Nuclear Energy in a Climate-Constrained World: The Impact of Waste Disposal Constraints and Fuel Recycling

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  ■ Value of Synergistic Nuclear System with Fuel Recycling for Addressing Climate Change
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Once-through Nuclear Energy System
Global CO₂ Emissions Paths & Resulting Carbon Taxes for Stabilizing Atmospheric CO₂ Concentrations

**Global CO₂ Emissions Paths**

- **Ref**: 450 ppm
- **450 ppm**: 550 ppm
- **550 ppm**: 650 ppm
- **650 ppm**: 750 ppm

**Global Carbon Tax (2005 $/tC)**

- 100 $/tC = 1.76 c/kWh (24 % above base 7.4 c/kWh)

**550 ppm Scenario**

1990 2005 2020 2035 2050 2065 2080 2095

- Billion Tons of Carbon
- Global Carbon Tax (2005 $/tC)

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Pacific Northwest National Laboratory
Global Nuclear Power Capacity and Share
(No Nuclear Waste Disposal Constraints)

550 ppm Scenario with Nuclear & CCS

Global Nuclear Capacity and Nuclear Share of Generation

Proudly Operated by Battelle Since 1965
Global Spent Fuel and TRU Accumulation
(No Nuclear Waste Disposal Constraints)

Disposal requirement: 31 – 53 Yucca Mtns @ 70,000 tons legislated capacity.
Available capacity for nuclear waste disposal is a key challenge for the expanded
global deployment of nuclear power.
Once-through Nuclear Energy System: Scenario Definition

- Nuclear reactors
  - Legacy Reactors (Gen II)
  - Advanced Light-Water Reactors (Gen III)
- Once-through fuel cycle
- Global natural uranium market accessible to all regions
- Direct disposal of spent fuel for all regions

WASTE DISPOSAL CASES:
- Nuclear waste disposal constraint imposed on total global spent fuel production
- New nuclear deployment dependent on availability of waste disposal capacity
- Accounting of repository needs based on committed spent fuel waste production for reactor lifetime
- Older vintages of nuclear reactors
  - No disposal constraints
  - Constant waste disposal charge
Global Nuclear Power Capacity (With Waste Disposal Constraints)

Reference Scenario

550 ppm Scenario

Proudly Operated by Battelle Since 1965
Global Spent Nuclear Fuel Production
(With Waste Disposal Constraints)

Reference Scenario

550 ppm Scenario

Thousand Tonnes of SF

490 thou tons
700 thou tons
1,400 thou tons
2,100 thou tons
2,800 thou tons
3,500 thou tons
4,200 thou tons
4,900 thou tons
5,600 thou tons

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Capacity Additions for Global Nuclear Waste Disposal (Unconstrained Disposal Scenario)

Reference Scenario
Gen III LWR Deployment

550 ppm Scenario
Gen III LWR Deployment
Global Economic Cost - 550 ppm Scenario
(Once-through Nuclear Energy System)

Nuclear Moratorium

Repository Capacity (1,000 tons of SF)

(Discounted cost from 2005 – 2095 @ 5%)
Global Value of Nuclear Energy - 550 ppm Scenario
(Once-through Nuclear Energy System)

Repository Capacity (1,000 tons of SF)
(value of nuclear for 21st century)
Conclusions – Part 1: Once-through Nuclear Energy System

- A peak and decline behavior is observed in nuclear energy use under scenarios of waste disposal constraints.
- Once-thru fuel cycle requires significant and growing capacity for waste disposal with increasing global use of nuclear energy.
  - Ref: 3,500 thousand tons of SF repository capacity by 2100
  - 550ppm: 5,600 thousand tons of SF repository capacity by 2100
  - 430 thousand tons of repository capacity required for existing legacy reactors worldwide.
  - 30 – 50 thousand tons of TRU accumulation (in SF) by 2100
- Rate of repository capacity additions accelerates with growing nuclear deployment and under climate constraint.
  - 100 to 1,200 thousand ton capacity every 15 years.
- Cost of addressing climate change could rise by an additional ~1 trillion US$ if waste disposal constraints limit the global deployment of nuclear power.
- Value of once-thru nuclear system for addressing climate change is ultimately dependent on the waste repository capacity.
  - > 3,500 thousand ton capacity sufficient to capture 95% of the value (~1 trillion US$)
Nuclear Energy System with Fuel Recycling and Synergistic Deployment of Light-Water and Fast “Burner” Reactors
Synergistic Nuclear Deployment with Recycling: Scenario Definition

- **Nuclear synergy objective:**
  - Continuously recycle and “burn” all excess TRU
  - Minimize geologic waste disposal needs
    - Heat from TRU and fission fragments (Cs & Sr) limits geologic storage capacity
  - Reduce excess accumulation of TRU (reduce proliferation)

- **Nuclear reactors**
  - Legacy Reactors (Gen II)
  - Advanced Light-Water Reactors (Gen III)
  - Fast “Burner” Reactors (Gen IV)
    - Available for deployment after 2035

- Closed fuel cycle with continuous recycling of all spent fuel, including uranium.

- Total time (cooling, separation and fabrication) for LWR and FR used fuel to new FR fuel is 15 years.

- Fast reactor fuel is a mixture of TRU and reclaimed uranium.

- LWR fuel remains UOX from enriched natural uranium.
Potential Increase in Utilization of Repository Space

- With the processing of spent PWR fuel to remove the elements responsible for the decay heat that cause temperature limits to be reached, large gains in utilization of repository space are possible
  - The amount of gain is related to separation efficiency
  - Only considers thermal performance, not dose rate

- Pu, Am, Cs, Sr, & Cm are the dominant elements
  - The recovered elements must be treated
    - separate storage of Cs & Sr for 200-300 years

- Recycling of Pu, Am, & Cm for transmutation and/or fission
  - Irradiation in reactors

- No direct disposal of any spent fuel

Assumptions
- Burnup: 50 GWD/MTU
- Separation: 25 years
- Emplacement: 25 years
- Closure: 100 years
Radiotoxicity for Once-Through, Limited Recycle, Transitional Recycle and Sustained Recycle

(From 2005 Report to Congress. Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary)
Global constraint policy imposed on annual excess TRU production (each period)
- Total cumulative excess TRU (global) is gradually eliminated by 2095
- FR to LWR ratio dependent on excess TRU production and TRU constraint policy
- Penalty imposed on net TRU producer (LWR) and credit given to net TRU consumer (FR)

Geologic disposal of processed High-Level Waste (HLW) only
- 99.9% removal of minor actinides, Cs & Sr from spent fuel
- Processed HLW includes fission fragments and losses
- Repository capacity improvement factor is 225 times greater than direct disposal (Wigeland et al.)
- Additional cost for assumed alternative storage of separated Cs and Sr included

Global constraint imposed on committed processed HLW production for reactor lifetime

New nuclear deployment dependent on availability of constrained waste disposal capacity and policy on excess TRU production
Global Electricity Generation
LWR (Gen III) and Fast “Burner” Reactor (Gen IV)

- Reference Scenario
- 550 ppm Scenario

70 Thousand Ton SF Repository Capacity
(Waste Disposal Constraint Not Binding)
Global Nuclear Capacity and Share of Total Electricity Generation

70 Thousand Ton SF Repository Capacity
(Waste Disposal Constraint Not Binding)
Fast Reactor Global Capacity and Share of Nuclear Electricity Generation

(Fast Reactor CR = 0.5 with global excess TRU eliminated by 2095)
Global Annual Production and Consumption of TRU

Reference Scenario

550 ppm Scenario

(Fast Reactor CR = 0.5 with global excess TRU eliminated by 2095)
Global Availability of Excess TRU

Reference Scenario

550 ppm Scenario

(cumulative)
Impact of Higher Systems Cost from Fast Reactors and Recycling on Nuclear Electricity Generation

**Reference Scenario**

- LWR (once-thru)
- LWR/FR System (recycling)

**550 ppm Scenario**

- LWR (once-thru)
- LWR/FR System (recycling)

(Reference: 10% reduction)

(550 ppm: 12% reduction)
Global Cumulative Natural Uranium Production

(Reference: 19% reduction, 4 MTU)  
(550 ppm: 20% reduction, 6 MTU)
Global Economic Cost and Value of Nuclear for Addressing Climate Change - 550 ppm Scenario (LWR/FR Nuclear Energy System)
“Value Space” for Nuclear Energy Systems in Addressing Climate Change - 550 ppm Scenario

Trillion 2005 US $ vs. Repository Capacity (1,000 tons of SF) - not to scale

- LWR/FR (recycling)
- LWR (once-thru)

(value of nuclear for 21st century)
Conclusions – Part 2: Synergistic Nuclear System with Recycling

- **Waste repository capacity** is not a limiting factor in a nuclear energy system with synergistic deployment of light-water and fast “burner” reactors and continuous recycling of used fuels.
  - 70 thousand ton (SF) repository capacity sufficient to store processed HL waste from all nuclear plants deployed globally by 2095.
    - Compared to 5,600 thousand ton capacity needed with direct disposal in the 550 ppm scenario.
  - Synergistic nuclear system supports expanded global use of nuclear energy as a response to climate change without additional demands for repository capacity.
  - Nuclear capacity (LWR & FR) grows to 2,050 GWe (18%) in the Reference and 3,300 GWe (30%) in 550 ppm scenarios by 2095.

- **Relative share of FR to LWR falls** with greater deployment of nuclear power.
  - Shares of FR’s (CR=0.5) reach 29% and 23% in the Reference and 550 ppm scenarios.
  - Global FR capacity is 630 GWe in the Reference and 830 GWe in the 550 ppm scenarios by 2095.

- **Deployment of FR (CR=0.5) reduces cumulative natural uranium consumption**.
  - Up to 20 percent, 4 to 6 MTU, is saved in the Reference and 550 ppm scenarios by 2095.

- **Higher cost of nuclear electricity from FR deployment with fuel reprocessing does not significantly lower global nuclear energy use**.
  - 10 to 12% reduction in global nuclear electricity generation by 2095 compared to LWR only scenario with unconstrained waste disposal.

- The value of synergistic nuclear system (LWR/FR) in the 550 ppm scenario is 0.76 trillion US$ with 70 thousand ton repository capacity.
  - Direct disposal requires minimum of 430 thousand tons for legacy reactors alone.

- **Limited waste repository capacity implies significant value to recycling and FR technologies.**
### Nuclear Energy Technology Cost Assumptions: Gen II and Gen III LWR

<table>
<thead>
<tr>
<th></th>
<th>Gen II</th>
<th>Gen III</th>
<th>Gen III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year</strong></td>
<td>Legacy</td>
<td>2005</td>
<td>2095</td>
</tr>
<tr>
<td><strong>Burnup (GWd/MTHM)</strong></td>
<td>45</td>
<td>50</td>
<td>50</td>
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<tr>
<td><strong>Enrichment (%)</strong></td>
<td>4.08%</td>
<td>4.51%</td>
<td>4.51%</td>
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<tr>
<td><strong>Uranium Ore Cost</strong></td>
<td>Endogenous</td>
<td>Endogenous</td>
<td>Endogenous</td>
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<tr>
<td><strong>Conversion Cost ($/kgU)</strong></td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td><strong>Enrichment Cost ($/SWU)</strong></td>
<td>105</td>
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<td>105</td>
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<tr>
<td><strong>Fuel Fabrication Cost ($/kgHM)</strong></td>
<td>240</td>
<td>240</td>
<td>240</td>
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<tr>
<td><strong>Interim Storage Cost ($/kgHM)</strong></td>
<td>300</td>
<td>300</td>
<td>300</td>
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<tr>
<td><strong>Waste Disposal Cost ($/kgHM)</strong></td>
<td>548</td>
<td>548</td>
<td>548</td>
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<tr>
<td><strong>Capital Overnight ($/kW)</strong></td>
<td>Legacy</td>
<td>2,300</td>
<td>1,800</td>
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<tr>
<td><strong>O&amp;M Fixed ($/kW)</strong></td>
<td>Legacy</td>
<td>64</td>
<td>64</td>
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<tr>
<td><strong>O&amp;M Variable (mills/kWh)</strong></td>
<td>Legacy</td>
<td>1.8</td>
<td>1.8</td>
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<tr>
<td><strong>Efficiency (%)</strong></td>
<td>33%</td>
<td>34%</td>
<td>34%</td>
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<tr>
<td><strong>Capacity Factor</strong></td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
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<tr>
<td><strong>Lifetime (years)</strong></td>
<td>60</td>
<td>60</td>
<td>60</td>
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</table>

*Note: $ year is 2005*

*Ref: Advanced Fuel Cycle Cost Basis 2007, INL.*
Nuclear Energy Technology Cost Assumptions: Gen IV Fast Reactor

<table>
<thead>
<tr>
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<th>Gen IV (FR)</th>
<th>Gen IV (FR)</th>
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<tbody>
<tr>
<td>Year</td>
<td>2035</td>
<td>2095</td>
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<tr>
<td>Conversion Ratio</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Burnup (GWh/MTHM)</td>
<td>132</td>
<td>132</td>
</tr>
<tr>
<td>Fuel</td>
<td>TRU/RU</td>
<td>TRU/RU</td>
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<tr>
<td>Reprocessing and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Fabrication Cost ($/kgHM)</td>
<td>5,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Interim Storage Cost ($/kgHM)</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Waste Disposal Cost ($/kgHM)</td>
<td>311</td>
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<tr>
<td>Capital Overnight ($/kW)</td>
<td>2,900</td>
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<tr>
<td>O&amp;M Fixed ($/kW)</td>
<td>68</td>
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<tr>
<td>O&amp;M Variable (mills/kWh)</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Efficiency (%)</td>
<td>38%</td>
<td>38%</td>
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<tr>
<td>Capacity Factor</td>
<td>0.82</td>
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<tr>
<td>Lifetime (years)</td>
<td>60</td>
<td>60</td>
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</table>

Note: $ year is 2005
Ref: Advanced Fuel Cycle Cost Basis 2007, INL.

<table>
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<tr>
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<tr>
<td>Year</td>
<td>All</td>
</tr>
<tr>
<td>Additional Cost for Reprocessing ($/kgHM)</td>
<td>502</td>
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## Gen III LWR and Gen IV FR Fuel Composition

<table>
<thead>
<tr>
<th></th>
<th>Gen III</th>
<th>Gen IV</th>
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</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td>UOX</td>
<td>TRU/Spent U</td>
</tr>
<tr>
<td><strong>Burnup (GWd/MTHM)</strong></td>
<td>50</td>
<td>132</td>
</tr>
<tr>
<td><strong>Enrichment (%)</strong></td>
<td>4.51%</td>
<td></td>
</tr>
<tr>
<td><strong>Conversion Ratio (TRU)</strong></td>
<td></td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Input:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uranium</td>
<td>70.6%</td>
<td></td>
</tr>
<tr>
<td>Pu</td>
<td>26.4%</td>
<td></td>
</tr>
<tr>
<td>MA</td>
<td>3.0%</td>
<td></td>
</tr>
<tr>
<td>TRU</td>
<td>29.4%</td>
<td></td>
</tr>
<tr>
<td><strong>Output:</strong></td>
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<td></td>
</tr>
<tr>
<td>Uranium</td>
<td>93.4%</td>
<td>62.3%</td>
</tr>
<tr>
<td>Pu</td>
<td>1.3%</td>
<td>21.2%</td>
</tr>
<tr>
<td>MA</td>
<td>0.1%</td>
<td>2.3%</td>
</tr>
<tr>
<td>TRU</td>
<td>1.5%</td>
<td>23.5%</td>
</tr>
<tr>
<td>Fission Products</td>
<td>5.1%</td>
<td>14.1%</td>
</tr>
</tbody>
</table>
Global Primary Energy Consumption

Reference Scenario

550 ppm Scenario

(LWR w/ unconstrained disposal)
Global Processed High-Level Waste Accumulation

Reference Scenario

- Gen IV FR
- Gen III LWR
- Gen II LWR

550 ppm Scenario

- Gen IV FR
- Gen III LWR
- Gen II LWR

Thousand Tons of HLW

Years: 1990, 2005, 2020, 2035, 2050, 2065, 2080, 2095