Prof. Yang graduated from the Seoul National University with a B.S. in metallurgical engineering in 1973 and from the Northwestern University with a Ph.D. in materials science and engineering in 1984. He has been working at KAERI (Korea Atomic Energy Research Institute) for 30 years on the Research and development of PWR/CANDU fuel fabrication, quality control of fuel, DUPIC (direct use of spent PWR fuels in CANDU) cycle and the pyroprocessing. He gained his experience in nonproliferation while participating to the GIF Proliferation Risk and Physical Protection (PR/PP) activities as well as the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) activities.

He served as the President of KAERI during 2007 to 2010 and he is a member of the National Academy of Engineering of Korea. He is a professor at the Institute of Energy and Environment at Youngsan University of Republic of Korea since 2015.

He received a decoration “Woong-Be Order” from the Korean government in 2011, and a WNA (World Nuclear Association, London) Award in 2009 for his contribution to the peaceful use of nuclear energy.

Email: myangkorea@gmail.com
OUTLINE

- Concept of Nuclear Fuel Cycle
- Spent Nuclear Fuel Management
- Nuclear Fuel Cycle Technology
- Summary
NUCLEAR REACTOR

- Neutron Energy
  - Thermal (< 0.1 eV)
  - Fast (0.1 ~ 2 MeV)

- Moderator
  - Light Water (H₂O)
  - Heavy Water (D₂O)
  - Graphite (C)

- Coolant
  - Light Water (H₂O)
  - Heavy Water (D₂O)
  - Liquid Metal (Na, Pb)
  - Gas (He)

- Reactor/Fuel
  - LWR (PWR, BWR)/ Fuel: Enriched UO₂
  - PHWR (CANDU)/ Fuel: Natural UO₂
  - LMR (SFR)/ Fuel: (U/Pu)O₂, U-TRU
NUCLEAR FUEL CYCLE:

1. **Mining**
   - Uranium ore

2. **Milling & Refining**
   - Yellow cake $U_3O_8$

3. **Conversion**
   - UF₆

4. **Enrichment**
   - Enriched UF₆

5. **Reconversion**
   - MOX/TRU fuel

6. **Pu Fuel Fabrication**
   - Fuel assembly

7. **Fuel Fabrication**
   - Low-level waste

8. **Reprocessing**
   - Plutonium recycling
   - High-level waste
   - Uranium recycling

9. **Interim Storage**
   - Spent fuel
   - Low-level waste

10. **Reactor**
    - Spent fuel

11. **High-level Waste Treatment**
    - Vitrified high-level waste

12. **High-level Waste Disposal**

13. **Low-level Waste Disposal**

- Uranium recycling
- Yellow cake $U_3O_8$
- Enriched UF₆
- MOX/TRU fuel
- Fuel assembly
- Spent fuel
- Low-level waste
- Vitrified high-level waste
- Uranium ore
FUEL CYCLE ALTERNATIVES

U Fabrication

Conversion

Enrichment

MOX Fabrication

PWR

U, Pu, MA

Wastes Disposal

Spent Fuel Storage

DUPIC

DUPIC Fuel Fabrication

Purex

U, TRU, FP

U, Pu

Natural U

Metal Fuel Fabrication

U, TRU

PYRO PROCESS

Dry Processing

FP

Wastes Disposal

Dry Processing

Pyro Process

PyrOx

Hyper Fuel Fabrication

TRU, Impurity FP, I, Tc

ADS (Burner)

U, Pu

Ma = Np, Am, Cm, ...

TRU = MA + Pu
CHARACTERISTIC OF NUCLEAR FUEL CYCLE

**Peaceful Use**
- Uranium Ore
- Milling/Conversion
- Fuel Fabrication
- NPP
- Storage

**Industrial Use**

**Strategic Use**
- Highly Enriched Uranium
- Pure Plutonium

**Military Use**

**Internationally Sensitive**
COMPOSITION OF SPENT NUCLEAR FUEL

Fresh Fuel

Spent Fuel

1.1% : Plutonium  →  Recycle
0.2% : Neptunium, Americium, Curium
0.2% : Long Half-life (I, Tc)
0.5% : High Decay Heat (Cs, Sr)
4% : Short Half-life (less than 300 yr)
94% : Uranium  →  Recycle

4yr burn

* 4.5wt% U\(^{235}\)
55 GWd/tU
10 yrs cooling

U-235 (4.5wt/%)  
U-238 (95.5wt/%)
DECAY HEAT OF SNF

Cooling Time (Year) vs. Decay Heat (Watts/MtU) for PWR 45 GWd/tU (PWR45)

- Cs+Ba
- Sr+Y
- Total Fission Products
- Total Actinides
- Pu
- Po
- Np
- Pm
- Eu
- Sb
- An
- U
- Th
- Grand Total

The graph shows the decay heat of SNF for different elements and their total over time.
Radiotoxicity with SNF management (\(\approx\) Disposal site management period)

- Direct disposal: Over 300,000 yrs
- Pu separation from SNF: Below 15,000 yrs
- TRU(Pu + MA) separation: About 300 yrs
SNF STORAGE

Wet

Dry
HLW DISPOSAL

Surface Facilities:
- Encapsulation Plant
- Bentonite Plant
- Crushed Rock Plant
- Utilities

Underground Facilities:
- Shafts: Operation, Ventilation
- Access Tunnel
- Disposal Area
CONSIDERATIONS FOR DISPOSAL SITE

☐ How will prolonged exposure to heat and radiation affect the surrounding rock?
  ▪ Radiation shielding of canister
  ▪ Maximum allowable thermal loading per disposal package
  ▪ Long-term integrity of engineering & natural barriers under high radiation and heat environments

☐ How soon will the repository be filled with groundwater?
  ▪ Prevention of groundwater intrusion/retardation → buffer and backfill material with low permeability.

☐ How fast will the disposal canister corrode?
  ▪ High corrosion resistance of canister material → Cu, titanium, stainless-steel, etc

☐ How fast will the various radionuclides dissolve?
  ▪ Waste matrix → insoluble solid form

☐ How will the dissolved substances travel through rock?
  ▪ Buffer/backfill material with high sorption ability
  ▪ Groundwater movement in the rock → natural process (dilution effect, additional sorption effects)
INNOVATIVE NUCLEAR ENERGY SYSTEM

- GIF (Generation IV International Forum)
- INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles)

- Sustainability
  - Proliferation Resistance
  - Environmental Effect
  - Economics
  - Waste Management
REQUIREMENT OF ADVANCED NUCLEAR FUEL CYCLE

- **Environmental Aspects**
  - Reduction of environmental burden: Reduction of radiotoxicity
    - Time of decay to the toxicity level of the initial uranium ore < 300 yrs

- **Waste Aspects**
  - Minimization of repository footprint
    - Reduction of the heat load of HLW to be disposed off < 1/100
    - Reduction of needed repository footprint < 1/100

- **Proliferation Resistance Aspects**
  - Enhancement of proliferation resistance
  - “Dirty fuel-clean waste” with homogeneous recycling of all TRUs

- **Economics Aspects**
  - Economic compatibility with the current options
PROCESS FLOW OF WET/DRY FUEL CYCLE

Pu with TRU & others

Spent Fuel

Interim storage

High purity Pu

DUPIC

Pyroprocess

Rod cutting
Decladding

PUREX

Dissolution in nitric acid

Spent Fuel

Reduction

Refining

(U+TRU+RE) metal

Melting /injection

(U+Pu) Fuel

(OrU+Pu+FP)O2

High decay heat(Cs, Sr)

Volatile (I2, Kr, Ru)

OREOX

DUPIC Fuel

CANDU

GEN-IV Reactor

PWR

HLW

Separation (U, Pu)

MOX(U+Pu)

PWR GEN-IV Reactor

Separation (U+ Pu)

U
## PUREX(EX) - UNIT PROCESS AND EQUIPMENT

<table>
<thead>
<tr>
<th>Process</th>
<th>Equipment</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disassembly Chopping</td>
<td>. Mechanical . Laser</td>
<td>. Cutting fuel rods (4~5 cm)</td>
</tr>
<tr>
<td>Dissolve</td>
<td>. Dissolver</td>
<td>. Dissolution in hot and high HNO₃ (~130°C)</td>
</tr>
<tr>
<td>Solvent Extraction</td>
<td>. Mixer-Settler . Pulsed Column</td>
<td>. Separation of U-Pu/FP . Partition of U/Pu (with oxidation control of Pu)</td>
</tr>
<tr>
<td>U Purification</td>
<td>. Mixer-Settler . Pulsed Column</td>
<td>. Purification by solvent extraction</td>
</tr>
<tr>
<td>Pu Purification</td>
<td>. Ion Exchanger column . Mixer-Settler</td>
<td>. Purification by ion exchange/solvent extraction</td>
</tr>
<tr>
<td>U/ Pu concentration</td>
<td>. Evaporator</td>
<td>. Evaporation/concentration/denitration</td>
</tr>
</tbody>
</table>
SOLVENT EXTRACTION:
U-PU COEXTRACTION, U/PU PARTITION, U & PU PURIFICATION

◆ Solvent extraction principle

◆ Solvent extraction equipment

Mixer-Settler

Pulsed Column
## Advanced Wet Processes

### Commercial PUREX
- PUREX → pure Pu extraction → MOX fuel fabrication → LWR (Pu-thermal)
- 5 nuclear weapon states & Japan, India (PUREX)
- Economics of utilization of MOX fuel in LWR

### Advanced Wet Processes
- **Improved economics & proliferation resistance & HLW volume reduction**
  - Transmutation of long-lived nuclides → Environmentally friendly
  - Improved U utilization (closed fuel cycle)
  - Partition of long-lived and highly heat-generating nuclides
    → Improved disposal efficiency (reduced HLW volume, short management term)
  - Reuse of valuable elements (PGM, Pu, etc)
- **Advanced wet process:** CoDCon and ALSEP (U/Pu and TRU: USA), NEXT (U-Pu-Np: Japan), COEX (U-Pu: France)
  - Improve the recovery of TRU, Cs/Sr, long-lived fission products
  - Reducing secondary process waste amounts
  - Co-separation of U, Pu, MA, and Ans⁺³/Lns⁺³ partition
  - Use of eco-friendly salt-free solvents
NUCLEAR FUEL CYCLE STRATEGY (EXAMPLE)

DUPIC

Pyro-SFR Closed Fuel Cycle

Pyroprocess

FR Metal Fuel (U-TRU-Zr)

(Cs, Sr) Decay Storage

GEN-IV FR(SFR)

Benefits
- Save disposal space
- Increase U utilization
- Intrinsic proliferation resistance

Save disposal space
Increase U utilization
Intrinsic proliferation resistance
DUPIC (DIRECT USE OF SPENT PWR FUEL IN CANDU REACTORS)

Spent PWR Fuel

- Cut to Size
- Decladding
- Oxidation/Reduction
- Pelletizing/Sintering
- Welding

- Skeleton
- Volatiles
- Cladding Hulls
- Volatiles & Semi-volatiles

Fuel Rods

Structural Parts

Fuel Rods

CANDU Fuel Bundle
### DRY PROCESS TECHNOLOGY

<table>
<thead>
<tr>
<th>Process</th>
<th>Fuel</th>
<th>Operation</th>
<th>Chemical agents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyro-metallurgical</td>
<td>Metal fuel (EBR-II)</td>
<td>Batch</td>
<td>UCl$_3$, ZnCl$_2$, MgCl$_3$, LiCl-NaCl-MgCl$_2$</td>
</tr>
<tr>
<td>Pyro-chemical</td>
<td>Oxide fuel</td>
<td>Batch</td>
<td>LiCl-KCl-MgCl$_2$, Cu-&lt;g-Ca alloy</td>
</tr>
<tr>
<td>Fluoride volatility</td>
<td>Metal &amp; Oxide fuel</td>
<td>Batch</td>
<td>UF$_6$, PuF$_6$, F$_2$, ClF$_3$</td>
</tr>
</tbody>
</table>

- High PR due to no Pu separation, Fuel type with Mixture of U+TRU (Pu+MA) linking to Gen-IV SFR
- Korea, USA, China, India, Russia, etc.
PYRO-SFR CLOSED FUEL CYCLE

- Save disposal space by a factor of 100
- Shorten the management period to a few hundred years
- Increase U utilization by a factor of 100
- Ensure intrinsic proliferation resistance

MA: Np, Am, Cm

(U,Pu,MA)O₂ → Oxygen Removal → Electro-reduction → Electro-refining → Electro-winning → SFR Fuel Fabrication

Spent SFR Fuel → Uranium Recovery → U,Pu,MA Co-Recovery → SFR Metal Fuel → Burning of Pu, MA

U Recycle
PYROPROCESSING - PROCESS FLOW

TRU: TRansUranium (Pu, Np, Am, Cm)
REE: Rare Earth Element (Eu, Gd, Nd, Ce)
NM: Noble Metal (Pd, Ru, Rh)

Salt Waste

TRU Electro-winning

Electro-refining

U Recovery

U Recycle, Low-level Waste

UO₂

U₂O₈+(TRU+FP) Oxide

Air

I₂, Kr, Xe

PWR Spent Fuel

Declad

High Temp Treatment

Electro-reduction

Salt Waste

Treatment & Recycle

Low-level Waste

Cladding Hull

Declad

High Temp Treatment

Electro-reduction

Salt Waste

U Recovery

U Recycle, Low-level Waste

TRU Fuel Fabrication

SFR Spent Fuel

SFR
Electrolytic reduction in molten salt: Metal product (U+TRU+Some FPs) for electrorefining

**Cathode : Reduction**
- $\text{UO}_2 + 4e^- \rightarrow \text{U} + 2\text{O}^{2-}$
- $\text{Li}^+ + e^- \rightarrow \text{Li}$
- $\text{U}_x\text{O}_y + 2y\text{Li} \rightarrow x\text{U} + y\text{Li}_2\text{O}$
- $2\text{Li}_2\text{O} \rightarrow 2\text{Li}^+ + \text{O}^{2-}$

**Anode : Oxidation**
- $\text{O}^{2-} \rightarrow \frac{1}{2}\text{O}_2 + 2e^-$

**Metal product**

- **Reduction to metal**
  - U, TRU(Pu, Am, Cm, Np)
  - NM(Zr, Pd, Rh, Ru etc.)

- **No reduction**
  - RE(Y, Pr, Nd, La etc.)

- **Salt**
  - Remaining salt phase
  - AM & AEM(Cs, Sr, Ba)
## COMPARISON OF WET & DRY PROCESS

<table>
<thead>
<tr>
<th>Process</th>
<th>PUREX</th>
<th>Pyroprocess</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of components(^1) [Compactness]</td>
<td>About 180</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Cooling time</td>
<td>&gt; 5 years</td>
<td>&lt; 1 year</td>
</tr>
<tr>
<td>Criticality hazard</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Pure Pu separation</td>
<td>Yes</td>
<td>No [U+TRUs]</td>
</tr>
<tr>
<td>Operation mode</td>
<td>Continuous type</td>
<td>Batch type</td>
</tr>
<tr>
<td>Waste generation(^2) (HLW)</td>
<td>230 te (UREX+)</td>
<td>490 te</td>
</tr>
<tr>
<td>Demonstration</td>
<td>Commercial</td>
<td>Laboratory</td>
</tr>
</tbody>
</table>


\(^2\) USDOE, AFCI Comparison Report, May 2005 [Basis: 2,000 MT of Spent Fuel].

### Process Development
- High throughput reactor system
- Corrosion-resistant materials including electrodes

### Process Waste Minimization
- Recycling of used salts
- Waste form integrity

### Safeguardability Improvement
- Near real time accounting
- Safeguards by design

### Economical Feasibility
- Process modeling & simulation
- Integrated engineering-scale demonstration
NUCLEAR NONPROLIFERATION REGIME

- **System** to prevent the diversion of peaceful use technology from military use and to prevent the nuclear weapon test to improve nuclear weapon
  - **Vertical Proliferation**
    - Increase in the nuclear arms of the five nuclear weapon states
    - Preventive measures: Test-ban, Fissile material cutoff
  - **Horizontal Proliferation**
    - Increase the number of countries with nuclear weapons
    - Preventive measures: Safeguards, Exports control, Physical protection

- **Safeguards: Activities** that impede the diversion of undeclared production
  - **Material control and accounting, Containment and Surveillance (C/S)**
  - **IAEA inspection, Record/Reporting/Verification**

- **Safeguardability**
  - **Degree of ease** with which IAEA technical objectives can be, Including features to help the implementation of safeguards (e.g., Material control, Facility design) met in cost effectiveness and to establish facilities whose process, design, and layout support the effective and efficient implementation of IAEA safeguards
Pyroprocess has lower proliferation potential
- Limited capability in separating Pu, additional chemical separation activity is required for further separation of Pu
- Less flexibility in changing product purity and throughput
- High dose of U/TRU product requires additional radiation shielding

Safeguards challenges
- Less safeguards experience (no commercial scale facility)
- Larger measurement uncertainties of feed, product, waste and process material
- Sampling procedures, DA(destructive analysis), NDA and process parameters are not yet established
- Signature and indicators of the IAEA physical model need to be updated

- To develop the nuclear material accounting and surveillance technology
- To design a safeguards system based on the concept of Safeguards-by-Design
- To Investigate the safeguardability of a pyroprocessing facility
SAFEGUARDS R&D

- Safeguards Neutron Counter and C/S system
  - Development of built-in safeguards system in international cooperation with IAEA
  - Passive neutron coincidence counter with full remote maintenance capabilities
  - C/S monitoring data transmitted to Regulator and IAEA through Virtual Private Network
  - Upgrade with enhanced remote control capability

- LIBS (Laser Induced Breakdown Spectroscopy) Monitoring system
  - To determine the elemental composition of the samples of interest through real-time analysis, in-situ measurement, and multi-elemental analysis
  - Applicability test to address safeguards and process monitoring
The dynamic behavior of nuclear energy system economics (from 2013 to 2100) by comparing the total system costs for the once-through fuel cycle with those for the closed fuel cycle associated with pyroprocessing and SFR

- For the total system costs, the closed nuclear energy system is more expensive than that the once-through system.
- For the fuel cycle costs only, the once-through fuel cycle is expected to increase the cost of nuclear generated electricity compared to the fuel cycle cost of the closed fuel cycle.
- However, the levelized cost distributions of the two nuclear energy systems largely overlap because of large cost uncertainties involved with all system steps.
- Cost saving for the closed system is to be proved and requires further development and demonstration of the technology on the engineering-commercial scale basis.
### POLICY FOR SNF MANAGEMENT (EXAMPLE)

<table>
<thead>
<tr>
<th></th>
<th>Korea</th>
<th>USA</th>
<th>Japan</th>
<th>France</th>
<th>Russia</th>
<th>China</th>
<th>India</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel Cycle Policy</strong></td>
<td>Wait &amp; See</td>
<td>Direct disposal/Wait &amp; see (P&amp;T)</td>
<td>Recycle (P&amp;T)</td>
<td>Recycle (P&amp;T)</td>
<td>Recycle (P&amp;T)</td>
<td>Recycle (P&amp;T)</td>
<td>Recycle (P&amp;T)</td>
</tr>
<tr>
<td><strong>Target Yr for INS</strong></td>
<td>2020's</td>
<td>2040s</td>
<td>2040s</td>
<td>2020 ~ 2040</td>
<td>2020s</td>
<td>2020s</td>
<td>2020s</td>
</tr>
<tr>
<td><strong>Reactor (Fuel)</strong></td>
<td>SFR (Metal)</td>
<td>SFR (Metal, Oxide)</td>
<td>SFR (Oxide)</td>
<td>SFR (Oxide) GFR (Carbide, Nitride)</td>
<td>SFR (Oxide) GFR (Carbide, Nitride)</td>
<td>SFR (Mixed oxide)</td>
<td>SFR (Mixed carbide, Oxide, Metal)</td>
</tr>
</tbody>
</table>
SUMMARY

◆ Benefits of closing nuclear fuel cycle
  ● Sustainability
  ● Management of high level waste
  ● Environmental friendly
  ● Management of repository for permanent disposal
  ● Enhanced proliferation resistance

◆ Advanced wet & dry fuel cycle processes along with safeguards technology under development

◆ National policy of spent fuel management to be decided
UPCOMING WEBINARS

22 November 2016  Introduction to Nuclear Reactor Design  Dr. Claude Renault, CEA, France

15 December 2016  Sodium Cooled Fast Reactors  Dr. Robert Hill, ANL, USA

25 January 2017  Very High Temperature Reactors  Mr. Carl Sink, DOE, USA