of development and promotes active initiatives by private sector
  1. Financial support according to technology maturity
  2. Provide development base (JAEA)
  3. Pursuit of safety considering the adaptation to regulation
Development Strategy of Fast Reactor in JAEA

Roadmap to be implemented  | 5 years later (Evaluation)  | 10 years later

Innovative technologies to be collected from the public to advance fast reactor concepts (Phase I)  |  | Studies of selected design concepts (Phase II)

Development of Technology Base

1. Integrated design evaluation system (a risk-informed system for life-cycle design) including design support tools.
2. Codes & standards to be met by design by making practical use of the evaluation system.
3. Safety technologies that rapidly improves the safety of fast reactor design concepts.

Experiments and studies using irradiation test facilities (e.g. Joyo), PIE facilities, hot labs, AtheNa, and liquid metal facilities

Global standardization

Bilateral collaboration on R&D of common technologies, Design evaluation system to be general for various concepts, to obtain common Demonstration data

GIF, IAEA: To promote international standardization of codes and standards, safety design criteria

R&D resources to be enhanced

- R&Ds for selected design concepts
- Global standardization to be promoted
  - Design basis to the concepts to be provided

Technology to be provided to regulatory bodies
Prospects of Japan Sodium-cooled Fast Reactor
Introduction

- JAEA has developed conceptual design of an advanced loop-type SFR, named JSFR.
- R&Ds for innovative technologies adopted in JSFR have been conducted as well as design study for improving maintainability and repairability and safety measures based on lessons learned from the Fukushima Daiichi Nuclear Power Plants accident.
- JAEA is developing the design concept of a pool-type SFR based on the technology obtained from the above.
- The development of this concept will broaden not only options for reactor types in Japan but also the range and depth of international cooperation.
### Design concept of a pool-type SFR

#### Horizontal seismic isolation system in the reactor building

<table>
<thead>
<tr>
<th>Item</th>
<th>Value or System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical output</td>
<td>650 MWe</td>
</tr>
<tr>
<td>Core inlet/outlet coolant temperature</td>
<td>550/400 deg. C</td>
</tr>
<tr>
<td>Primary pumps</td>
<td>3 mechanical pumps</td>
</tr>
<tr>
<td>Intermediate heat exchangers (IHXs)</td>
<td>4 IHXs (Straight tube containing secondary coolant inside)</td>
</tr>
<tr>
<td>Secondary pumps</td>
<td>4 mechanical pumps</td>
</tr>
<tr>
<td>Power conversion</td>
<td>4 steam generators, 1 water-steam turbine</td>
</tr>
<tr>
<td>Spent fuel storage</td>
<td>Ex-vessel storage tank</td>
</tr>
</tbody>
</table>
Study of safety design
## Safety design concept

| (i) Reactor shutdown measure | - Two active reactor shutdown systems  
- Passive reactor shutdown measure; the SASS using a Curie point electro magnet |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(ii) Measures to achieve in-vessel retention (IVR) of damaged core</td>
<td>-Measures to mitigate the consequence of core damage resulting from ATWS</td>
</tr>
</tbody>
</table>
| (iii) Measures to ensure the decay heat removal | -Prevention of complete loss of decay heat removal function  
-Prevention of core uncovering and ensuring a primary coolant path for decay heat removal |
| (iv) Formation of a containment vessel (CV) boundary | -Rectangular SCCV |
| (v) Measures against sodium leakage/combustion | -Double-wall structure for all sodium boundaries  
-Compartmentation of the CV, and inert atmosphere  
-Transfer and storage of leaked sodium |
| (vi) Measures against sodium-water reaction | -Water/steam leak detection system, pressure relief system, means for isolation of sodium from steam/water, and so on |

SASS: Self Actuated Shutdown System, ATWS: Anticipated Transient Without Scram,  
SCCV: Steel plate reinforced Concrete CV
Applicability evaluation of SASS

BCR is held by an electromagnet of CRDM (Control Rod Drive Mechanism) at the adsorption face. If the sensing part temperature reaches a certain temperature, the BCR is detached by reduction of electromagnet holding force due to increase in magnetic resistance of sensing part.

Structure of Self Actuated Shutdown System (SASS) using a Curie point electro magnet

SASS  Holding force vs temp.
Applicability evaluation of SASS

Safety requirements
- To prevent the core damage by using a passive reactor shutdown mechanism and/or a inherent reactivity feedback even if the function of the active reactor shutdown system is lost.

Requirements for the passive reactor shutdown mechanism
- To cope with all types of ATWS (TOP type, LOF type, LOHS type)
- To provide irreversible negative reactivity
- To achieve reactor shutdown without core damage
- To actuate in direct response to natural phenomena

Design policy
- To adopt SASS which is a promising concept for the pool-type SFR as well.
  - Effective for all types of ATWS (TOP type, LOF type, LOHS type)

TOP: Transient Over Power
LOF: Loss of Flow
LOHS: Loss of Heat Sink
Applicability evaluation of SASS

Characteristics of the pool-type SFR for SASS

- Disadvantage
  - Low sodium boiling temperature due to low cover gas pressure
    Since the sodium boiling temperature during operation is low compared with the loop-type next generation SFR (1,020 → 940°C), the margin from the viewpoint of preventing the coolant from boiling during abnormal event might be lowered.

- Advantage
  - Long primary flow halving time
    Since the primary flow halving time is long compared with the loop-type next generation SFR (9 → 15 seconds), the flow reduction rate is small and SASS fall is early.

⇒ It is required to confirm that the coolant temperature does not exceed the coolant boiling temperature in LOF type ATWS in which the coolant temperature increase is severe.
Applicability evaluation of SASS

Confirmation of the feasibility of SASS

- Transient: LOF type ATWS
- Primary flow halving time: nominal value 15 seconds (sensitivity with time shorter than 15 seconds is confirmed)

If nominal flow halving time is 15 seconds, the safety criterion is satisfied with the initial power of both 100% and 30%. (if the halving time is shorter, the criterion is not satisfied in some cases)

⇒ It was confirmed that the coolant boiling can be avoided by securing the sufficient primary flow halving time.
Study of reactor structure
Structural design

Reactor structure with enhanced anti-seismic capability

- Enhanced RV support
- Flat plenum separator with ribs
- Enhanced core support
- Thickened knuckle part
- Cylindrical wall
- Thermal insulator plates
- Plenum separator
- Rib
Seismic evaluation – Conditions -

Input of ground motion spectra

◆ SPECTRUM B: standard condition in Japan
  - Maximum Horizontal Acceleration
    : 6.4 m/s² (0.65 G)
  - Maximum Vertical Acceleration
    : 4.3 m/s² (0.44 G)

◆ SPECTRUM A: higher condition in Japan
  - Maximum Horizontal Acceleration
    : 9.6 m/s² (0.98 G)
  - Maximum Vertical Acceleration
    : 6.4 m/s² (0.65 G)

Evaluation method

To prevent buckling under seismic loadings, the thickness of RV are set to meet the criteria with taking into account the interaction of shear-bending buckling modes and effects of additional axial load.
Seismic Evaluation - Results (required wall thick) -

<table>
<thead>
<tr>
<th>SPECTRUM</th>
<th>PART</th>
<th>600MWe</th>
<th>1000MWe</th>
<th>1500MWe</th>
<th>1500MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>CYLINDER</td>
<td>50 mm</td>
<td>55 mm</td>
<td>60 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td>KNUCKLE</td>
<td>100 mm</td>
<td>110 mm</td>
<td>120 mm</td>
<td>80 mm</td>
</tr>
<tr>
<td>A</td>
<td>CYLINDER</td>
<td>55 mm</td>
<td>60 mm</td>
<td>65 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td></td>
<td>KNUCKLE</td>
<td>100 mm</td>
<td>120 mm</td>
<td>130 mm</td>
<td>80 mm</td>
</tr>
</tbody>
</table>

Three-dimensional seismic isolation system

Horizontal seismic isolation system

Vertical FRS at the RV support level

Response acceleration / m/s²

0.01 0.1 1 10

Period / sec.

SPECTRUM A

Damping : 1%
Thermal hydraulic evaluation – Conditions -

- Quadrant RV model including core, IHX, DHX, Pump and flat-shaped plenum separator
- Thermal insulation plates, gaps and ribs are simulated in detail
- Number of meshes is 3.7 million

Analysis Method

- CFD code: STAR-CCM+ Ver.11
- Turbulent Model: Realizable k-ε
- Differencing Scheme: 2nd order, up-wind
Thermal hydraulic evaluation – Results -

- **Hot Pool**: large circulation flow, no stagnant region
  - small temperature distribution

- **Cold Pool**: small velocity above IHX outlet
  - weak thermal stratification under plenum separator

![Velocity Distribution](image1)

![Temperature Distribution](image2)
Thermal hydraulic evaluation – Results -

Temperature reduction effect of approx. 50°C was confirmed
Concluding Remarks

- JAEA is developing the design concept of pool-type sodium-cooled fast reactor (SFR) that addresses Japan’s specific siting conditions such as earthquakes and meets safety design criteria (SDC) and safety design guidelines (SDGs) for Generation IV SFRs.
- The development of this concept will broaden not only options for reactor types in Japan but also the range and depth of international cooperation.
Thank you for your attention!!
Backup Slides
Safety design principle in JSFR

<table>
<thead>
<tr>
<th></th>
<th>Active system against AOO and DBA</th>
<th>Passive system against DEC (ATWS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unreliability</td>
<td>$10^{-2}$/d $10^{-4}$/d $10^{-6}$/d</td>
<td>$10^{-1} - 10^{-2}$/d</td>
</tr>
<tr>
<td>PCR (Primary Control Rod)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BCR (Backup Control Rod)</td>
<td></td>
<td>SASS (Self Actuated Shutdown System)</td>
</tr>
</tbody>
</table>

- Independence and diversity are taken into account:
  - Driving force for rod insertion.
  - De-latch mechanism.
  - Detector.

- Introduced as a passive shutdown mechanism to the detach device of the BCR.
- Curie point electromagnet SASS was introduced.

AOO: Anticipated Operational Occurrences
DBA: Design Basis Accident
DEC: Design Extension Condition
ATWS: Anticipated Transient Without Scram
What is response time?

- Response time was considered under two kinds of delay, $\tau_A$ and $\tau_B$, for safety analysis using 1D plant dynamics analysis code.

  - **Coolant transport time ($\tau_A$)**
    The $\tau_A$ is a delay time of coolant transport from the neighboring fuel subassembly outlet to the slit area of the sensing part, when assuming 100% flow rate.

  - **Structural response time ($\tau_B$)**
    The $\tau_B$ is a heat transfer time from the slit area to the sensing part.

- These values, which are identified as important parameters for safety analyses, are determined by 3D thermal-hydraulic analysis.
Design modifications of SASS

Based on the latest design, the temperature response time of SASS can be improved by eliminating the increment of stable-holding force margin.

α) The straight part is extended in order to bring the sensing part closer to the outlet of neighboring fuel subassemblies.

→ Improvement of $\tau_A$

β) The fin thickness is reduced in order to improve the thermal conductivity and heat transfer coefficient.

→ Improvement of $\tau_B$

From the viewpoints of the response time and magnetic property, the option-β is superior.

Therefore, the option-β was selected for the basic specification of the SASS.