Advanced Nuclear Fuel Cycle Options

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Background

- **A study supported by the U.S. DOE to review and evaluate nuclear fuel cycle options for their ability to address nuclear power issues**
  - Comprehensive consideration of all fuel cycle options
    - No constraints on the choice of fuel cycles or technologies
    - No presumption of technical maturity or current viability
- **Several major activities**
  - Recognition of previous studies
  - Identify issues hindering use and expansion of nuclear power
  - Develop a set of performance measures for each issue
  - Collect and evaluate options based on the measures
  - Summarize the impact of alternative fuel cycles on the issues
- **The purpose of the study is to provide information**
  - Inform policy and decision-makers about alternative fuel cycles and their performance capabilities

Nuclear Power Issues

- **Consider all major issues with the use of nuclear power**
  - Nuclear waste management
  - Proliferation risk
  - Safety
  - Security
  - Economics and affordability
  - Sustainability
- **Relative importance of issues has varied with time and events**
  - Provide information on all issues without ranking importance
- **Identify fuel cycle options that make a "significant" improvement**
  - Reference is today's once-through fuel cycle using LWRs
  - "Significant" is assumed to mean an order of magnitude or more
    - All options are summarized, but not all make a significant improvement
      - Depends on the measure(s) one is considering

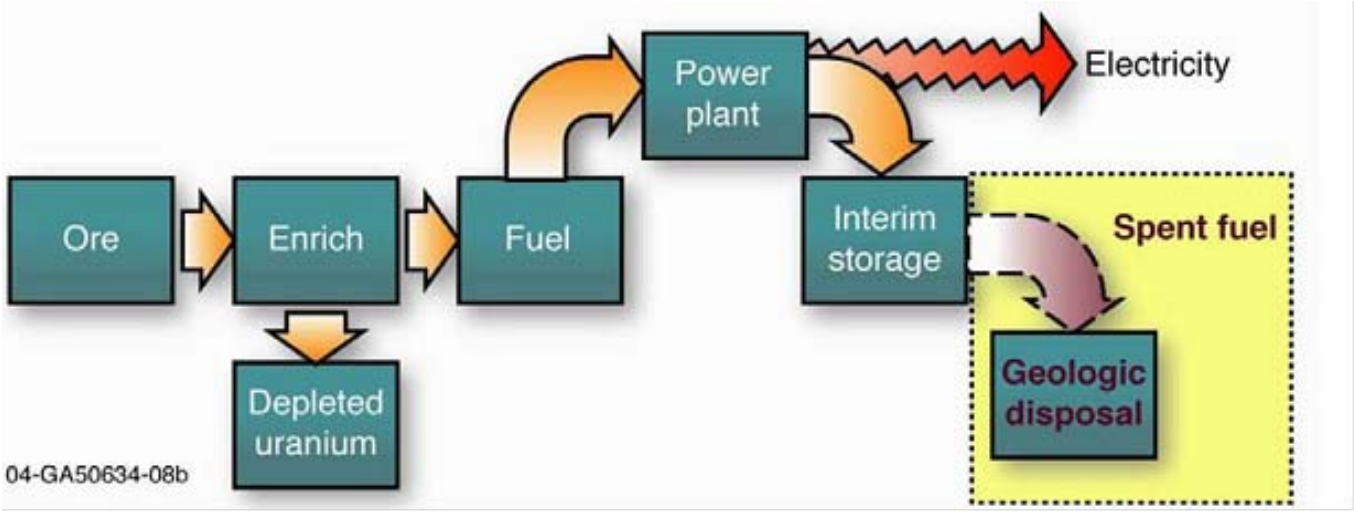
Evaluation Criteria / Performance Measures

- **Waste management**
  - Estimated peak dose rate, radiotoxicity, waste (UNF, HLW, LLW), impact of decay (or interim) storage, and heat load
- **Proliferation risk**
  - Inventory of weapons-usable materials, material attractiveness, enrichment, and safeguardability
- **Safety**
  - Ability to develop facilities that can be licensed
- **Security**
  - Inventory of radioactive materials, physical security
- **Economics and affordability**
  - Similarity to existing infrastructure, capital cost, technical maturity, technical risk, development time, life cycle cost
- **Sustainability**
  - Natural resources for fuel, natural resources for waste disposal

Nuclear Fuel Cycle Strategies

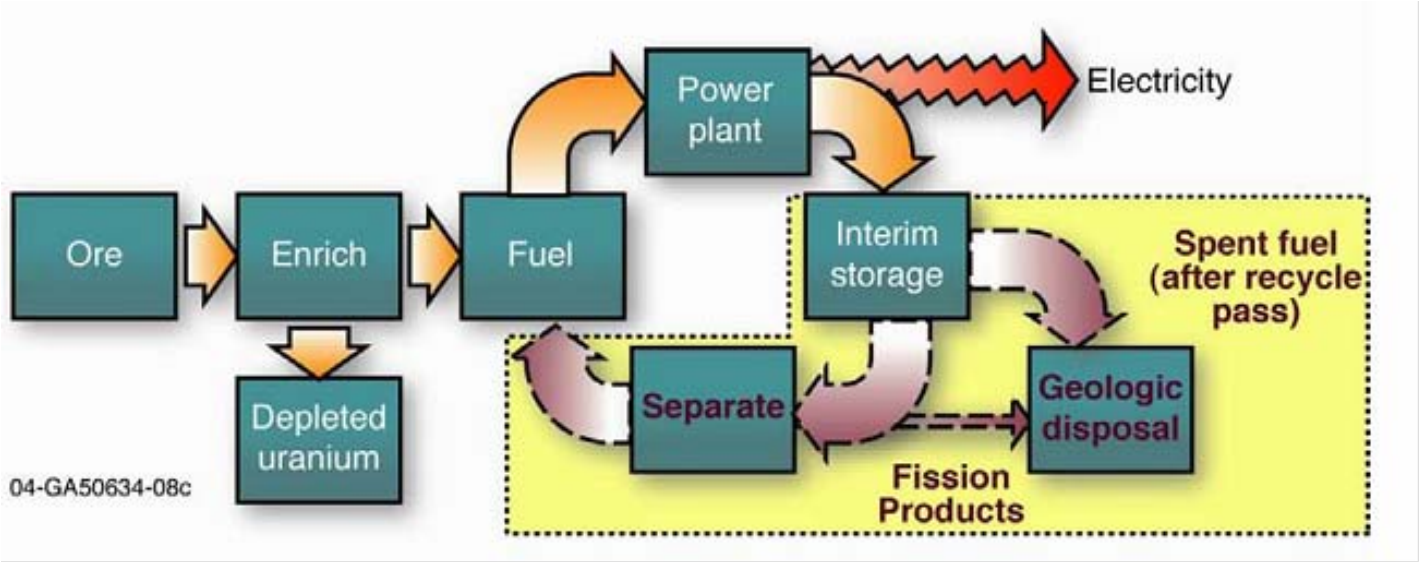
- **Two basic types of nuclear fuel cycles**
  - Once-through
  - Recycle
    - Limited recycle
    - Continuous, or unlimited, recycle
- **It appears that the choice of fuel cycle can directly affect the ability to have an impact on the performance measures**
  - Potential impact on the performance measures can be limited for once-through and limited recycle options, regardless of the technology choices
  - Impact of recycle options depends on the issue being considered and the specific characteristics of the recycle option

Once-Through Nuclear Fuel Cycle



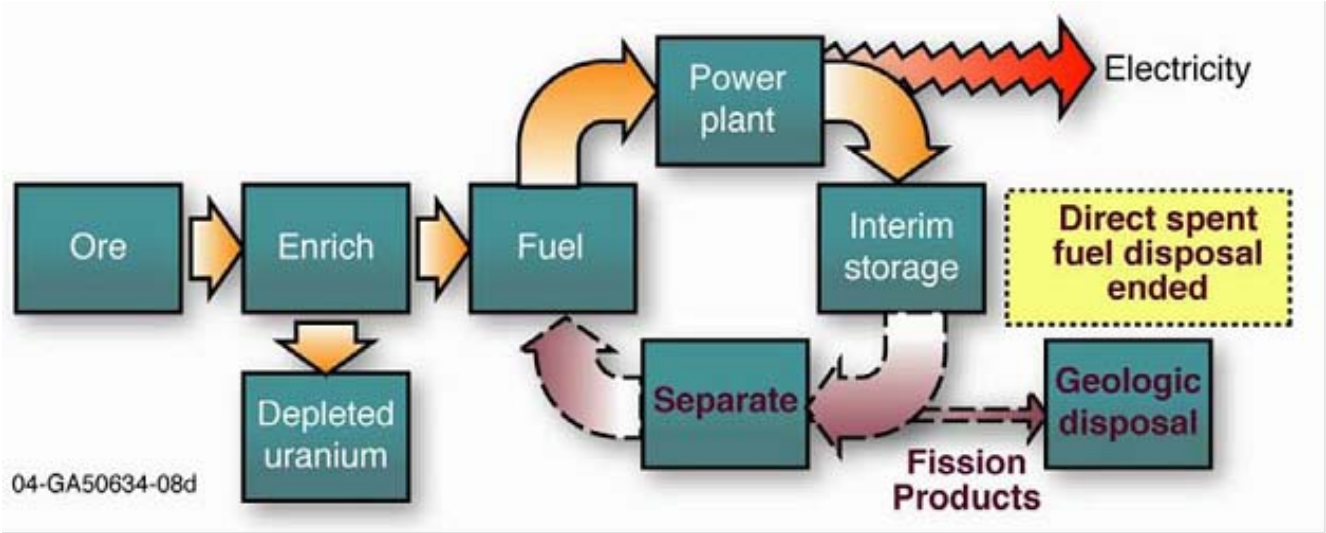
- **Fuel is only used once, followed by disposing of all materials**
  - No recycle
  - Direct disposal of spent nuclear fuel
- **Relatively few opportunities for advanced technologies to make a difference (e.g., once-through fast breeder, high burnup, …)**
  - Fissile fuel resources and uranium enrichment likely required
  - Interim storage after use may benefit disposal

Recycle Nuclear Fuel Cycle – Limited Recycle



- **Recycle elements of used nuclear fuel one or a few times**
  - Dispose of both HLW and spent nuclear fuel
- **Opportunities for advanced technologies to have an impact**
  - Less fuel resources and uranium enrichment with Pu recycle
  - Interim storage may affect processing, recycle, and waste disposal

Recycle Nuclear Fuel Cycle – Continuous Recycle



- **Recycle is repeated without limit**
  - One or more elements in used nuclear fuel is recycled
  - Only HLW is disposed
- **More opportunities for advanced technologies to affect the causes**
  - Potentially significantly less resources; may eliminate enrichment
  - Interim storage may benefit processing, recycle, and waste disposal

Impact of Fuel Cycle Strategy Choice

- **Waste Management**
  - With once-through or limited recycle, impact may be limited due to the need to dispose of spent fuel
    - Radiotoxicity, dose rate, decay heat, etc. can only be slightly affected with continued disposal of spent fuel due to the actinide content, unless the fuel is nearly completely consumed
  - Continuous recycle may offer opportunities
    - Keeping the actinides in the fuel cycle
    - Fission products must still be disposed
      - If fission products dominate risk, recycle may be ineffective
- **Proliferation risk**
  - Once-through requires enrichment and disposes SNM in spent fuel
  - Similarly, limited recycle also needs reprocessing
  - Continuous recycle needs reprocessing, may need enrichment, but may not require disposal of SNM
  - Relative risk depends on the risk from each part of the fuel cycle and assumptions made about adversary capabilities
    - No clear indication at this time on differences

Impact Table

Fuel Cycle Strategy	Alternate Once-Through	Limited Recycle	Continuous Recycle
Nuclear Waste Management			
Estimated Peak Dose Rate	No significant change due to UNF disposal	No significant change due to UNF disposal	*Possibly significantly* lower with actinide (TRU) recycle and HLW disposal
Radiotoxicity of Disposed Materials	No significant change due to UNF disposal	No significant change due to UNF disposal	Significantly lower with actinide (TRU) recycle and HLW disposal
UNF & HLW Mass for Disposal	Similar UNF and HLW content; less UNF with higher burnup	Less combined UNF & HLW content due to recycle	No UNF disposal; TRU content in waste is significantly lower due to TRU recycle
LLW Mass for Disposal	No significant change in LLW	*Possibly significantly* more LLW due to processing	*Possibly significantly* more LLW due to processing
Effect of Interim Storage	Lower near-term radiotoxicity and heat load for UNF and HLW	Lower near-term radiotoxicity and heat load for UNF and HLW	Lower near-term radiotoxicity and heat load for UNF and HLW
Heat Load	No significant change due to UNF disposal	No significant change due to UNF disposal	Significantly lower with TRU recycle, Cs/Sr management, and HLW disposal

Impact Table

Fuel Cycle Strategy	Alternate Once-Through	Limited Recycle	Continuous Recycle
Proliferation Risk			
SNM Inventory	No significant change	Higher fuel cycle inventory, lower waste disposal inventory	Higher fuel cycle inventory, significantly lower waste disposal inventory
Material Attractiveness	No significant change	Technology dependent; may be lower or higher	Technology dependent; may be lower or higher
Uranium Enrichment	Technology dependent; may be lower or higher	Technology dependent; may be lower or higher	Technology dependent; may be lower or higher
Safeguardability	No significant change	No significant change	No significant change
Sustainability			
Fuel Resources	*Possibly significantly* lower with fast breeder reactor	*Possibly significantly* lower with fast breeder reactor	Significantly lower with actinide recycle
Disposal Needs	No significant change	No significant change	Significantly lower with actinide recycle

Impact of Fuel Strategy Choice (cont'd)

- **Sustainability**
  - Fuel resources are affected by the internal conversion of the irradiation environment
    - Significant breeding can offset fuel resources or eliminate enrichment
  - Disposal needs are affected by the content of disposed materials
    - Recycle may reduce needed disposal space
- **Safety**
  - Appears that all fuel cycle options may be safely used
- **Security**
  - All fuel cycles have substantial inventories of radioactive materials
    - No clear difference between fuel cycles at this time
- **Economics and affordability**
  - Tradeoff between more complex fuel cycles and disposal needs, i.e., costs of additional complexity vs. disposal costs
  - Initial costs appear to be a significant factor

Technology Options

- **A comprehensive range of technology options is being considered for each part of the fuel cycle**
  - Fuel
  - Irradiation Environment
  - Processing
  - Disposal
- **In principle, each of the technology options could be applied to any of the fuel cycle strategies**

Fuel Options

- **There are two general fuel options**
  - Uranium / plutonium
    - TRU fuel is a subset of this option
  - Thorium / uranium
- **Waste Management**
  - Thorium/uranium options may have waste management benefits as compared to uranium/plutonium, but the differences do not appear to be significantly large
  - Strongly dependent on the details of the implementation
- **Proliferation Risk**
  - Thorium/uranium and uranium/plutonium appear to have similar proliferation risk (U233 and Pu239 have similar attractiveness)
- **Sustainability**
  - Both uranium/plutonium and thorium/uranium have similar resource requirements for the same fuel cycle implementation
- **Both fuel types affect the other performance measures in a similar manner, i.e., no significant difference between U/Pu and Th/U**

Irradiation Options

- **A wide range of irradiation options is being considered**
  - Neutron-based irradiation
    - Critical systems (reactors)
      - Thermal neutron systems
      - Fast neutron systems
    - Sub-critical systems (externally driven)
      - Accelerator-driven systems (ADS)
      - Fission-Fusion hybrids
  - Non-neutron irradiation
    - Particle and non-particle approaches
- **Non-neutron irradiation systems are less effective due to fundamental physics limitations**
- **Externally driven systems introduce new safety concerns, costs, and economic penalties that appear to make them less favorable**
- **Critical systems still appear the best choice for irradiation**

Processing Options

- **Processing options are only relevant for recycle fuel cycles**
- **Processing covers a wide range of activities**
  - From simple reconstitution into new fuel for further irradiation to a complete separation of the chemical elements for waste management and fabrication into recycle fuel
  - In the broader context, processing is designed to separate UNF into chemical elements or groups of elements
    - Some elements destined for transmutation
    - Other elements to be discarded as waste
- **Processing technologies can be structured to separate and recover any desired set of elements, either singly or in groups**
- **The ability of a processing technology to impact the performance measures mainly depends on the purity of the separation**
  - Losses can dominate the impact on performance measures
  - Waste generation is also important
  - No apparent difference in proliferation risk between processing technologies so far

Disposal Options

- **One or more disposal environments will be needed, regardless of the fuel cycle strategy**
  - Highly radioactive materials, such as spent fuel or HLW
  - LLW from many activities
  - All disposal must be included in evaluating advanced fuel cycles
- **There are many options for disposal of spent fuel or HLW**
  - Mined geologic repositories
  - Non-retrievable disposal such as boreholes
- **Risk from disposal can be considered in two parts**
  - Undisturbed or normal evolution of the conditions in the repository
  - Disturbances by either natural or man-made causes
- **Fission products dominate risk for undisturbed conditions, while actinides can dominate risk for a disturbed environment**
  - Fuel cycle strategies that greatly reduce the hazardous content of disposed materials can have a significant impact on disposal
- **Addressing engineering issues like decay heat can also have large benefits depending on the disposal environment**

Summary

- **Results to date indicate that relatively few options lead to significant benefits with respect to the issues with nuclear power**
- **For the choice of fuel cycle, once-through and limited recycle options do not generally provide significant opportunities**
  - Disposal of spent fuel limits opportunities for waste management and resource benefits
- **Recycle strategies may only impact issues related to TRU, not fission products**
  - Fast neutron spectrum transmutation of TRU may be preferable
    - More surplus neutrons, less disturbance to the reactor
  - Processing is more a matter of preference, but impact on the issues will mainly be dominated by losses
    - Processing, fuel fabrication, etc. must be considered
  - The waste disposal environment can have a profound effect on the impact of the overall fuel cycle
- **The study is continuing, quantifying benefits for specific fuel cycle options and disposal environments**