Transmutation of nuclear wastes by metal fuel fast reactors


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What is nuclear wastes problem?

The biggest problem on nuclear wastes

↓

Disposal of high-level radioactive waste

↓

How should we manage used nuclear fuel?
Many valuable and few harmful elements in used fuel

- **Fission products (Half-life > one year)**: 1%
- **Fission products (Half-life < one year)**: 4%

**Transmute to stable or short-lived nuclides by neutron reaction in reactors**

**Natural decay to short-lived nuclides in a short time**

**Fuel materials**: 95%

**Recycling use as energy resources**
Radioactivity and half-life of fission products

LLFPs are only a few nuclides among all FPs

Radioactivity > 0.1 Bq/g-fuel
10^{10} year > Half-life > one year


LLFP : Long-Lived Fission Product


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Preferred reactor type for transmutation?

Long-lived radioactive nuclides is transmuted to stable or short-lived radionuclides by neutron capture reaction

\[ \downarrow \]

Transmute using neutrons in fission reactors

\[ \downarrow \]

Reactors with many excess neutrons are preferred
## Comparison of excess neutron capability

<table>
<thead>
<tr>
<th>Types of neutron reaction</th>
<th>LWR</th>
<th>FR</th>
<th>Oxide fuel</th>
<th>Metal fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yield</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fission</td>
<td>2.4</td>
<td>2.9</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td><strong>Consumption</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Chain (fission) reaction</td>
<td></td>
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</tr>
<tr>
<td>fission</td>
<td>1.0</td>
<td>0.8</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>fertile fission</td>
<td>~0</td>
<td>0.2</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Fuel production for conversion ratio 1.0</td>
<td>1.25</td>
<td>1.0</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Parasitic capture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fissile capture</td>
<td>0.25</td>
<td>0.2</td>
<td>0.14</td>
<td>0.2</td>
</tr>
<tr>
<td>others (structural materials and coolant)</td>
<td>0.4</td>
<td>0.25</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

### Excess neutrons

- Preferred reactor type for transmutation -

<table>
<thead>
<tr>
<th>LWR</th>
<th>Oxide fuel FR</th>
<th>Metal fuel FR</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.5</td>
<td>0.45</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Toshiba long-term vision - metal fuel fast reactor -

Toshiba has been developing actinide recycling technologies:
- Long-term energy security
- Nuclear waste transmutation (environmental harmonization)
- Economical FR cycle
- High proliferation resistance

TRU: Transuranium
Roadmap

Phase 1
〜2030
Technology development

Phase 2
〜2050
Transmutation of LWR nuclear wastes (LWR-dominant era)

Phase 3
Sustainable nuclear energy system by FR

U+TRU+LLFP recycling FR

High-efficient transmutation by uranium-free metal fuel FR

MONJU utilization etc.
Phase 1: Transmutation study assuming MONJU

Features

● Replace the current MONJU core with metal fuel and LLFP target sub-assemblies (S/A) without major modification of the reactor structure:

- Core fuel → U+TRU metal fuel
- Radial blanket (1st row) → LLFP target S/A
  - I129: 7 S/As, Tc99: 4 S/As
  - Cs135, Sn126: 21 S/As for each
  - Zr93: Utilize as fuel alloy material
- Radial blanket (2nd, 3rd row) → U+TRU metal fuel

● Thermal power output: 714MWt

● TRU and LLFP amount to be charged in core
  - TRU 1.9t (10 years’ operation of 1 GWe-LWR)
  - LLFP I129 0.1t (10 years’ operation of 1 GWe-LWR)
    - Tc99 0.3t (10 years’ operation of 1GWe-LWR)
    - Cs135 0.2t (4 years’ operation of 1GWe-LWR)
    - Sn126 0.3t (120 years’ operation of 1GWe-LWR)
    - Zr93 0.38t (20 years’ operation of 1GWe-LWR)

Core layout

(The study funded by JAPC.)
Phase 2: Uranium-free metal fuel FR cycle

- TRU transmutation at LWR-dominant era -

20 GWe

LWR \[\rightarrow\] Reprocess \[\rightarrow\] TRU

5 GWe

FR cycle

\[\rightarrow\] TRU-Zr metal fuel
\[\rightarrow\] Pyroprocess
\[\rightarrow\] Injection casting

\[\rightarrow\] Burn TRU from LWR by uranium-free metal fuel FR

20 GWe LWR \[\rightarrow\] Reprocess \[\rightarrow\] TRU

4 tTRU/yr

U

U,TRU

Temporary storage for future FR

\[\rightarrow\] No production of new TRU due to “uranium-free” → Minimize the required number of FR units → Only 5 GWe FR can burn TRU from 20 GWe LWR

\[\rightarrow\] Uranium-free metal fuel could be reprocessed by conventional pyroprocess → Minimize new R&D items
Features

- **Electrical power output:** 300 MWe
- **Core fuel:** TRU-35Zr 及び TRU-19Zr metal fuel (uranium-free)
- **Core height:** 65cm
- **Operating cycle length:** 150 days
- **Neutron moderator, BeO** in fuel S/A for safety performances (e.g., Doppler feedback)
- **Safety parameters:** equivalent to conventional metal fuel FRs
  - Doppler coefficient: \(-3 \times 10^{-3} \, \text{Tdk/dT}\)
  - Effective delayed neutron fraction: 0.0026
  - Sodium void reactivity: \(< 0 \, \%\text{dk/kk}'\)
- **Net burning rate of TRU:** 260 kg/year
  -> Capable to burn TRU from 1.2 GWe LWR every year

Phase 2: Uranium-free metal fuel FR cycle

Toshiba Advanced Aqua-Pyro Process

Process description
1. The Toshiba Advanced Aqua-Pyro Process recovers MA metal from HLLW of PUREX.
2. The recovered MA is mixed with Pu nitrate in PUREX process.
3. Finally, TRU metal is recovered by electro-reduction following Pu-MA co-denitration

Phase 3: Sustainable nuclear energy system by FR

**Features**

- **Thermal power output:** 780 MWt
- **Core fuel:** U-TRU-10Zr metal fuel
- **Core height:** 90 cm
- **Operating cycle length:** 2 years
- **Four-zones’ core on TRU enrichment**

**Fuel conversion ratio:** 1.0 → long-term energy security

- **U-TRU grouped recycling and LLFP (I129, Tc99, Cs135, Sn126, Zr92) transmutation**
  → Possibility of no high-level waste repository
  → Significant public perception on nuclear power
  → Significant reduction of waste disposal burden

- **No blanket fuel core** → High proliferation resistance

**Sustainable nuclear power system after LWR era**


(The study funded by JAPC.)
Toshiba FR component development

Sodium test of the full-scale EM pump for Toshiba Small FR, 4S

No moving parts of main pump

Diameter 3.3 m

Helical processed double-wall tube

Prevention of Na-water reaction

Enlarged photograph of double-wall tube section

Outer tube

Inner tube

Steam generator with double-wall tube for FR


(The part of present study is the result of “Development of high temperature electromagnetic pump with large diameter and a passive flow coast compensation power supply and development of a Helical-coil double wall tube steam generator to be adapted into medium and small reactors of GNEP” entrusted “Toshiba Corporation” by the Ministry of Economy, Trade and Industry (METI) of Japan.)
Toshiba advanced fuel cycle development

Toshiba has been developing pyroprocess technology with CRIEPI for more than 20 years

1 kg metal uranium deposited by electro-refining (in cooperation with CRIEPI)

Glove box for engineering-scale electro-refiners

Concluding remarks

• Scientific feasibility of nuclear waste transmutation has already been confirmed, and the engineering feasibility is being clarified.

• There are further R&Ds need to be done. However, we believe nuclear waste problem must be solved by the steady and continuous development of related technologies.

• Toshiba is committed to contribute to its realization in cooperation with associated organizations.