Advanced Fuel Cycle with Pyroprocessing and Sodium-cooled Fast Reactor in Korea

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Outline

- Backgrounds
- Advanced Fuel Cycle Options Considered in Korea
- R&D of Pyroprocessing Technology
Backgrounds
Nuclear Energy in Korea

24 NPPs are operating (2017.10)

Radioactive Waste Disposal Facility
1st stage: 100,000 drums
2nd stage: 125,000 drums (under construction)

Hanul (#1,2,3,4,5,6)
Shin-Hanul (#1,2)

Wolseong (#1,2,3,4)
Shin-Wolseong (#1,2)

Gori (#1,2,3,4,5,6)

Hanbit (#1,2,3,4,5,6)

Under Construction
- APR1400: Shin-Gori (#4,5,6), Shin-Hanul(#1,2)

As of October, 2017

<table>
<thead>
<tr>
<th>Site</th>
<th>In Operation (MWe)</th>
<th>Under Construction (MWe)</th>
<th>Total (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gori</td>
<td>6 (5,950)</td>
<td>3 (4,200)</td>
<td>9 (10,150)</td>
</tr>
<tr>
<td>Wolseong</td>
<td>6 (4,779)</td>
<td>-</td>
<td>6 (4,779)</td>
</tr>
<tr>
<td>Hanbit</td>
<td>6 (5,900)</td>
<td>-</td>
<td>6 (5,900)</td>
</tr>
<tr>
<td>Hanul</td>
<td>6 (5,900)</td>
<td>2 (2,800)</td>
<td>8 (8,700)</td>
</tr>
<tr>
<td>Total</td>
<td>24 (22,529)</td>
<td>5 (7,000)</td>
<td>29 (29,529)</td>
</tr>
</tbody>
</table>

Source: www.khnp.co.kr

Ratio of Electricity Generation (2016)

- Nuclear: 31.7%
- Fossil Fuel: 64.0%
- Hydro, etc: 4.3%

Source: www.epsis.kpx.or.kr

24 NPPs are operating (2017.10)
## Current status of SF storage (As of Dec. 2016)

- All PWR spent fuels are stored in the pool of NPP sites
- Some part of CANDU spent fuels are stored in AR dry storage
- On-site SF storage limit will be reached by mid of 2020s

### Spent Nuclear Fuel Generation

<table>
<thead>
<tr>
<th>Sites</th>
<th>Capacity</th>
<th>Current storage</th>
<th>Saturation Rate</th>
<th>Expected saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gori</td>
<td>7,994</td>
<td>5,834</td>
<td>73.0%</td>
<td>2024</td>
</tr>
<tr>
<td>Hanbit</td>
<td>9,017</td>
<td>5,965</td>
<td>66.2%</td>
<td>2024</td>
</tr>
<tr>
<td>Hanul</td>
<td>7,066</td>
<td>5,123</td>
<td>72.5%</td>
<td>2037</td>
</tr>
<tr>
<td>Sin-Wolseong</td>
<td>1,046</td>
<td>253</td>
<td>24.2%</td>
<td>2038</td>
</tr>
<tr>
<td>Sum</td>
<td>25,123</td>
<td>17,175</td>
<td>68.4%</td>
<td>-</td>
</tr>
<tr>
<td>CANDU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wolseong</td>
<td>499,632</td>
<td>422,908</td>
<td>84.6%</td>
<td>2019</td>
</tr>
</tbody>
</table>

(As of the end of 2016)

(about 15,000 tHM)
7,000 tons from PWR, 8,000 tons from CANDU
Decisions Regarding Spent Fuel Management

  - Establishment of Korea Radioactive-waste Management Corporation of which responsibilities includes spent fuel interim-storage and disposal
  - Establishment of RWM fund

  - Recommendation of basic direction for three areas; spent fuel management option, direction of support for local communities, law and institution

- **Basic Plan on HLW Management by MOTIE (2016)**
  - Announcement of basic plan on HLW management based on the PECOS recommendation

  - Sodium cooled fast reactor (SFR) technology development (~2028)
  - Pyroprocessing technology development (~2025)

# KAEPC : Korea Atomic Energy Promotion Commission
# MOTIE : Ministry of Trade, Industry and Energy
Recommendation by PECOS (2015)

- Korean government-launched PECOS* made recommendations to the Government for a spent fuel management policy on July 2015
  - *Public Engagement Commission on Spent Nuclear Fuel Management
- Suggestion of 10 Recommendations from 20 Months Public Discussion
- Suggestion of Construction Milestone of HLW Management Facilities; Three Facilities at the Same Site
- Legislation of Spent Fuel Management Law for Assuring Transparency, Safety and Sustainability
- Continuation of R&Ds for Volume and Radio-toxicity Reduction at the Same Time
Basic Plan on HLW Management (2016)

- Suggestion of **Step by Step Method and Procedure for Site Selection**
- Same site for Licensing URL, Interim Storage and Disposal, at the same time, Continuing Effort for the International Storage and Disposal
- Site Acquisition from Scientific Examination and Democratic Procedure
  - Exemption of unsuitable region of all national land
  - Invitation of local governments in suitable regions
  - Basic examination for the site including site characteristics and suitability
  - Confirmation of the public opinion of the region passed the basic examination
  - Detail examination of the site confirmed the public opinion
  - Final decision
- Establishment of the Independent Organization for the Site Selection

<table>
<thead>
<tr>
<th>Step</th>
<th>Exemption of unsuitable region</th>
<th>Invitation of local governments</th>
<th>Confirmation of the public opinion</th>
<th>Basic Examination</th>
<th>Detail examination of the site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>8 years</td>
<td></td>
<td></td>
<td></td>
<td>4 years</td>
</tr>
</tbody>
</table>
Basic Plan on HLW Management (2016)

- Interim Storage Construction After Site Acquisition (7 years) and Disposal Facility Construction After Site Acquisition (24 years)

- R&Ds on Key technologies
  - Transportation, interim storage and disposal
  - General URL for disposal safety
  - Technologies for volume and radio-toxicity reduction of spent fuel

- Transparency and Public Acceptance
  - Open information and related data
  - Site selection organization consisting of neutral persons and experts
  - Monitoring organization governed by local government in a HLW management region
Advanced Fuel Cycle Options Considered in Korea
Issues in Spent Fuel Disposition

- Do we have an intermediate measure to store the SNF?
  - 2024 *(Urgently need expansion of storage capacity)*

- Do we have a good geological formation to dispose of all SNF in ROK?
  - Need more than 10 repositories same size with Finish Olkiluoto

- Do we have a measure to assure the long term safety of a repository over millions of years?
  - TRUs are concerns along with some fission products

- Do we have support from public and stakeholders for waste disposal?
  - A bridge too far yet
Option studies are needed to provide technical information for policy-making

- Pyroprocessing-SFR Closed fuel cycle and nonproliferation acceptability
- Long-term storage of spent fuel and associated wastes
- Direct disposal
Future nuclear fuel cycle (NFC) options

Once-through cycle:
- Mining & Milling → Conversion → Enrichment → PWR Fuel Fabrication → PWR → Interim Storage
- Disposal

Pyro-SFR cycle:
- Mining & Milling → Conversion → Enrichment → PWR Fuel Fabrication → PWR → Interim Storage
- Disposal → Pyro-processing → SFR → SFR Fuel Fabrication → Pyro-processing
Approved by the AEC (2008.12, 2011.11, 2016.07)

Construction of a Prototype Pyro. facility will start after evaluating the technical feasibility, economic viability and nonproliferation acceptability in the JFCS.

Research on electro-reduction using US-origin SF can be carried out in KAERI according to the new Agreement for cooperation between the U.S. and Korea
Partitioning & Transmutation Plan in Korea

Fresh Fuel

Trans Uranics

5 yrs

Fission Products

U-235 (4.5\%)
U-238 (95.5\%)

55 GWd/tU
10 yrs cooling

Spent Fuel

TRU (1.4\%)

High activity & Long-lived

I, Tc (0.18\%)

Long-lived & high effective dose

FPs (4.95\%)

Short-lived

Cs, Sr (0.53\%)

High heat, but short-lived

U (92.95\%)

Feed for Fuel

Fast Reactor

Deep Geological Disposal

Independent Storage

Recycled / Storage
Primary Goal

- Partitioning and Transmutation of TRU (Lv.4)

- Partitioning of Cs/Sr is pursued to reduce the repository size (Lv.5)

- Partitioning of LLFP is also considered
# Decay Heat of Spent Fuels

## Cooling time vs. Decay heat

<table>
<thead>
<tr>
<th>Decay Heat (W/ton)</th>
<th>Total</th>
<th>TRU</th>
<th>Cs/Sr</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 yr</td>
<td>1,110</td>
<td>472.01</td>
<td>632.09</td>
<td>5.9</td>
</tr>
<tr>
<td>(%)</td>
<td>100.00</td>
<td>42.52</td>
<td>56.95</td>
<td>0.53</td>
</tr>
<tr>
<td>100 yr</td>
<td>494.7</td>
<td>343</td>
<td>151.5</td>
<td>0.2</td>
</tr>
<tr>
<td>(%)</td>
<td>100.00</td>
<td>69.33</td>
<td>30.62</td>
<td>0.04</td>
</tr>
</tbody>
</table>

## Separation efficiency (SE) of TRU, Cs/Sr
- SE = 99%, Heat loading can be reduced to a factor of 66
- SE = 99.9%, a factor of 160
Based on one of the FS version, footprint was quantified and compared for two fuel cycle options:

- Separation efficiency (TRU recovery ~99.9%, Cs/Sr ~99.9%)
- Direct disposal footprint for ~60,000 tons of SF (~13.5km²)
- Repository footprint for HLW (~0.132 km²)
Radiotoxicity of PWR SF

Plus7 (4.5 wt.%, 55 GWD/MtU)

Time after discharge [yr]

Toxicity [m$^3$ Water/MtU]
Radiotoxicity after partitioning

- Radiotoxicity is reduced to ~1/1000
Dose Rate (Long-term Safety of Repository)

Direct disposal

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Direct disposal case: 34,893 canisters

- **Annual Dose Rate, mSv/yr**
  - **Time after disposal, yr**
  - **Dose Rate (Long-term Safety of Repository)**
  - **2 mrem/yr**
  - **Disposal canister lifetime: 10,000 years**
  - **Total**

- **Elements**:
  - C-14
  - Cl-36
  - Cs-135
  - I-129
  - Ra-226
  - Se-79
  - Total

- **Canisters**: 34,893
Dose Rate (Long-term Safety of Repository)

- Deep geological disposal of Tc/I containing waste after partitioning
  - Direct disposal of SF, $2.26 \times 10^{-3}$ mSv/yr
  - HLW from pyroprocessing, $2.36 \times 10^{-3}$ mSv/yr

![Graph showing dose rates over time](image-url)
R & D of Pyroprocessing Technology in Korea
Group recovery of reusable elements from spent fuel using electro-chemical reaction in high temperature (500~650 °C) molten salt electrolyte.

Closed fuel cycle system (Pyroprocessing combined to a SFR) can reduce the disposal area and radio-toxicity dramatically and resolve spent fuel management challenges.
Flow Diagram of Pyroprocessing
PRIDE (PyRoprocess Integrated inactive Demonstration facility)

- **Overview**
  - Reuse of discarded U-conversion facility after decontamination and remodeling works
  - Milestone: Design (‘07~’08), Installation (‘09~’12.6), Test-run & Operation (‘12.7~)

- **Purposes**
  - Test and demonstration of Eng.-scale full-spectrum pyroprocessing performance with depleted uranium (DU) and simulated fuel (50 kgU/batch)
  - Experimental activities of PRIDE also included in a research item of JFCS

- **Main Features**
  - Environment: Air (glove-box, 1st floor), Ar (air-tight cell, 2nd floor)
  - Ar-cell: Dimension L40.3 x W4.8 x H6.4 m, Impurity (moisture & oxygen) < 50 ppm
  - Integrated pyroprocessing equipments (17 workstations each equipped with 2 MSM)
  - Remote handling equipments, monitoring system, and Ar purification system
Process Development Objectives and Achievements

- Increased throughput, process efficiency and scale-up
  - Graphite cathode employment to recover U in electorefining system
  - Application of residual actinides recovery (RAR) system
  - High performance electrolytic reduction process

- Reduced waste volume
  - Crystallization to recover pure salt from waste mixture

- Simple / easy remote operability and enhanced inter-connection between unit processes
  - PRIDE experience
Unit operation test with uranium and simulated fuel completed.

- UO₂ porous pellet with surrogates (Ln oxides-1.8%, Ba/Zr/Sr oxides - 1.1%) fabricated
- Anode and cathode module for oxide reduction equipment tested
- Self-scraping property of U deposit with graphite cathodes for electrorefiner tested
- Crystallization for LiCl waste salt and precipitation for LiCl-KCl waste salt performed
Integration test (pretreatment-OR-ER) using simulated fuel

- Simfuel fabrication for OR process:
  • 100 kg of UO$_2$ porous pellets with simfuel composition (Heavy metal basis, tab density: 4.88 g/cm$^3$)

- Oxide Reduction Processes
  • 3 consecutive runs using 60 kg of simulated fuels (50 kg in U-base)
  • Applied current: >1,000 A

- Electrochemical Recovery Processes
  • Electrorefining: current efficiency higher than 75%
  • Electrowinning: recovery of 7wt% HM(U+RE)/Cd product

- Waste salt purification
  • melt crystallization & reactive distillation salt regeneration/FPs separation: 90~99%
Strategy to Move Forward for Pyroprocess

- **Prove and Develop Technical & Economical Viability**
  - Lab-scale experiments for innovative technologies
  - High-efficiency process system, scale-up technology development
  - Economy assessment

- **Enhance Safeguardability and Proliferation Resistance**
  - Development of advanced safeguards tools (process monitoring)
  - System design improvement (towards Safeguards-by Design)
  - Contribution to the IAEA safeguards implementation (support program, training course, etc)

- **International Cooperation**
  - International project for process viability
  - Meeting for transparency
  - JFCS (Joint Fuel Cycle Study)
On 13 April 2011, the ROK and US entered into a new era of bilateral nuclear energy partnership.

Purpose of the Joint Fuel Cycle Study

- To jointly evaluate the technical feasibility, economic viability and nonproliferation acceptability of the electrochemical recycling process

History of JFCS

- ’11.04: Agreement for JFCS
- ’11.07: Signed CRADA of Phase I (’11~’12) in JFCS
- ’12.12: Completion of Phase I ✚ Confirmed technical feasibility on lab-scale basis
- ’13.07: Signed CRADA of Phase II-A (’13~’14) in JFCS
- ’13.11: Approval of NTT (Nuclear Technology Transfer) between USA and ROK
- ’15.01: Start Phase II-B (’15~’17) in JFCS

* CRADA : Cooperative Research And Development Agreement
### Overview of Joint Fuel Cycle Studies (JFCS) (II)

- **10-year JFCS is divided into three phases**
- **All phases include joint safeguards development and evaluations of technologies important to major alternatives**
  - Phase I - Evaluation of the laboratory-scale feasibility of electrochemical recycling
  - Phase II - Determination of reliable integrated process operation with used LWR fuel
  - Phase III - Evaluation of the irradiation performance of fuel fabricated from recycled LWR fuel

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II-A</th>
<th>Phase II-B</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
<td>’11.7 ~ ’12.12 (1.5 yrs)</td>
<td>’13.1 ~ ’14.12 (2 yrs)</td>
<td>’15.1 ~ ’17.12 (3 yrs)</td>
</tr>
<tr>
<td><strong>Main Activities</strong></td>
<td>• Production of TRU Button by LSFS (30~50g/ Batch) (Lab.-Scale Feasibility Study)</td>
<td>• Process Equipment for IRT (<del>2 kg/Batch) : Design (’13</del>’14) : Manufacturing (’14~’15)</td>
<td>• Installation &amp; Commissioning of IRT Equipment in HFEF at INL</td>
</tr>
<tr>
<td></td>
<td>• Analysis of state-of Art of SGs</td>
<td>• Prepare SGs Equip. for IRT</td>
<td>• Production of U/TRU ingot for metal fuel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• SGs Equipment Demonstration &amp; Analysis of Eng.-scale SGs System</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* IRT: Integral Recycling Test
Korea has not a definite spent fuel management policy and still so-called ‘wait and see’.

Based on the public engagement activities from 2014 to 2015, major milestones on spent fuel management were established by government (Basic Plan on HLW Management)
  - Site acquisition of URL and repository, Interim storage of spent fuels, Disposal of HLWs

Pyro-SFR advanced fuel cycle is considered to reduce the repository footprint and radio-toxicity
  - Full recycling of TRU(Pu+MA) and Cs/Sr separation

R&Ds on spent fuel management options will continue by the end of 2020’s
  - Evaluate the technical feasibility, economic viability and nonproliferation acceptability of the electrochemical recycling process