Present Status on the Development of Advanced Reprocessing Technology for FBR Spent Fuel and Related Criticality Safety Design Issues

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OECD/NEA Workshop on Future Criticality Safety Research Needs
FBR Cycle Development Program in Japan

2005
Feasibility Study (FS) (JFY 1999-2005)
Identify the most promising candidate concept

Experimental FR “Joyo”

R&D at Prototype FBR “Monju”

2010


Conceptual Design of Commercial & Demonstration FR Cycle Facilities

Fast Reactor Cycle Technology Development Project (FaCT)

2015 (JFY)

Approved Confirmation (2015)

R&D of Innovative Technologies

Validation of Economy & Reliability

Commercially Introducing of FR Cycle Facilities

2025

Operation Start of Demonstration FR & its Fuel Cycle Facility

Basic Design & Construction

2050

R&D at “Monju”

◆ Demonstrate its Reliability as an Operation Power Plant
◆ Establish Sodium Handling Tech.

Production of the Conceptual Designs of Commercial and Demonstration FR Cycle Facilities with R&D Programs

R&D at “Monju”

◆ Cooperation with related Organization
◆ International Cooperation (GNEP, GEN-IV, INPRO etc.)
Development Targets and Design Requirements of Fuel Cycle Commercial Facility

Safety and Reliability
- Not influence on the significant radiation risk to public
- Prevent the occurrence of off-site emergency
- Establish the design concept possible to achieve the maintainability and repairability

Sustainability

Environment Protection
- Keep the influence of the radioactive release on the environment through normal operation below the current fuel cycle

Waste Management
- Reduce the amount of radioactive waste to 1/2 - 1/5 of the current fuel cycle facilities
- Recover more than 99.9% of U and TRU

Efficient Utilization of Nuclear Fuel Resources
- Possible to treat the SF with the heat power of 3kW/Assy (in the case that the out-of-core time is around 5 years)

Economic Competitiveness
- Fuel cycle cost should be < 340,000 JPY/kgHM
  (reprocessing : < 180,000 JPY/kgHM, fuel fabrication : < 160,000 JPY/kgHM)

Nuclear Non-Proliferation
- Pure Pu should not appear in any process
- It should be difficult to access the nuclear materials by handling low-decontamination TRU fuel
The Selected Most Promising FBR Cycle System on the FaCT Project

**Selected Reactor Concept**
- Throughput: 1500 MWe/core
- Maximum Burn-up: 150 GWd/t
- Cooling System: 2 loop with Integrated IHX with Primary Pump
- Coolant: Sodium
- Structural Material: High-chromium Steel
- Fuel: Mixed Oxide with Oxide Dispersion Strengthen (ODS) Steel Cladding

**Fuel Assembly with Inner Duct Structure for Re-criticality Free Core Concept**

**Selected Fuel Cycle Concept**
- Throughput: 200 ton-HM/year
- Fuel Fabrication Concept: Simplified Pelletizing Process
- MA Recovery and reloading
"NEXT" means the New Extraction System for TRU Recovery, which consists of advanced aqueous reprocessing system with some innovative technologies.

Concept of the NEXT Process and Its Major Improvements

Conventional LWR Fuel Reprocessing (PUREX Process)

Spent Fuel of LWR

Shearing

Dissolution & Clarification

Solvent Extraction (Pu Separation)

Solvent Extraction (U Purification)

Spent Fuel of FR

Disassembling/Short-length Shearing

Dissolution & Clarification

Crystallization

Single Cycle Solvent Extraction

MA Recovery by extraction chromatography

Salt-free waste treatment

Removing specific structures of a FR fuel assembly

U Pre-recovery to minimize following process throughput

Simplified solvent extraction (U/Pu/Np co-recovery)

MA (Am, Cm) recovery to reduce HLW

Vitrification

Vitrification

to Fuel Fab.
Innovative Technology for the NEXT Process
(1) Fuel Disassembling

[Process Features]
• Mechanical cutting of wrapper tube and cross-section of assembly by grindstone
• Pulling out fuel pin bundle from wrapper tube

ODS pins bundle crop-cutting test and cross-section

Cutting of wrapper tube with wheel

Disassembling machine
Innovative Technology for the NEXXT Process

(1) Fuel Disassembling

Procedure:

1. Receiving fuel assembly
2. Tilting
3. Transfer to the table
4. Mechanical cutting
5. Transfer to the shearing stage

To shearing device

12 m
[Process Features]

- Fuel fragments released out of the cladding and powdered by short-length shearing facilitates the fuel dissolution process.

**Short-length Shearing Effect**

On the short stroke shearing, major fuel were fragmented and released out of the hulls.

It was confirmed quantitatively that the released fuel ratio increased in inverse proportion to the length of shearing.

The conventional shearing machine was modified to treat fuel pin bundle and control the shearing stroke.

**Effect of shearing length to released fuel ratio**

<table>
<thead>
<tr>
<th>Shearing length</th>
<th>5mm</th>
<th>10mm</th>
<th>30mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight ratio (%)</td>
<td>50</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>shearing length (mm)</td>
<td>6</td>
<td>10</td>
<td>13</td>
</tr>
</tbody>
</table>
Innovative Technology for the NEXT Process
(3) Effective Dissolution

[Process Features]

• Provide high heavy metal concentration solution to the following crystallization process.
  \[ \sim 500 \text{gHM/L}, 4.5\text{M-HNO}_3, \text{within 4 hours} \]
• The continuous process with high throughput using a rotary dissolver is realized through improvement by powdering with short-length shearing.

Fuel fragments is highly powdered and released from claddings.

The rotary dissolver would be scaled-up and modified to treat powdered fuel and short length sheared hulls.

Rotary Dissolver

The rotary dissolver concept were developed for a FBR-reprocessing test plant by JAEA and ORNL in the ’80s.
Innovative Technology for the NEXT Process

(4) Crystallization

[Process Features]
- Separating excess uranium from dissolver solution by decreasing temperature.
- The process rationale which denies pure Pu would involve inherent proliferation resistance.

Factors to increase uranium recovery rate:
1. Increase of uranium concentration
2. Decrease of operation temperature
3. Increase of nitric acid concentration

Feeding dissolver solution condition

Decreasing temperature ...

UNH crystallizing along with the solubility change to the temperature decreasing.

The limitation of UNH crystallization

Uranyl Nitrate Hexahydrate (UNH) Crystal

1mm
Innovative Technology for the NEXT Process
(5) U-Pu-Np Co-recovery by Single Cycle Solvent Extraction

[Process Features]

- U, Pu and Np concurrent recovery from dissolver solution by single cycle (a pair of extraction and stripping operation) solvent extraction.
- Compactness and rapid dynamics of the single-stage centrifugal contactors would improve facility economics, operability and solvent degradation problem.

**Extractant**

- Extractant (TBP)

**Stripping Solution**

- Nitric Acid Solution

**Diluent**

- n-Dodecane

**Washing**

- Diluent Washing

**Scrubbing Section**

- Scrubbing Solution (Nitric Acid Solution)

**Extraction Section**

- Extractant after Crystallization

**Acidity Conditioning Solution**

- Nitric Acid Solution

- U-Pu-Np Co-Stripping Section

**Stripping Solution**

- Nitric Acid Solution

**Raffinate**

- to MA Recovery

**U-Pu-Np Product Solution**

**Spent Solvent**

- to Regeneration Process

Simplification of matured PUREX technology without Pu separating function.
Innovative Technology for the NEXT Process
(6) MA Recovery by Extraction Chromatography

[Process Feature]
- Am and Cm recovery from raffinate (High Level Liquid Waste) of the U-Pu-Np co-recovery process.
- Extraction chromatography would be compact and less-reagent-usage process for minor component recovery from a large amount of dilute solution.

Chromatographic Separation Test by CMPO/SiO2-P column (RI Column Test)
Criticality Safety Approach in the NEXT Process Equipment

(1) Continuous Dissolver

[Criticality Safety Features]

- Geometrically favorable equipment design under any credible conditions:
  Fuel pin arrays in the optimum moderated condition by water was considered.

- The neutron absorber (B$_4$C) is inserted in the center of the rotating drum core.

- Throughput: ~100 tHM/y
Criticality Safety Approach in the NEXT Process Equipment

(2) Crystallizer

[Criticality Safety Features]

- Geometrically favorable equipment design under any credible conditions
  - Precipitation of plutonyl nitrate hexahydrate crystal were considered.
- Throughput: \( \sim 100 \text{L/h} \) (Equivalent to 200tHM/y NEXT plant)

Criticality safety analysis modeling part

Annular shape with B\(_4\)C neutron absorber mandrel

Motor and Bealing

Slow Rotation

Dissolver Solution Inlet

Cooling Jacket

Body

Drive Shaft

Inner Neutron Absorber (B\(_4\)C)

Annulus Crystallization Cell (Filled with PuNH Crystal)

UNH Crystal Outlet (Filled with PuNH Crystal)

Criticality Safety Analysis Model

Dissolver

Solution

Inlet

UNH

Crystal Outlet

Mother Liquid Outlet

UNH Crystal Outlet
Criticality Safety Approach in the NEXT Process Equipment

(3) Centrifugal Contactor

[Criticality Safety Features]

• Geometrically favorable equipment design under any credible conditions: All range of Pu content/concentration changes in the nitric solution.
• Throughput: \(~550\text{L/h}\) (Equivalent to 200tHM/y NEXT plant)

The throughput depends on the rotor diameter and height which are restricted by criticality safety geometry.

A compact housing block containing 4 contactors.
Critically Safety Approach in the NEXT Process Equipment

(4) Multi-Slab Tanks

[Critically Safety Features]
- Geometrically favorable vessel design for any plutonium content/concentration of Pu nitric acid solution.
- Extreme thin slab-shape tanks connected by piping.
- Neutron absorbers (borated concrete) located between and on both side of the slab tanks.
- Capacity: \(~1m^3\)
- Capability to layout side-by-side infinitely.

![Cutaway view of a Typical Double Slab Tank](image)

- Tank Space
- Structures
- Slab Tank
- Connecting Pipe
- Internal Stay
- Neutron Absorber

Periodical Boundary Condition

Criticality Safety Analysis Model

Boron-Containing Concrete

Filled with Pu Solution
History of the FBR Reprocessing Criticality Safety Study in Japan

[US DOE – PNC Joint Criticality Data Development Program]

• From 1983 to 1988, US DOE and PNC (JAEA) had jointly developed new criticality experiment data of Pu+U at PNL/ORNL.
• Valuable data of 77 cases were acquired.
  • Geometry for solution: Slab, Cylinder, Annular
  • Chemical forms: Solution, MOX fuel pin
  • Moderator for fuel pins: Water, Organic solvent, Fuel solution, Fuel solution with Gd

The Data were Utilized to benchmark the criticality calculation code (SCALE-4).
It contributed to safety design and licensing of the Recycle Equipment Test Facility (RETF) in 1990s.

It also contributed to OECD/NEA international handbook of evaluated criticality safety benchmark experiments.
Transition from LWR cycle to FBR cycle

To realize FBR cycle commercialization in Japan, reasonable transition scenario from existing LWR cycle to FBR cycle is needed.
What is expected in future?

• More and more Pu will appear in fuel cycle.
• From economical viewpoint, large reprocessing plant will be required.
• LWR-UO2 reprocessing plant could be scaled up to 1200tHM/y. However, how about MOX reprocessing plant?
• For FBR reprocessing, 200tHM/y plant is envisioned and designed to adopt NEXT process and equipments of high performance.
• Some equipment seems getting closer to upper limit of single process line capacity with the present criticality design concept.
• Yet no concrete investigation for FBR reprocessing plant of 500-800tHM/y or multi-purpose plant of 1400tHM/y.
A Perspective of Criticality Safety Issues to Increase the Future Plant Throughput

- The criticality safety exclusively depends on geometrical control. It requires no significant operational control or severe criticality accident analysis.
- But geometrical restriction spoils equipment design flexibility.
- Multiple process lines and equipments may drastically ruin the economy.

Perspectives for the Optimization ...

* Eliminate unreasonable conservatism.
* Re-evaluate criticality design condition such as reflection, isotopic composition, and so on.
* Investigate whether more precise operational analysis would improve criticality analysis model. But this may require additional important safety instruments and a variety of research work.
* Subcriticality measurement system might be solution?
A Perspective of Criticality Safety Issues to Increase the Future Plant Throughput

[An idea to be more realistic criticality analysis model through equipment design improvements]

Continuous Dissolver Design

- Jamming and clogging of solid (sheared fuel or hull) inside may not be evitable.
- But assumption of flooding might be unrealistic.
- Accidentally filled fuel and normal solution level would be more favorable model.
- We have to ensure no possibility of flooding.

Sizing up to be enabled.
A Perspective of Criticality Safety Issues to Increase the Future Plant Throughput

[Improving equipment design and applying process control]

Centrifugal Contactor

• Implementation of inner neutron absorber could enhance the throughput in some degree. (Assuring the hydraulic performance would be needed)

• In addition, concentration limitation of Pu by rationale of the chemical properties and dynamic process control would be possibility to remarkably enhance the throughput.
A Perspective of Criticality Safety Issues to Increase the Future Plant Throughput

[Conventional simple equipment may be more difficult to scale-up]

**Solution Tank**
- Needs to be large (~10m³)
- Needs to be easy to homogenize the solution
- Scaling up would spoil ability to homogenize or space utility.

**Pu Evaporator**
- No experience of large equipment

**MOX conversion**
- Denitration tray applies mass control

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*Multi-slab tank: Space utility is excellent, but uneasy to fabricate and to homogenize.*

*Annular tank: Space utility is poor. Not preferable for hot solution because of organic moderator inside.*
Perspective for future criticality safety issue

- Huge amount of plutonium will be handled in future fuel cycle.
- Scaling up will play an important role to improve economy especially for FBR fuel reprocessing plant.
- Simple criticality design may not be available for it. We need a breakthrough to improve criticality design.
- Dense cooperation between engineers of criticality safety and chemical engineering would be a key for more precise and rationale design.
- More activities for R&D, design, and licensing will be necessary to guarantee its exactness.
- However, we should be careful to apply operational control because it may lead to equipment increase and possibility of a failure.
Thank you

Chemical Processing Facility (CPF)