Fuel Cycle Research and Development

U.S. Study on Impacts of Heterogeneous Recycle in Fast Reactors on Overall Fuel Cycle

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Scope of Activities

- Evaluation of fuel cycle technology and economics issues associated with use of heterogeneous recycle approach in fast reactors
  - Compare to homogeneous recycle approach where pertinent
  - Review, assess, and integrate past and ongoing national and international studies
  - Participate in international studies on subject
Homogeneous and Heterogeneous Recycle Approaches

**Heterogeneous Recycle**

- Figure shows TRU path only
- Driver Assemblies → FRs
- FR SNF
- FR SNF Separations
- Driver Fuel Assembly Fabrication
- Target Fuel Assembly Fabrication
- Process Waste
- Pu Product Stream (or with Np)
- MA Product Stream
- LWR SNF Separations
- LWRs

**Homogeneous Recycle**

- Figure shows TRU path only
- Fuel Assemblies → FRs
- FR SNF
- FR SNF Separations
- FR Fuel Assembly Fabrication
- Process Waste
- Grouped Pu+MA Product Stream
- MA Product Stream
- LWR SNF Separations
- LWRs

SNF = Spent Nuclear Fuel
FR = Fast Reactor
LWR = Light-Water Reactor
MA = Minor Actinides
## Reasons for Heterogeneous Recycle Approach

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<th>Reason</th>
<th>Comments</th>
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| Existing fuel recycle infrastructure (in particular fuel fabrication) | ▪ Not an issue in some countries such as the U.S. (no facilities yet), but could be in Europe and Japan, which have existing MOX fuel facilities  
▪ Incentive to minimize MA handling equipment and assemblies containing MA in the fuel cycle |
| Rapid initiation of transmutation campaign with fast reactors as part of an advanced fuel cycle strategy | ▪ Fast reactors can be used for material burning and fissile material production to support nuclear sustainability  
▪ Intent is to delay utilization of MA in initial fuel to allow additional R&D, qualification and regulatory acceptance of innovative transmutation fuels  
  ○ Very active fuel to be handled  
  ○ No large experimental database for innovative fuel and its behavior under irradiation |
Areas and Items Covered

BACKGROUND
- Background on Plutonium and Minor Actinides (MA) Production
- Strategies for MA Management with HR Approach – burn-down and stabilization
- Recycle Approaches by Countries

FUEL RECYCLE, SEPARATIONS AND PARTITIONING IMPACTS
- UREX+ Aqueous Separation for HR Approach
- Pyrochemical Processes
- Impacts of HR Approach on Pyrochemical Separations Processes
- Future Studies to Support Heterogeneous Recycle

FAST REACTOR TRANSFORMATION ISSUES ASSOCIATED WITH HETEROGENEOUS RECYCLE (HR)
- Fast Reactor Types for HR
- Assessment of Reactor Safety as Basis for Utilization of HR Approach
- TRU Composition of Driver and Target Fuels
- Fuels for HR Cores
- Systematic Study of Characteristics of Heterogeneous Versus Homogeneous Recycle
- Core Residence Times
- Core Conversion Ratio Impacts
- Impact of Moderation in Target Fuel Assemblies
- Location of Target Assemblies
- Minor Actinide Core Loading Impacts
- Helium Generation in Metallic Target Fuel
- Spent and Fresh Fuel Handling Issues
- Systems Scenario Issues Associated with Minor Actinide Recovery and Utilization
- Fraction of Target Assemblies in HR Core
Areas and Items Covered (Cont’d)

**FUEL FABRICATION IMPACTS**
- Assessment of Homogeneous and Heterogeneous Recycle Driver and Target Fuels
- Cost Comparison of Heterogeneous Recycle Oxide Fuels and LWR MOX Fuels
- Innovative Production Pathway for HR Metallic Fuels
- Assessment and Processes for HR Oxide and Hydride Fuel Fabrication
- Measures for Heat Generation During TRU Fuel Fabrication
- Conclusions on Driver and Target Fuels Fabrication

**TRANSPORTATION IMPACTS**
- Assembly Transport – On-Site
- Target Assembly Transport – Off Site
- Criticality of Target Assembly
- Location of Target Recycle Facilities

**PROLIFERATION RISK IMPACTS**
- Fuel Cycle Options
- Fabrication of Fast Reactor Fuels
- Separations Facilities
- Delayed Introduction of Minor Actinides in Fast Reactor Fuel Cycle
- Enrichment of Fuels for LWRs
- Target Potential as Breeder
- Used Fuel Cooling
Review indicated that limits have been imposed on MA loading in homogeneous recycle cores based on safety considerations

- Homogeneous recycle core designs are robust, but detailed design and safety evaluations still required to confirm appropriate limits
- Required MA/HM content in homogeneous recycle fast reactor decreases with fuel recycle stages, relative to ratio in LWR UNF – fast spectrum reduces higher MA
- Homogeneous recycle reactor could progressively load more MA in fuel cycle

Fuel performance and handling impose limit on MA content in target fuel

- Results of U.S. and international studies analyzed
- Studies suggest MA content in U-MA oxide fuel must be less than 20% (maybe closer to 10%)
Locations of Target Assemblies/Pins in Heterogeneous Recycle Concepts

Am Target In-Core
- Annulus -
(Am contents: 10 – 20%)

Am Target Ex-Core
Loading

Reference Core Layout (12 Target Assemblies)

Primary Control Rods
Ultimate Shutdown
Inner Core (Lowest TRU Enrichment)
Middle Core
Outer Core (Highest TRU Enrichment)
Reflector
Shield
Targets

Homogeneous Target Assembly

Heterogeneous Target Assemblies with Target and Moderator

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Strategies for Am and Cm Management in Heterogeneous Recycle Fast Reactor Fuel Cycle

- Co-extract Am and Cm and transmute in same fuel pin
  - As MA content increases, fuel handlers and fabricators must contend with high heat and radiation levels

- Separate Am from Cm and transmute only Am
  - Removes most neutron radiation hazard during fresh fuel handling/fab
  - Curium continues to build-up in fuel cycle, and significantly with use of moderated, non-uranium targets
  - Separated Cm could be stored to decay or just sent to repository
  - Long-term Cm storage could be expensive, but would offer opportunity for re-use of Pu (predominant decay product) and residual Cm

- Separation of Am and Cm is a major challenge
### Fraction Target Assemblies in Heterogeneous Recycle Reactor

<table>
<thead>
<tr>
<th>Case</th>
<th>Am+Cm in target</th>
<th>Np+Am+Cm in target</th>
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<tbody>
<tr>
<td></td>
<td>Number of assemblies</td>
<td>Fraction of target assemblies</td>
</tr>
<tr>
<td></td>
<td>Driver</td>
<td>Target</td>
</tr>
<tr>
<td>5</td>
<td>132</td>
<td>9</td>
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<tr>
<td>15</td>
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<tr>
<td>30</td>
<td>132</td>
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*For evaluation, driver assembly has 96 kg of heavy metal (HM) and the target assembly has 43 kg HM. TRU content of 20.4% is assumed in the driver assembly, and a MA content of 40% in the target assembly.*

- If 20% loading is appropriate, then fractions in core would double or MA would pile-up in ex-core storage facilities.
- To accommodate all 20% MA content assemblies, core radial size needs to increase, requiring bigger core vessel, which might be undesirable and would penalize capital cost.
- CEA study indicated that at 10% MA content (MOX fuel), about ~18% of core is target assemblies in all fast reactors in nuclear park.
Homogeneous and Heterogeneous Recycle Approaches Considered with Different Fuel-Target Options

- **Am targets**: Decay heat constraints and shielding requirements are more severe.
  - Remote fabrication. Decay heat constraints on loading limits. Very low TRL.
  - Matrix material is an issue.

- **Am - Cm**: Similar to Am targets. Decay heat constraints and shielding requirements are more severe.
  - Remote fabrication. Decay heat constraints on loading limits. Very low TRL.
  - Matrix material is an issue.

- **U-Pu-Np-Am**: Remote fabrication. Neutron shielding of equipment. Very low TRL but effect of Cm on performance is expected to be negligible.
  - Remote fabrication. Low TRL: proof-of-concept completed.
  - Remote fabrication.
  - Glovebox fabrication with additional shielding. Low TRL but Np is expected to behave like Pu metallurgically.
  - Remote fabrication. Neutron shielding of equipment. Very low TRL but effect of Cm on performance is expected to be negligible.

- **U-Pu-Np-Am-Cm**: Remote fabrication.
  - Remote fabrication. Decay heat constraints on loading limits. Very low TRL.
  - Matrix material is an issue.
  - Remote fabrication.
  - Glovebox fabrication with additional shielding. Low TRL but Np is expected to behave like Pu metallurgically.

**Np addition to targets does not further complicate technology.**

**Moderated targets increases complexity.**
Advantages and Disadvantages of Heterogeneous Recycle

**Advantages**

- Allows use of technology similar to existing recycle fuel fabrication and co-extraction processes for early deployment of advanced fuel cycle technology
  - Conventional recycle fuel form for driver assemblies easier to fabricate (at least the first recycle of Pu or Pu-Np will not need to be remote)
  - Potential to permit time for additional R&D to find manageable solutions to handling of high dose/heat minor actinides (MA)
- Reduces number of MA-containing assemblies to be fabricated and handled prior to core loading
- Potential to confine remote fabrication of MA-containing fuels with lower throughput to dedicated sub-facility for fabrication
- Flexible management of MA loading in the core

**Disadvantages**

- Number of assemblies containing MA is reduced, but still significant
  - Target-containing reactors still a large fraction of nuclear park
- Target assemblies difficult to handle during manufacture and transport
  - High radiation dose and decay heat
- He production in target assemblies is significant and must be managed
  - Development of advanced fuel that is stable under irradiation
  - R&D to investigate fabrication routes and to investigate behavior under irradiation
- Core fuel management difficulties; e.g., “ex-core” targets are exposed to strong neutron flux gradient
  - Difficult to achieve high transmutation within irradiation damage limit for structural material
  - Accommodate with core optimization