Status of R&D Activities on Pyroprocessing Technology at KAERI

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Nuclear Fuel Cycle Technology Development

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Outline

I Nuclear Energy and Spent Fuel in Korea

II R&D Activities at KAERI: Pyroprocessing Technology and Related Facilities

III Summary
Nuclear Energy and Spent Fuel in Korea
Status of Energy Supply in Korea

- Annual energy consumption (263 Mtoe): Ranked No. 8 in the world
- Import of energy resources accounts for 97% of total energy
  - Energy security: Top national priority
  - Nuclear energy: Improves the energy self-sufficiency by more than 6 times

* IEA, Energy balance of OECD countries 2013

* Self-sufficiency [%]

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy self-sufficiency (w/o nuclear power)</th>
<th>Energy self-sufficiency (including nuclear power)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korea</td>
<td>3</td>
<td>166</td>
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<tr>
<td>Japan</td>
<td>18</td>
<td>156</td>
</tr>
<tr>
<td>Germany</td>
<td>6</td>
<td>166</td>
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<td>France</td>
<td>9</td>
<td>85</td>
</tr>
<tr>
<td>U.S.</td>
<td>53</td>
<td>75</td>
</tr>
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<td>U.K.</td>
<td>51</td>
<td>61</td>
</tr>
<tr>
<td>Canada</td>
<td>18</td>
<td>156</td>
</tr>
</tbody>
</table>
Nuclear Power Plants in Korea

[Generating Capacity (MWe) as of Dec. 2014]

<table>
<thead>
<tr>
<th>Site</th>
<th>In operation</th>
<th>Under Construction</th>
<th>Total (2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gori</td>
<td>6 (5,137)</td>
<td>2 (2,800)</td>
<td>8 (7,937)</td>
</tr>
<tr>
<td>Wolseong</td>
<td>5 (3,779)</td>
<td>1 (1,000)</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>23 (20,716)</td>
<td>5 (6,600)</td>
<td>28 (27,316)</td>
</tr>
</tbody>
</table>

*Source: www.khnp.co.kr

[Share of Electricity Generation]

*Source: www.Kepco.co.kr, #2012e: estimated

- OPR1000: Shin-Wolseong (#2)
- APR1400: Shin-Gori (#3,4), Shin-Hanul (#1,2)
Spent Fuel (SF) Generation

Current status of SF storage (as of Dec. 2013)

- On-site SF storage limit will be reached in the near future

<table>
<thead>
<tr>
<th>Site</th>
<th>Capacity (t)</th>
<th>Current storage (t)</th>
<th>Expected saturation (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gori (PWR)</td>
<td>2,691</td>
<td>2,081</td>
<td>2016 (2026*)</td>
</tr>
<tr>
<td>Hanbit (PWR)</td>
<td>3,318</td>
<td>2,146</td>
<td>2019 (2024*)</td>
</tr>
<tr>
<td>Hanul (PWR)</td>
<td>2,961</td>
<td>1,848</td>
<td>2021 (2025*)</td>
</tr>
<tr>
<td>Wolseong PWR</td>
<td>219</td>
<td>27</td>
<td>2022</td>
</tr>
<tr>
<td>Wolseong CANDU</td>
<td>9,441</td>
<td>7,152</td>
<td>2018 (2026*)</td>
</tr>
<tr>
<td>Total</td>
<td>18,630</td>
<td>13,254</td>
<td>* Capacity Extension case</td>
</tr>
</tbody>
</table>

Annual generation & projection

- Annual generation & projection

95 t/yr, unit
- 4 units
- 380 t/yr

[Annual Generation : 720t/yr]

Accumulated Spent Fuel (ton)
- Total
- PWR SF
- CANDUSF

[Projection of SF Generation : 2nd NEBP]
Public & Stakeholder Engagement Program (PECOS) has been launched

- Mission: Proposal of basic direction for spent fuel management including interim storage by participating public and stakeholders

Spent fuel management policy will be established based on recommendations by PECOS

- R&D activities are needed to provide technical information for decision-making
  - Transportation and interim storage of spent fuel and associated wastes
  - Pyroprocessing-SFR Closed fuel cycle and Proliferation-resistance
  - Direct disposal

*PECOS: Public Engagement Commission Of Spent fuel management
R&D Activities at KAERI

- Pyroprocessing Technology and Related Facilities -
Pyro-SFR Fuel Cycle for SF Management

Reduction of Spent Fuel Disposal Area & Radiotoxicity

* TRU (Transuranics) : Pu + MA
* MA (Minor Actinides) : Np, Am, Cm

**Diagram Details:**
- **PWR**
  - SNF
  - Interim storage
  - Pyroprocessing
  - I, Tc
  - HLW
  - Cs, Sr
  - Long-term storage
  - HLW repository
  - SFR
  - U, TRU
  - U-TRU-Zr fuel

**Uranium Composition:**
- Fresh Fuel (100% U)
  - U-235 (4.5\%)
  - U-238 (95.5\%)
- Spent Fuel
  - Pu (1.16\%)
  - MA (0.20\%)
  - I, Tc (0.16\%)
  - Cs, Sr (0.53\%)
  - U (92.94\%)

**Cooling Times:**
- 4 years burning
- 10 years cooling

**Power Generation:**
- 4.5\% U235
- 55 GWd/tU
R&D Plans for Future Nuclear Energy System

- Long-term R&D plan for Pyro-SFR closed fuel cycle development
  *(255th AEC on 2008, 1st AEPC on 2011)*

- Advanced Design Concept
- System Performance Test
- Specific SAR
- Specific Design Approval
- Detailed Design
- Construction

- PRIDE ('12)
- Completion ('20)
- Prototype Facility ('25)

- Pyro Equipment Development and Mock-up Facility
- ROK-US Joint Fuel Cycle Study
- PRIDE Operation & Improvement
- ACPF/DFDF Operation and Improvement

AEC: Atomic Energy Commission
AEPC: Atomic Energy Promotion Commission
Flow Diagram of Pyroprocessing

**Pyroprocessing technology**: Electrochemical recycling technology to recover valuable resources (U, TRU, etc.) from spent fuels in molten salt media at 500~650°C

- **PWR SF**
  - Decladding/Voloxidation/Pelletization
  - Off-gas Treatment
  - Semi-volatile FPs
  - $\text{O}_2/\text{Ar}$
  - Hull
  - LLW

- **Salt Treatment**
  - [UO$_2$+TRU+FP]
  - Oxide (Pellet)
  - Used Salt
  - Clean Salt
  - Clean Salt
  - Used Salt
  - (U+TRU+FP)

- **Electrolytic Reduction**
  - (U+TRU+FP)
  - Metal
  - Clean Salt
  - Used Salt

- **Electro-Refining**
  - U recovery
  - U Ingot

- **Electro-Winning**
  - (U+TRU+FP)
  - (Metal)

- **Final Waste Form**

- **Storage Reuse**
  - Spent SFR Fuel
  - SFR Fuel

- **SFR**
  - SFR Fuel Fabrication

**Legend**
- TRU: Transuranic elements
- NM: Noble metal elements
- FP: Fission products
Pyroprocessing R&D Status

◆ Objectives and R&D strategies

● Increasing throughput, process efficiency and scale-up capability
  ▪ Development of core and leading-edge pyro-technologies by using Lab.-scale equipments
  ▪ Combination of U tests at PRIDE and hot-tests at INL through JFCS*
  ▪ ACPF/DFDF Facilities Operation

● Simple / easy remote operability and enhanced inter-connectivity between unit processes
  ▪ Construction and long-term operation of Eng.-scale PRIDE facility

● Reducing high-level waste generation
  ▪ Waste minimization by FPs separation and refined-salt recycling

● Safeguards approach and enhanced proliferation-resistance
  ▪ PR/PP enhancement and 3S by Design

* JFCS : Joint Fuel Cycle Study

Exterior of PRIDE
Pyroprocessing Technology Development

◆ Recent R&D status (I)

● High throughput
  ▪ Suitable feed material fabrication for accelerating electrolytic reduction reaction
  ▪ Semi-continuous operation of electrorefiner by adding a bucket-type uranium deposit transfer system
  ▪ Self-scraping of U dendrite by application of graphite cathode at electrorefiner

● Process Efficiency
  ▪ Higher group recovery efficiency of TRU by Residual Actinides Recovery (RAR) process using LCC electrolysis and CdCl₂ oxidant

● Scale-up Capability
  ▪ Design and fabrication of Eng-scale PRIDE based on Lab-scale performances
Recent R&D status (II)

- **Enhance remote operability and inter-connectivity**
  - Remote operability and maintainability improvements of unit pyroprocessing equipments with 3-D digital simulator, mock-up facility, and at PRIDE facility
  - Material flow analysis between up- and down-process
  - Integrated test of full-spectrum pyroprocessing system at PRIDE facility

- **Experience on spent-fuel test**
  - **Surrogates (DU and SimFuel) tests** with Lab-scale and PRIDE equipments
  - **Spent fuel tests** with IRT(Integrated Recycling Test) at INL under JFCS
  - **Coupling both test results** to get experiences on handling of spent fuel under Ar atmosphere and on design/operation of Ar hot-cell

- **Minimization of HLW waste generation**
  - Selective FPs (Cs,I etc.) off-gas capturing test at DFDF
  - Removal of FPs from salt waste ➔ Recycling of purified salt
  - Zr recovery from cladding hull and its reuse
3S-by-Design for Pyroprocessing

◆ Main achievement

● Safeguards technologies
  ▪ Design of safeguards system for REPF
  ▪ Modeling for performance evaluation (MUF evaluation)
  ▪ NDA technologies: Unified NDA system, LIBS, XRF
  ▪ Performance test (ACPF, PRIDE, INL facilities)

● Security technologies
  ▪ Vital Area identification based on design basis threat
  ▪ Design of the physical protection system

● Safety technologies
  ▪ Hazard analysis and design basis accident scenario determination
  ▪ Determination of safety requirements for hot-cell design

◆ International cooperation

● In collaboration with the IAEA and the US
  ▪ [MSSP] Design of a REPF and its safeguards system
  ▪ [JFCS] Application of existing safeguards techniques and development of new ones
Pyro-related Facility : 1. PRIDE

◆ Engineering-scale pyroprocessing facility

- **PRIDE** : PyRoprocessing Integrated inactive DEMonstration facility (10 ton-HM/yr)
  - **Purpose**: Demonstration of full-spectrum pyroprocessing performance with depleted uranium and surrogate materials in an Ar-environment cell (L40 x W4.8 x H6.4 m)
  - **Milestones**: Design (‘07~’08), Installation (‘09~’12.6), Blank tests (‘12.7~)
  - **Operation**: Salt test (‘13), DU test (‘14~’15), SimFuel(surrogate) test (‘15~’16)

- **Future R&D plan**
  - Demonstration of Eng-scale integrated pyroprocessing facility with surrogates (DU and SimFuels)
  - Experiences in scale-up and in-cell remote handling systems and utilities
  - Securing commercialization technology in connection with JFCS results
  - Development of safeguard technology through close cooperation with IAEA
Feed material fabrication for PRIDE OR

- Crushed UO₂ Fragment & Porous UO₂ Pellet

  1) Crushed UO₂ Fragment
     - With UO₂ pellet, prepare 1-4 mm fragment by crushing equipment
     - 1-4mm fragment yield : 75%

  2) Porous UO₂ Pellet
     - Porous pellet : φ 5.7 mm, h. 8 mm, d. 8.3~8.8 g/cm³
Pyro-related Facility : 1. PRIDE – 1.2 Oxide Reduction

◆ Engineering-scale PRIDE Oxide Reduction process development

● PRIDE Electrolytic Oxide Reducer(OR)
  ▪ **Purpose**: Metallization of oxide feeds supplying metal fuels to an electorefiner. Separation of high heat load alkali and alkaline earth elements from the metal products.
  ▪ **Characteristics**: 50 kg-U/batch, 1 cathode basket, 6 Pt anodes

● Experimental Results
  ▪ Salt level of 400 kg LiCl in the PRIDE OR was measured by both dip stick technique & radar sensor and the two methods are proven to be comparable and reliable.
  ▪ 3 batches of uranium tests (5 kg-DU, 15 kg-DU, 5 kg-DU per batch) were carried in the PRIDE OR to find out an optimum operation condition. Efforts to increase current will continue.
**Electro-refining experiment with uranium**

- **Basic electrochemical test**
  - CV (Cyclic Voltammetry) for LiCl-KCl-UCl$_3$ salt
  - Measurement of I-V curve: determine the cut-off voltage

- **Uranium electro-refining experiment with graphite cathode**
  - Electro-deposition of uranium dendrites on graphite cathode was successful.
  - Self-scraping characteristic of graphite cathode was verified and pure uranium metal was successfully recovered after residual salt distillation.

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**U deposits on Graphite cathode**

**Self-scraped & recovered U deposits**
Electro-winning experiment with uranium

- Basic electrochemical test
  - CV (Cyclic Voltammetry) for LiCl-KCl-UCl$_3$-NdCl$_3$ salt
  - Measurement of I-V curve

- Uranium electro-winning experiment with LCC
  - Electro-deposition of uranium and neodymium with a liquid cadmium cathode was successful and they were recovered after distillation of cadmium and residual salt
  - RAR (Residual actinide recovery) experiment was also conducted with CdCl$_2$
Pyro-related Facility: 1. PRIDE – 1.5 Waste salt treatment

**Waste Salt (LiCl, LiCl-KCl) Purification**

- **LiCl purification test**
  - Operation condition test for crystallization
  - 6-cooling plate: 650 → 590°C in melt temperature
  - Slower crystallization reaction for high purity of LiCl crystal

- **LiCl-KCl purification test (20 kg/batch)**
  - Operation test from precipitation to distillation step
  - Obtained proper conditions for recovery of LiCl-KCl

<table>
<thead>
<tr>
<th>&lt; LiCl purification &gt;</th>
<th>FPs separation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salt recovery</td>
<td>Cs</td>
</tr>
<tr>
<td>2605.84 g</td>
<td>99.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>&lt; LiCl-KCl purification &gt;</th>
<th>Salt recovery</th>
<th>Rare earths separation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99.75 %</td>
<td>&gt; 99.99</td>
<td></td>
</tr>
</tbody>
</table>

**Residual waste (LiCl, RE) solidification**

- **Preliminary test for 30cm- Wasteform**
  - Ln oxides (50wt%), ~1450°C: LABS glass
  - Consolidation condition test

Rare earth wasteform (Dia.: 30 cm)
Pyro-related Facility : 2. DFDF

◆ DFDF : DUPIC* Fuel Development Facility

● Purpose : Improvement of DUPIC technology on a laboratory-scale & Development of key technologies for dry treatment of PWR spent fuel

● General Features
  ▪ History: Construction(‘97~’99), Qualification Test(‘99~’04), Test and Operation (’05~ )
  ▪ Highly shielded air-cell facility w/ 25 pieces equipment & devices: L24 x W2 x H4 m
  ▪ Remote handling system: Crane1 set, MSM 10 sets (10 windows workstation)
  ▪ Development of S/G system in cooperation with LANL and IAEA

● Future R&D plan
  ▪ Key technology Improvement & demonstration for head-end process of SF
    – Burn-ups effect : Decladding, Powder homogeneity, Off-gas capturing, Sintering
  ▪ Demonstration of feed material fabrication for ACPF OR (under Pyro JD)
    – Feed form : Fragment, Porous pellet
    ❖ Acquisition of revised FA (Facility Attachment) from IAEA under new DIQ : Jan. 18, 2013

* DUPIC : Direct Use of PWR fuel in CANDU reactor
Pyro-related Facility : 3. ACPF

◆ ACPF : Advanced spent fuel Conditioning Process Facility

● Purpose : To verify feasibility of an electrolytic oxide reduction process for PWR spent fuel in combination with DFDF

● General features
  ▪ History: Const’n(‘03~‘05), Inactive Test(‘06~), Refurbishment(‘13~‘14), Op’n (‘15~)
  ▪ Highly shielded hot cell( L11 x W2 x H4 m) : equipped with a modular type Ar compartment inside hot cell after refurbishment work
  ▪ Remote handling system: Crane1 set, MSM 5 sets (5 window workstations)

● Future R&D plan
  ▪ Key technology development for electrolytic reduction process (under Pyro JD)
    – Assessment of electrochemical reaction behaviors : Potential of electrodes, Reduction yields(U/TRU/NMs), and FPs behaviors (Ar cell: L1.8 x W1.8 x H2.4 m)
    – Assessment of OR system : Stability, remote operability and maintainability
  ▪ R&D to enhance safeguards ability for electrolytic reduction process
    – Demonstration of ASNC(ACP Safeguards Neutron Counter)
    – Study of LIBS(Laser-Induced Breakdown Spectroscopy Instrumentation)
Pyro-related Facility : 3. ACPF

◆ ACPF Oxide Reduction process development

- APCF electrolytic oxide reduction
  - **Characteristics:** 1 kg-HM/batch, 1 cathode basket, 2 Pt anodes
  - **Operation:** Mock-up test (’14), Hot cell surrogate test (’15), SimFuel (and SF, if possible) test (’16~)

- **Experimental results**
  - As a preliminary step for the ACPF hot tests, an ACPF OR mock-up system was constructed and OR tests with Simfuel were carried out in 2014.
  - 3 batches of Simfuel tests (0.4 kg-U/batch, 0.6 kg-U/batch, 1.1kg-U/batch) showed 99.91%, 99.83%, 99.93% of uranium reduction yield, respectively. Efforts to secure safe hot-cell operation will continue.
On 13 April 2011, the ROK and USA entered into a new era of bilateral nuclear energy partnership. We launched the Joint Fuel Cycle Studies (JFCS), which includes:

- Electrochemical Recycling (CRADA),
- Safeguards and Security, and
- Fuel Cycle Alternatives.

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
Summary

◆ Public and stakeholder engagement program has been started to recommend a national spent fuel management policy by June 2015.

◆ KAERI has full spectrum R&D programs for SF management
  ● Transportation, (interim) storage, and geological disposal system for HLW
  ● Pyroprocessing - SFR system

◆ KAERI has been developing a viable pyroprocessing system with
  ● Engineering-related leading-edge technologies and
  ● High proliferation resistance with respect to strict safeguards through
    ➢ Demonstration of PRIDE/ACPF/DFDF facilities to test the performance and integrity of unit processes and pertaining scale-up technology
    ➢ JFCS to evaluate the technical and economic feasibility and nonproliferation acceptability of the pyroprocessing process
    ➢ IAEA cooperation with respect to safeguards and transparency

◆ Adopting AFC (Pyro-SFR system) is a promising strategy for resolving the issues of spent fuel management and energy security in Korea.
Thank you for your attention..!!

Clean Energy!  Clean Korea!