Views on Practical Approaches to Recycling Used Fuel

Emory D. Collins
Oak Ridge National Laboratory
collinsed@ornl.gov

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A Practical Solution to Used Nuclear Fuel Treatment to Enable Sustained Nuclear Energy and Recovery of Vital Materials

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Authors: Emory D. Collins
          Guillermo D. Del Cul
          James E. Rushton
          Kent A. Williams
Public Perception for Nuclear Energy — Favorable or Not?

- Nuclear energy is a large, economical source of clean energy with very low carbon emission
- Public perception has become increasingly favorable
- The unresolved problem of nuclear waste disposal remains a major concern
- Safe disposal has been considered to be transportation to and emplacement in a geologic repository
- Finding an acceptable site for a geologic repository is a social and political problem
- Continued used fuel storage is not a permanent solution
- Situation may be a deterrent to public acceptance of nuclear energy
Advanced Fuel Recycle is a Practical Solution

• Base recycling technology deployment has occurred in other countries

• Advanced R&D studies have developed significant improvements

• Advanced fuel cycle approach would:
  – Deploy proliferation-resistant recycle facilities
  – Process oldest-fuels-first (~50-year-old fuels)
  – Incorporate more complete recycling of used fuel components by means of focused R&D to minimize eventual impact of geological disposal of radioactive waste
More complete recycling (>90% of mass components) can be done

- Current industrial treatment performed in other countries to recycle plutonium
- Uranium is separated and recovered—some is recycled
- Additional components can be recycled if R&D is focused
  - Other transuranium actinides
  - Zirconium from fuel cladding
  - Valuable gases, rare earth elements, and noble metals

- Need for a geologic repository will remain, but methods recommended can:
  - Delay the need
  - Minimize the capacity needed
  - Significantly reduce the hazard of the wastes disposed
Uranium Recycle into CANDU Reactors

- The standard CANDU reactor uses natural uranium oxide fuel
- CANDU reactors are capable of operating with a full RU core
  - The Canadian CANDU fleet could use 2000 to 2800 MT/y RU
  - Average burnup will increase from 7.5 GWd/MT to about 10 GWd/MT
  - $^{236}\text{U}$ penalty is 1/5 of that for PWR reactors

Main Issue: RU will require extensive licensing and safety assessments with the Canadian Nuclear Safety Commission
Zirconium Recovery from Cladding

- Purified zirconium will remain radioactive
  - $^{93}\text{Zr}$ is not a significant radiological problem
    - Half-life is 1.53M years
    - Beta emission at only 90 keV (max.)
Cost of Recycle — Is it an impediment?

- Reactor costs dominate
- Fuel cycle costs are <15%
- Variation in fuel cycle costs differ by insignificant amounts
- Future need for breeding fissile materials from depleted uranium and thorium resources will require more expensive reactor and fuel designs

<table>
<thead>
<tr>
<th>Fuel cycle type</th>
<th>UOX LWR direct disposal</th>
<th>UOX/MOX LWR current recycle (Pu only)</th>
<th>LWR advanced recycle (U, TRUs, Zr, and some fission products)</th>
<th>Advanced reactors breeder recycle (U, Pu) drivers DU blankets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of used fuel assembly mass in waste</td>
<td>100</td>
<td>99</td>
<td>5</td>
<td>5–10</td>
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<tr>
<td>Comparable levelized costs, mills/kWh</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>U ore/U enrichment/UOX fabrication/UOX credits</td>
<td>4.3</td>
<td>3.9</td>
<td>3.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Reactors</td>
<td>49.5</td>
<td>49.5</td>
<td>49.5</td>
<td>59.0</td>
</tr>
<tr>
<td>Used fuel dry storage</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Recycling</td>
<td>0.0</td>
<td>3.4</td>
<td>3.9</td>
<td>5.0</td>
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<tr>
<td>Waste disposal</td>
<td>1.6</td>
<td>1.0</td>
<td>0.3</td>
<td>1.5</td>
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<tr>
<td>Total</td>
<td>55.7</td>
<td>57.8</td>
<td>57.2</td>
<td>65.6</td>
</tr>
<tr>
<td>Fuel cycle component of above costs</td>
<td>6.2</td>
<td>8.3</td>
<td>7.7</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Identification of Proliferation-Resistance Factors — Used Fuel Components

- Used fuel inherently contains the chemical element, plutonium, and its fissile isotopes
- Plutonium can be chemically separated and separation methods are well known
- Physical protection and other proliferation-resistance means are necessary to prevent diversion
- Used fuel and recycled fissile material must be protected for either:
  - Continued storage
  - Direct disposal
  - Treatment and recycle
- Engineered safeguards can provide adequate proliferation resistance
Engineered Safeguards — The Radiation Barrier

- Radiation barrier is provided by presence of short-lived and intermediate-lived radioactive fission products
- Barrier decays at exponential rate, making used fuel older than several decades more vulnerable to diversion and theft
- Vulnerability can be eliminated if fuel recycle is begun before radiation barrier has decreased to a susceptible level—re-irradiation will restore the effective radiation barrier
Engineered Safeguards — Co-location and Integration of Used Fuel Treatment Facilities

- Fissile material entry and removal in form of large, heavy, easily accountable fuel assemblies
- Effective monitoring/surveillance of wastes and personnel exiting recycle plant
- Minimized inventory of separated fissile material and recycle fuel
  - No separated plutonium
- Use of “near-real-time” monitoring and accounting of fissile material location and movement
Engineered Safeguards — No Separated Plutonium

- Plutonium can be recycled without being separated from “non-neutron-poison” components
- Industrial plant can be designed to prevent plutonium separation
- Selected fission products (cesium) could be added to recycle fuel, but recycle fuel fabrication, transportation, and handling operations would be more difficult
- Physical protection requirements for treatment plant and recycle fuel transportation are not decreased
Time factors for implementing fuel recycle must be considered

• The importance of spent fuel decay time on recycle processing and waste disposal — advantages are gained from processing older spent fuels

• In the U.S., a “50/50” concept could be considered (process 50-year-old spent fuel/store Cs-Sr-Eu within the separations facility)

• Less heat generation in stored wastes — $^{90}\text{Sr}$,$^{137}\text{Cs}$ — 10% of decay heat at 100 years

• Future impact of HLW emplacement into a geologic repository will be lessened

• Volatile radioactive emissions are lower — $^{3}\text{H}$, $^{85}\text{Kr}$ capture/storage likely not required

• Separations processes required can be simplified and made less costly
Transmutation Benefits of Older Fuel

- Alters transmutation pathway to produce lighter plutonium nuclides rather than heavy curium nuclides
- Allows use of existing LWRs and HWRs for transmutation of all long-lived TRU actinides

![Diagram of transmutation pathways]
Optimum Processing Time

- Overall, an “optimum” age of 30–70 years for processing used fuels can:
  - Maximize safety
  - Reduce environmental effects
  - Lower costs
  - Maintain adequate proliferation resistance

- By processing the “oldest-fuels-first,” the age of fuels processed can be kept in the range of 40–60 years
Time required to implement industrial-scale recycling — not an overnight process!

<table>
<thead>
<tr>
<th>Event</th>
<th>2010</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
<th>2060</th>
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<tbody>
<tr>
<td>Number of reactors</td>
<td>104</td>
<td>108</td>
<td>116</td>
<td>124</td>
<td>132</td>
<td>136</td>
</tr>
<tr>
<td>Event</td>
<td>Decision to treat used fuel</td>
<td>1st treatment plant begins operation</td>
<td>2nd plant begins operation</td>
<td>3rd plant begins operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment capacity (MT/year)</td>
<td>0</td>
<td>0</td>
<td>1,000</td>
<td>2,000</td>
<td>3,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Used fuel generation rate (MT/year)</td>
<td>2,200</td>
<td>2,250</td>
<td>2,300</td>
<td>2,700</td>
<td>2,900</td>
<td>3,000</td>
</tr>
<tr>
<td>Storage capacity required (MT)</td>
<td>64,000</td>
<td>87,000</td>
<td>110,000</td>
<td>126,000</td>
<td>134,000</td>
<td>134,000</td>
</tr>
</tbody>
</table>

- Design and construction of each plant requires 15–20 years
- Multiple plants are needed to obtain capacity required to process amounts of used fuels currently generated and expected
- Based on world-wide experience, deployment of industrial-scale recycling is a multi-decade process
Time and sustainability are strong factors toward implementing fuel recycle

- Nuclear energy use is strong, with expected growth in the U.S., Europe, Japan, Russia, and others

- Rapid growth of nuclear energy is occurring in China and India, possibly in the U.K. and other countries

- At some time the availability of low-cost natural uranium (NU) will decline — but when?

- If nuclear energy is to be sustained beyond availability of NU, then there will be a future need for breeder reactors and industrial-scale fuel recycle capability

- Therefore, strong considerations for implementing fuel recycle are:
  - Future need for breeder reactors to use tremendous potential energy in fertile materials
  - The uncertainty of “when in the future” that NU will become unavailable
  - Multi-decade process required to implement industrial-scale recycle at capacity needed
Summary and Recommendations

- Our analysis concluded that:
  - The cost of implementing fuel recycle will be an insignificant change to the cost of nuclear electricity
  - Engineered safeguards can be used to provide adequate proliferation resistance
  - Continuing delay will likely occur in locating and operating a geologic repository
  - Continued storage of used fuels is not a permanent solution

- With no decision, the path forward for used fuel disposal will remain uncertain, with many diverse technologies being considered and no possible focus on a practical solution to the problem

- However, a decision to move forward with used fuel recycling and to take advantage of processing aged fuels and incorporation of near-complete recycling can provide the focus needed for a practical solution to the problem of nuclear waste disposal
Back Up Slides
Continued Storage Concerns — increasing inventory and decreasing radiation barrier

- Current inventory contains ~500 MT and annual production is ~20 MT/year
- Radiation barrier decreasing exponentially with time
- At least 50 years required to build recycle capacity needed to match annual production
- With equal recycle capacity and production rates, inventory will continue to increase because of incomplete burnup in each partitioning-transmutation cycle
- Implementation of fuel recycle is needed
Transplutonium-Element Yield and Fission Loss During Thermal Neutron Irradiation of Plutonium

\[ ^{239}\text{Pu} \rightarrow ^{242}\text{Pu} \quad 3\text{ n}, \quad 90\% \text{ fission loss} \]
\[ ^{242}\text{Pu} \rightarrow ^{244}\text{Cm} \quad 2\text{ n}, \quad \sim1\% \text{ fission loss} \]
\[ ^{244}\text{Cm} \rightarrow ^{252}\text{Cf} \quad 8\text{ n}, \quad \sim8.7\% \text{ fission/decay loss} \]
\[ ^{252}\text{Cf} \rightarrow ^{257}\text{Fm} \quad 5\text{ n}, \quad \sim0.3\% \text{ fission/decay loss} \]
Transplutonium-Element Yield and Fission Loss During Irradiation of Plutonium

Thermal Neutron Irradiation

Fast Neutron Irradiation
TRU Actinide Yield and Fission Loss During Thermal Neutron Irradiation of \( ^{242}\text{Pu} \)

- \( ^{242}\text{Pu} \) ~100%
- \( ^{243}\text{Am} \) 8%
- \( ^{244}\text{Cm} \) 12%
- \( ^{245}\text{Cm} \) 7%
- \( ^{246}\text{Cm} \) 5%
- \( ^{247}\text{Cm} \) 0%

TRU Actinide Yield and Fission Loss During Fast Neutron Irradiation of \( ^{242}\text{Pu} \)

- \( ^{242}\text{Pu} \) 2.5%
- \( ^{243}\text{Am} \) 65%
- \( ^{244}\text{Cm} \) 58%
- \( ^{245}\text{Cm} \) 7%
- \( ^{246}\text{Cm} \) 29%
- \( ^{247}\text{Cm} \) 2.5%
Co-location and Integration of SNF Separations and Recycle Fuel/Target Fabrication at Nuclear Fuel Park

Safeguarded Facility with Physical Protection

Head End
- LEU/LWR SF
- LWR MOX SF
- LWR Am-Cm Targets
- FR Spent Fuel (SF)

Separations
- Disassembly
- Voloxidation
- Clad/Fuel Separation
- Fuel Dissolution
- Blending of Dissolver Solutions
- Separations
- HLW Surface Storage 50 years

Fuel Fabrication
- RU Fuel Fabrication
- LWR U-Pu-Np MOX Fuel Fab
- Am-Cm "Burnable Poison" Target Fab
- FR U-Pu-Np Fuel Fab (Oxide or Metal)

Geologic Repository

Spent Fuel Assemblies ~50-year decay

Fresh Fuel Assemblies