Nuclear Fuel Cycle Evaluation and Screening - Overview

National Academies of Sciences, Engineering and Medicine Virtual Meeting

Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and Waste Aspects of Advanced Nuclear Reactors

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U.S. DEPARTMENT OF
ENERGY

Presentation Outline

- Background for the Evaluation and Screening (E&S) Study
- Development of a comprehensive set of fuel cycle options
- E&S Study approach
- Key results and observations from the Study
- Closing Remarks

The Nuclear Fuel Cycle Evaluation and Screening Study - Background (1 of 2)

- DOE Roadmap, April 2010
- DOE chartered the Evaluation and Screening Study (12/15/2011) to strengthen the basis for DOE-NE R&D decisions
  - Identify the potential for a nuclear fuel cycle to provide substantial improvements as compared to the current U.S. fuel cycle, including both benefits and challenges for development
  - Identify promising fuel cycles with the potential to provide substantial improvements, not incremental or evolutionary changes
  - Identify the characteristics of promising fuel cycles
  - Identify the R&D needs for the promising options
- Nine Evaluation Criteria were specified by DOE-NE
  - Six for potential benefit, three on development and deployment challenges

The Nuclear Fuel Cycle Evaluation and Screening Study - Background (2 of 2)

- **The Study requirements**
  - Consider the complete nuclear fuel cycle system from mining to disposal
  - Develop a set of fuel cycles that is comprehensive with respect to potential fuel cycle performance
  - Develop appropriate evaluation metrics for the nine criteria
  - Evaluate the fuel cycle options with respect to the criteria
  - Screen the fuel cycle options to identify fuel cycles that are promising for R&D based on the potential for substantial improvement
  - Explore the range of possible policy guidance by weighting the criteria
  - Establish an Independent Review Team (IRT) to review the Study process, interim draft deliverables, and the final report
- **Study report posted 10/8/2014**
  - Study duration almost 3 years, about ~$8M direct costs, ~$10M in added support from the Fuel Cycle Options campaign
    - 11 member team, 10 member DOE independent review team

E&S Study and Geologic Disposal

- **DOE-NE's priority is to have an operating geologic repository**

- **All fuel cycles will require geologic disposal**
  - The report notes that the current U.S. fuel cycle is incomplete
  - The study assumed geologic disposal was implemented for the current U.S. fuel cycle in order to evaluate this fuel cycle and compare it to all other fuel cycles
  - No alternative fuel cycle can eliminate the need for a geologic repository
  - An alternative fuel cycle may make more efficient use of a repository

Evaluation and Screening Team (EST)

- Team Leader
  - Roald Wigeland (now retired from INL; fuel cycles, reactors, safety, proliferation risk)
- Deputy Team Leader
  - Temitope Taiwo (ANL; fuel cycles, reactors & EDS, thorium)
- Team Members
  - Michael Todosow (BNL; fuels, fuel cycles, reactors & EDS, safety, thorium)
  - The late Hans Ludewig (BNL; fuel cycles, reactors & EDS, safety, NRC regulation)
  - William Halsey (now retired from LLNL; fuel cycles, reactors & EDS, disposal, economics)
  - Jess Gehin (ORNL, now INL; fuel cycles, reactors, thorium, economics)
  - Robert Jubin (now retired from ORNL; separations, waste forms, environmental impact)
  - James Buelt (now retired from PNNL; fuel cycles, waste management)
  - The late Siegfried Stockinger (DOE-NV; front-end, waste, environmental impact)
  - Karen Jenni (Insight Decisions LLC, now USGS; decision analysis)
  - Brian Oakley (Scully Capital, now JLL; financial services)

Independent Review Team – Established by North Wind, LLC

Name	Affiliation
Michael Corradini, Chairman	University of Wisconsin
Tito Bonano	Sandia National Laboratory (SNL)
Bob Hill	Argonne National Laboratory (ANL)
Everett Redmond	Nuclear Energy Institute (NEI)
Neil Todreas	Massachusetts Institute of Technology (MIT)
Bob O'Connor	National Science Foundation (NSF)
Tom Cotton	Complex Systems Group, LLC (CSG)
Dick Stewart	New York University Law School
Tom Isaacs (retired, July 2013)	Lawrence Livermore National Laboratory (LLNL)
Keller Staley, Task Coordinator	Longenecker & Associates, Inc. (L&A)

Set of Fuel Cycle Options: 1 of 3

- **Comprehensive representation of fuel cycle performance**
  - Focus on the basic physics principles, not on specific technologies or facility designs (i.e., “technology neutral)
  - Study based on <u>what</u> supporting technologies must accomplish to implement a fuel cycle (<u>not a specific way to do it</u>)
  - Six fundamental principles characterized those aspects of the nuclear fuel cycle that have the potential to affect performance
    - *Once-through vs. recycle (limited or continuous)*
    - *Critical or sub-critical (externally driven systems)*
    - *Neutron spectrum – thermal, intermediate, or fast*
    - *Nuclear fuel – Uranium-based, thorium-based, or both*
    - *Need for uranium enrichment*
    - *Recycled elements (U, Pu, Minor Actinides, TRU, Th, FP)*
  - For example, a fuel cycle option is described as “once-through critical thermal reactor with enriched-U fuel”

Set of Fuel Cycle Options: 2 of 3

- **Each fuel cycle "option" developed using this approach is actually a fuel cycle group representing a (possibly large) group of specific fuel cycles**
  - A specific fuel cycle has all implementing technologies and performance parameters defined
- **This approach identified ~4,400 initial fuel cycle groups that represented the entire range of fuel cycle performance**
  - 30 Once-through fuel cycle groups
  - 336 Single-stage recycle fuel cycle groups (limited and continuous)
    - *Only one reactor , or "stage", e.g. a thermal reactor only*
  - 4032 Two-stage recycle fuel cycle groups (limited and continuous)
    - *Two reactors, e.g., thermal and fast reactors*
- **These fuel cycle groups were subsequently collected into 40 "Evaluation Groups", still representing the entire range of fuel cycle performance**
  - Collected based on similarity of performance for the criteria and metrics

Set of Fuel Cycle Options: 3 of 3

- **Each Fuel cycle is assumed to be implemented “well”**
  - Any fuel cycle can be implemented well or poorly, with poorly implemented fuel cycles not achieving the performance of a well-implemented fuel cycle
  - Study assumed that technology and design choices for implementation would be made recognizing the impact on performance, with favorable choices being used

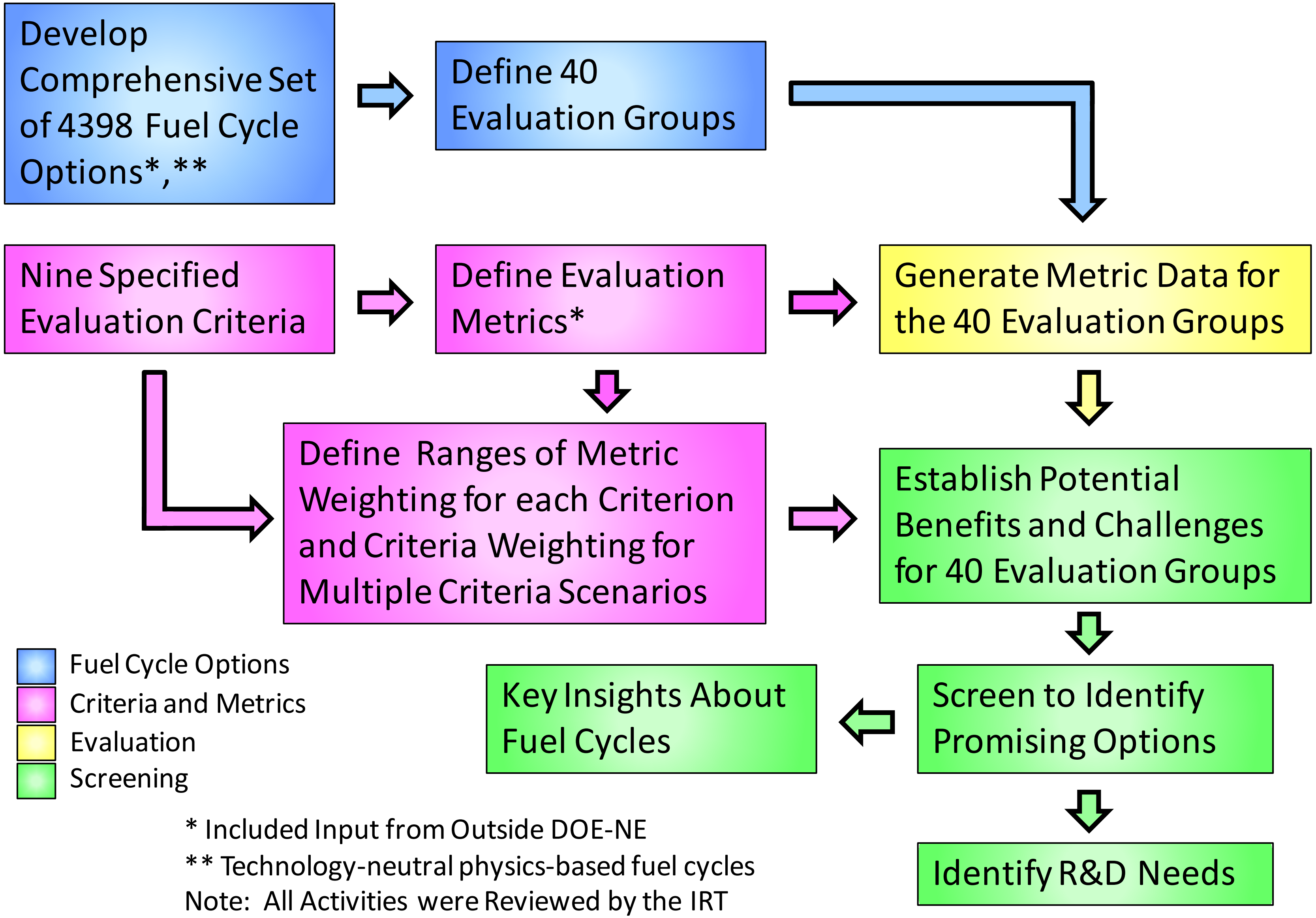
Scope Limitations of the Study: 1 of 2

- **E&S does NOT consider general nuclear power questions, such as:**
  - Deep geologic disposal viability
  - Public acceptance of nuclear power

Scope Limitations of the Study: 2 of 2

Nuclear Fuel Cycle Evaluation and Screening	
Does	**Does Not**
Provide a framework and process to allow decision makers to evaluate the impact of policy decisions	Make policy decisions
Provide a screening tool to identify fuel cycle options with the potential to provide substantial improvement	Decide on the preferred fuel cycle(s) or identify fuel cycle options that provide incremental improvement
Provide information for R&D prioritization	Decide what R&D will be conducted or how it will be conducted
Base the evaluation on fundamental fuel cycle characteristics (e.g. fast versus thermal reactor)	Evaluate at the specific technology level (e.g. gas cooled fast reactor versus lead cooled fast reactor), or evaluate engineering design of fuel cycle facilities
Provide extensive documentation for transparency of the process, credibility of the data, understanding of the methods, and applicability of the conclusions	Preclude incorporation of additional data and knowledge in the future, or inhibit reconsideration if issues or criteria evolve
Assess performance of a fully developed and deployed alternative fuel cycle and provide information on development R&D	Investigate the transition from the current U.S. fuel cycle to a fully deployed alternative fuel cycle

Study Approach



* Included Input from Outside DOE-NE
** Technology-neutral physics-based fuel cycles
Note: All Activities were Reviewed by the IRT

Evaluation Criteria

- **Six criteria were related to the potential for benefit**
  - Nuclear Waste Management
    - *Study focused on waste generation*
  - Proliferation Risk
    - *Proliferation is a host state issue; Study focused on material attractiveness*
  - Nuclear Material Security Risk
    - *Theft of nuclear materials; Study focused on material attractiveness*
  - Safety
  - Environmental Impact
    - *Environmental impacts not addressed by other criteria*
  - Resource Utilization

- **Three criteria related to the potential challenges**
  - Development and Deployment Risk
  - Institutional Issues
  - Financial Risk and Economics
    - *For continuing deployment and operation of the fuel cycle, not transition issues*

Evaluation Metrics

Nuclear Waste Management
- Mass of SNF+HLW disposed per energy generated
- Activity of SNF+HLW (@100 years) per energy generated
- Activity of SNF+HLW (@100,000 years) per energy generated
- Mass of DU+RU+RTh disposed per energy generated
- Volume of LLW per energy generated

Proliferation Risk
- Material attractiveness - normal operating conditions

Nuclear Material Security Risk
- Material attractiveness - normal operating conditions
- Activity of SNF+HLW (@10 years) per energy generated

Safety
- Challenges of addressing safety hazards
- Safety of the deployed system

Resource Utilization
- Natural Uranium required per energy generated
- Natural Thorium required per energy generated

Financial Risk and Economics
- Levelized Cost of Electricity at Equilibrium

Environmental Impact
- Land use per energy generated
- Water use per energy generated
- Carbon emission - CO_2 released per energy generated
- Radiological exposure - total estimated worker dose per energy generated (as leading indicator for public dose potential)

Development and Deployment Risk
- Development time
- Development cost
- Deployment cost from prototypic validation to FOAK commercial
- Compatibility with the existing infrastructure
- Existence of regulations for the fuel cycle and familiarity with licensing
- Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes

Institutional Issues
- Compatibility with the existing infrastructure
- Existence of regulations for the fuel cycle and familiarity with licensing
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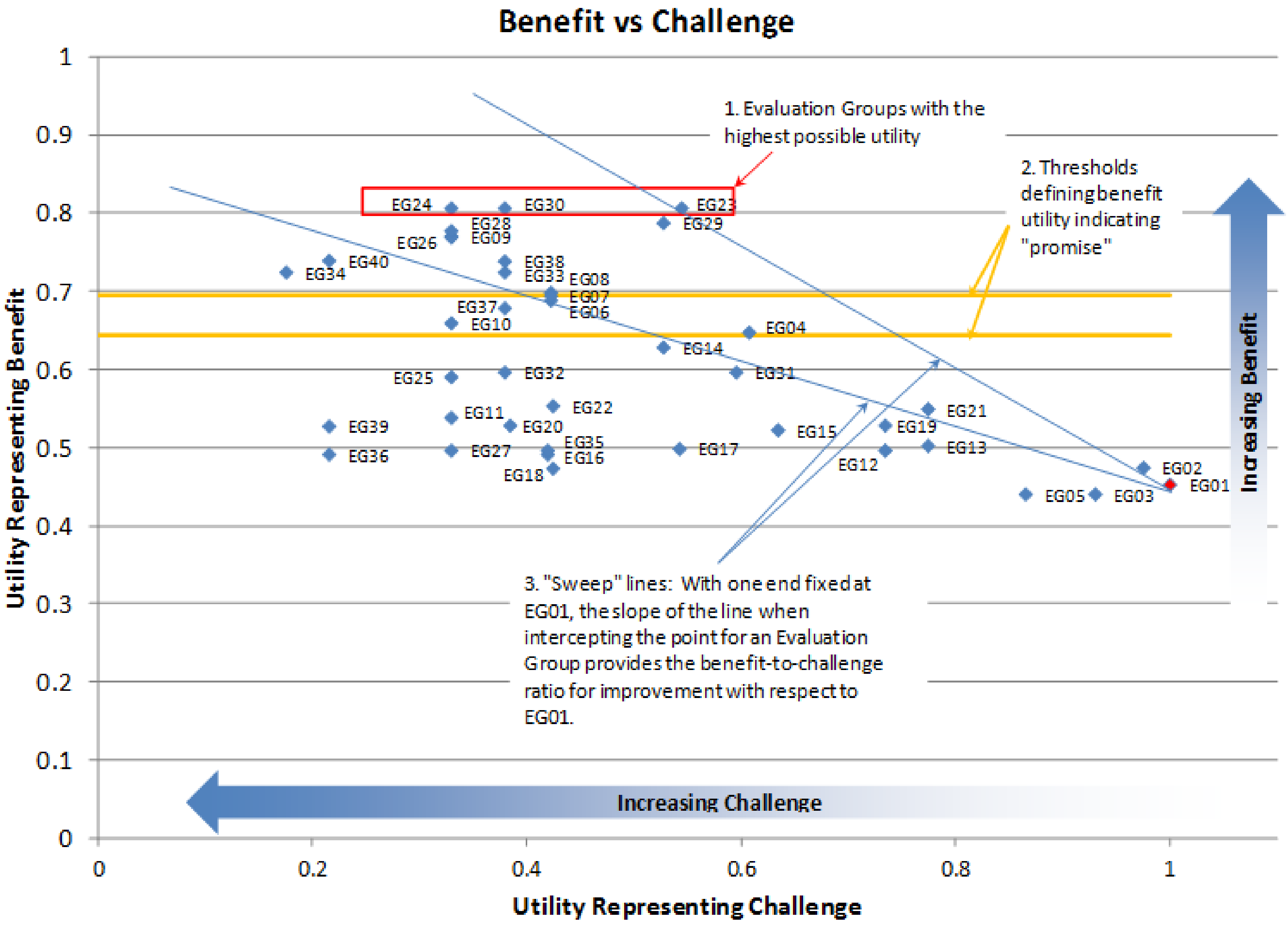
Use of Multiple Criteria Scenarios

- Decision-analysis principles were used
  - For each Evaluation Group, metric data was represented by "bins", with each bin covering a range of values (uncertainties were smaller than the bin ranges)
  - Metric data intended to reflect the best potential of the Evaluation Group
  - Each bin was assigned a non-dimensional "utility" representing "worth"

- A "scenario" considers multiple benefit criteria simultaneously, with weighting factors indicating the relative importance of each criterion
  - 11 scenarios were defined to explore the range of potential policy guidance, as required by the Charter
  - Results for the 11 scenarios were used to identify the potentially promising options
  - Variations of the relative importance of the metrics and criteria were used to confirm identification of the promising options and to evaluate "robustness" of the identification
    - *How sensitive are the results to the perspectives on the criteria?*
    - *Over 1,000,000 permutations of criteria tradeoff factors, metric tradeoff factors, and shape functions were considered*

Example of Using Scenario Results to Inform on Promising Options



Most Promising Fuel Cycle Options

- **Three fuel cycle groups consistently provided the highest improvements of all possible fuel cycles compared to the current fuel cycle in the U.S., regardless of perspective on relative importance of the benefit criteria**
  - Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors (EG23)
  - Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors (EG24)
  - Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors (EG30)
- **When considering both benefit and challenge, another group can be considered that has slightly less improvement but lower challenge compared to EG24 and EG30:**
  - Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors (EG29)
- **Most Promising Options**
  - These four groups are the most promising options if the amount of reduction provided by these fuel cycles in the amount of waste generated and fuel resources needed is considered to be both important and substantial, a judgment made by DOE decision-makers and others

Observations for the Benefit Criteria

- **Only the Nuclear Waste Management and Resource Utilization criteria were strongly affected by choice of fuel cycle**
  - Factor of 10 reduction in wastes requiring geologic disposal
  - Factor of 100 reduction in uranium disposal
  - Factor of 100 improvement in resource utilization
- **The Environmental Impact criterion was only modestly affected by choice of fuel cycle**
- **For the Safety criterion, all fuel cycles were evaluated as being capable of safe implementation, but varying challenge**
- **Proliferation Risk and Nuclear Material Security Risk were evaluated as being mainly affected by factors that are not determined by the choice of fuel cycle**
  - Facility location is a dominant factor, not an issue for the U.S.
  - Safeguardability and physical protection are affected by technology and design choices and operations

Observations for the Challenge Criteria

- **R&D to mature technologies to the point where they are ready for industrialization can be several billion dollars**
  - When major engineering demonstration facilities are included, such as reactors, processing plants, and fuel fabrication plants
  - Commercialization to the first-of-a-kind plant would also cost several billion dollars for the major facilities
- **Any transition to a new fuel cycle from the current U.S. fuel cycle would take decades to achieve**
  - Depending on the rate of construction and the replacement of existing facilities (as needed) – however, some benefits may accrue much more quickly
- **The total cost of deploying a new fuel cycle will require an investment of several hundred billion dollars, comparable to or somewhat greater than replacing the current U.S. reactor fleet with new LWRs**
  - Any promising fuel cycle option faces institutional issues related to the lack of regulations / licensing experience and the lack of supporting infrastructure
- **However, many of the promising options may be expected to have electricity production costs that are similar to, or close to, the estimated production costs for continuing the current U.S. fuel cycle**

Closing Remarks for the Completed Study

- The Evaluation & Screening is a framework and process and provides information about fuel cycle potential
- The full report is available at https://fuelcycleevaluation.inl.gov/SitePages/Home.aspx
- For each Evaluation Group, performance data for an example technology-specific fuel cycle are available from the fuel cycle options catalog, available at https://energy.sandia.gov/programs/nuclear-energy/advanced-nuclear-energy/nuclear-fuel-cycle-options-catalog/
- The interactive computer software (Excel-based), Screening and Evaluation (SET) Tool and the supporting Metric data also available
  - A user can repeat the Evaluation and Screening to gain insight into the results
  - A user can perform a new Evaluation and Screening with any desired set of functions and factors for the relative importance of the Metrics and Criteria
  - A user can add specific fuel cycles to the Evaluation and Screening by developing the Metric Data according to the documentation provided