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Nuclear Fuel Cycle Evaluation and Screening – Final Report

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy

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The authors also thank the Independent Review Team (IRT) for their reviews and comments on all parts of the Evaluation and Screening study that have contributed to ensuring that the Evaluation and Screening study meets the expectations set forth by DOE-NE in identifying promising fuel cycle options and providing the justification for such conclusions. Northwind LLC created the IRT at the request of DOE-NE. The IRT was composed of: M. Corradini (IRT Chairman), University of Wisconsin; T. Bonano, Sandia National Laboratory; T. Cotton, Complex Systems Group, LLC; R. Hill, Argonne National Laboratory; T. Isaacs, Lawrence Livermore National Laboratory; R. O'Connor, National Science Foundation; E. Redmond, Nuclear Energy Institute; R. Stewart, New York University Law School; and N. Todreas, Massachusetts Institute of Technology; with K. Staley, Longenecker & Associates, Inc. as the IRT Task Coordinator.

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Finally, the authors wish to express their appreciation to the members of universities, industry, and the DOE National Laboratories who have contributed to the development and review of the comprehensive list of fuel cycle options and the set of Evaluation Metrics, the key elements of the study.

MEMORIAM

The Evaluation and Screening Team was greatly saddened by the passing of one of its members, Dr. Hans Ludewig (BNL), shortly before the completion of the Study. Dr. Ludewig was a valued member of the team, especially contributing to the development of the comprehensive set of fuel cycle options and the evaluation metrics, the two key elements of the study. His extensive experience and knowledge from his long research career was a great asset to the team, as were his collegial interactions with every member of the team. He will be greatly missed.

EXECUTIVE SUMMARY

In late 2011, the U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) chartered a study[1] on the evaluation and screening of nuclear fuel cycle options, referred to as the Evaluation and Screening Study, or simply, the "Study". The Study Charter specified that the evaluation and screening consider the entire fuel cycle, i.e., the complete nuclear energy system from mining to disposal including both once-through and recycle fuel cycles to identify a relatively small number of promising fuel cycle options with the potential for achieving substantial improvements compared to the current nuclear fuel cycle in the United States. The results of this Study are intended to strengthen the basis for prioritization of the research and development (R&D) activities undertaken by the DOE-NE Offices of Fuel Cycle Technology and Nuclear Reactor Technologies by identifying potentially promising fuel cycle options and the corresponding required R&D and technology objectives, as shown in Figure ES1.

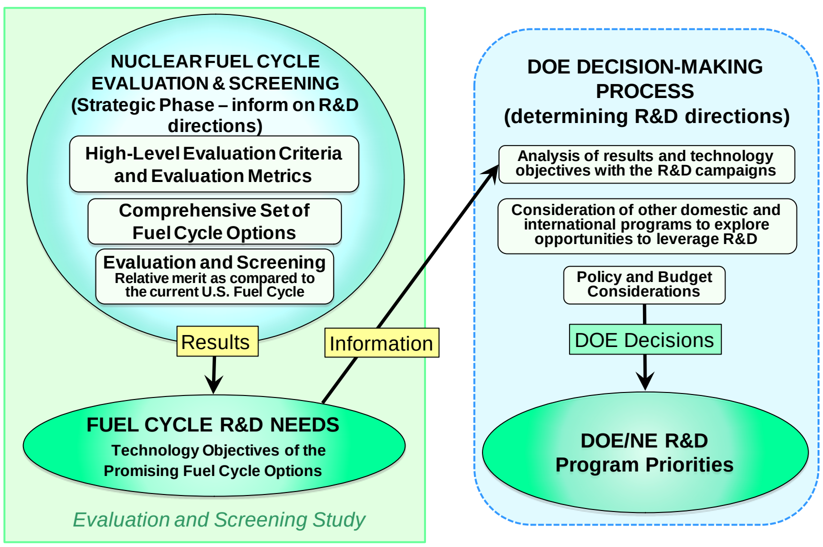

Figure ES1. Nuclear Fuel Cycle Evaluation and Screening Provides Input to the DOE Decision-Making Process.

DOE established an Evaluation and Screening Team (EST) consisting of national laboratory and industry experts in nuclear fuel cycles, financial risk and economics, and decision analysis to conduct the Study. The EST developed the evaluation and screening methodology and the technical information on fuel cycle options with assistance from industry, university collaborators, and others outside of DOE-NE. The EST used the evaluation and screening methodology as part of a systematic, transparent and independently reviewed process to provide information about the potential benefits and challenges of fuel cycle options. Under contract with DOE, Northwind LLC established an Independent Review Team (IRT) with members from national laboratories, industry, and universities to review all aspects of this Study.

The Study Charter specified nine evaluation criteria representing broadly-defined economic, environmental, safety, non-proliferation, security and sustainability goals to identify promising fuel cycle options and measure improvements as compared to the current nuclear fuel cycle in the United States, with the first six criteria related to the potential for benefit and the last three reflecting the challenges for developing and deploying a new fuel cycle. The set of fuel cycle options was to be as comprehensive as possible

Nine DOE-Specified Evaluation Criteria

- Nuclear Waste Management (Study considered waste generation only)
- Proliferation Risk
- Nuclear Material Security Risk
- Safety
- Environmental Impact
- Resource Utilization
- Development and Deployment Risk
- Institutional Issues
- Financial Risk and Economics

[1] Charter for the Evaluation and Screening of Nuclear Fuel Cycle Options, December 15, 2011, U.S. DOE; provided in this report as an Attachment to Appendix A.

with respect to potential fuel cycle performance. An approach based on the fundamental characteristics of nuclear fuel cycles rather than the specific fuel cycle implementation technologies (e.g., specifying a thermal reactor rather than a light-water reactor or gas-cooled reactor) allowed the EST to create a comprehensive set of options which included once-through and recycle fuel cycles; thermal, intermediate and fast neutron reactors; critical and sub-critical (externally-driven systems, EDS) reactors; and uranium and/or thorium for fuel along with other distinguishing fuel cycle features. Part of the process was to collect the resulting fuel cycle options with similar physics-based performance into groups, the 40 "Evaluation Groups" of fuel cycle options used in the Study.[2]

Figure ES2 shows the systematic logical framework developed and used by the EST to compare the relative performance of the Evaluation Groups. Metrics for the nine DOE-specified evaluation criteria facilitated the comparative assessment of the performance of the Evaluation Groups. The metric data developed by the EST for each Evaluation Group assumed that each fuel cycle was implemented "well", i.e., making development and deployment choices for technologies and facility designs that would favorably affect the evaluation metrics. Poorly-implemented fuel cycles would not achieve the same performance as well-implemented fuel cycles. The EST used the metric data to evaluate and subsequently screen the fuel cycles to identify the promising options based on the potential for improvement with respect to the evaluation criteria. Simultaneous consideration of multiple criteria using 11 sets of weighting factors and additional parametric variations reflected the range of possible policy guidance and illustrated the effects of specific policy choices. The required functional characteristics of the promising fuel cycle options provided the basis for identifying the R&D needs and identifying specific technical objectives for the essential enabling technologies.

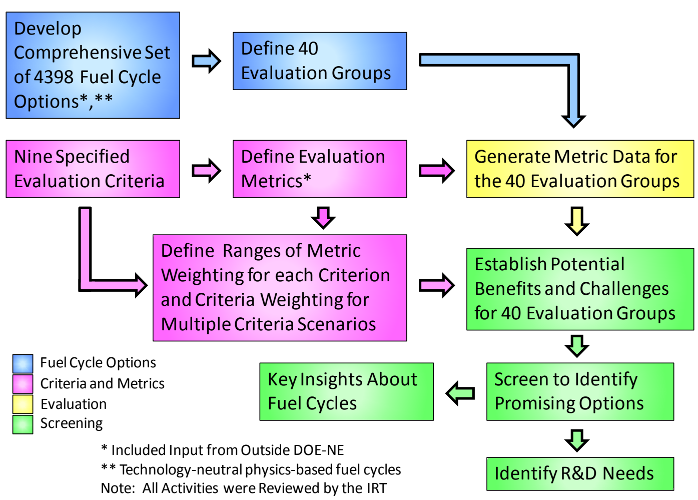

Figure ES2. Nuclear Fuel Cycle Evaluation and Screening Process.

Use of This Report

This report provides the results of the Study and the supporting analyses. The table on the next page highlights what this Study does and does not do, consistent with the purpose stated in the Study Charter of providing information for R&D prioritization. This report provides performance data for the 40 Evaluation Groups of fuel cycles on the metrics, the nine Evaluation Criteria, and for 11 scenarios, where the scenarios consider multiple criteria simultaneously assigning varying degrees of relative importance to the changes possible for each criterion to explore a potential range of policy guidance. This report identifies those Evaluation Groups where improvement with respect to the current U.S. fuel cycle is possible. Recognizing that what constitutes a "substantial improvement" as stated in the Study Charter is

[2] 40 groups of fuel cycle options, called Evaluation Groups (EGs), numbered from EG01-EG40 for identification purposes only, represented the comprehensive set of options encompassing all of the initially-identified 4398 fuel cycle groups

a judgment that may vary considerably among decision-makers, the report identifies multiple sets of promising Evaluation Groups based on the amount of potential improvement. Using this approach, decision-makers can find the appropriate promising Evaluation Groups corresponding to their view of what constitutes a substantial level of improvement. The report also provides the corresponding development and deployment challenges for all Evaluation Groups, allowing decision-makers to consider both the potential benefits and the associated challenges. The report then identifies the associated R&D that would be required to develop the fuel cycles in the promising Evaluation Groups.

The information in the report allows the reader to examine the results for each metric, criterion, and scenario to see when the choice of fuel cycle makes a difference and when it does not, what fuel cycle characteristics make such improvement possible, and why certain R&D directions support development of the fuel cycle options in the promising Evaluation Groups. The evaluation and screening software (the Evaluation and Screening Tool, SET) and metric data are also available for download and use along with this report on the INL website, allowing exploration of any desired combination of metrics and criteria.

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 cycles 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 R&D needs	Investigate the transition from the current U.S. fuel cycle to a fully deployed alternative fuel cycle

Key Results

The EST evaluated and screened nuclear fuel cycles only at what is termed the "functional" level, using the fundamental physics characteristics of each step in a fuel cycle (i.e., the physics principles defining *what* happens at each fuel cycle step, not the technologies for *how* it is accomplished) both to enable creation of a comprehensive set and to provide flexibility for future R&D directions into specific technology choices. The EST evaluated the alternative fuel cycles by comparing them to the current U.S. fuel cycle assuming successful implementation of all disposal paths. It is recognized that DOE-NE's first priority is developing and opening a geologic repository in the U.S., given that no alternative fuel cycle can eliminate the need for such a repository, although an alternative fuel cycle may make more efficient use of such a repository. The EST identified several promising Evaluation Groups that have the potential for improved performance relative to the current U.S. fuel cycle for three of the benefit criteria as follows:

– *Nuclear Waste Management Criterion*: On a per unit energy generated basis, reduction in generation of fuel cycle waste materials requiring geologic disposal by as much as a factor of 10 or more, reduction in long-term activity corresponding to a reduction in long-term radiation hazard by as much as a factor of 10 or more, and reduction in uranium (depleted from the enrichment process or recovered from reprocessing) and/or thorium (recovered from reprocessing) disposal needs by a factor of 100 or more, and without a large increase in low-level waste generation (up to about 50% higher).

– *Resource Utilization Criterion:* On a per unit energy basis, reduction in the amount of fuel resources needed by a factor of 100 or more.

– *Environmental Impact Criterion*: On a per unit energy basis, reduction in the amount of land required and in the amount of CO_2 emitted (always much lower for nuclear power than for fossil-based generation) by about a factor of 2.

For the remaining three benefit criteria, no fuel cycles were identified that would perform better than the current U.S. fuel cycle. The report discusses the limitations of the Study in addressing the Proliferation Risk, Nuclear Material Security Risk, and Safety criteria.

For the three challenge criteria, the EST determined the challenge of developing and deploying the promising Evaluation Groups as follows:

- *Development and Deployment Risk Criterion*: Alternatives to the current U.S. fuel cycle in the promising Evaluation Groups require R&D to bring the enabling technologies up to the level of successful engineering demonstration including pilot-scale facilities, which the Study results indicate as requiring several billion dollars over 10-25 years. Similarly, further development up to the first-of-a kind commercial facilities would require an additional several billion dollars. Any transition to a new fuel cycle would take decades to achieve, although some fuel cycle performance benefits such as wastes destined for deep geologic disposal would accrue more quickly. Fully deploying an alternative fuel cycle would likely require several hundred billion dollars or more, comparable to the cost of continuing with the current U.S. fuel cycle as new reactors replace existing reactors.
- *Institutional Issues Criterion*: Any of the alternative fuel cycles in the promising Evaluation Groups faces several institutional issues, including lack of supporting infrastructure, lack of regulations and licensing experience, and market barriers to commercial implementation.
- *Financial Risk and Economics Criterion*: Estimates of the electricity production cost for fuel cycles in the most promising Evaluation Groups and many of the promising Evaluation Groups are similar to, or close to, those for continuing with the current U.S. fuel cycle.

Most Promising Fuel Cycles and Their R&D Needs

The multiple criteria scenarios and parametric variations of the metric and criteria weighting factors were used to identify the promising Evaluation Groups and to determine the robustness of the identification with respect to changing perspectives on the relative importance of the benefit criteria. Among all options, the EST noted that three Evaluation Groups consistently provided the highest improvements compared to the current fuel cycle in the U.S., regardless of the perspective on the relative importance of the six benefit criteria. These Evaluation Groups all have the same metric data values for the six benefit criteria, and perform as well as, or better than, any other Evaluation Group. These groups contain the most promising options if the amount of reduction provided by these fuel cycles in the amount of waste generated or fuel resources needed is considered to be both important and substantial (since as noted above, choice of fuel cycle for most of the remaining benefit criteria did not result in any improvement), a judgment made by DOE decision-makers and others. Note that the Evaluation Groups (EGs) are listed in numerical order, with a short description indicative of the fuel cycles included in each group:

- EG23 - Continuous recycle of U/Pu[3] with new natural-U fuel in fast critical reactors
- EG24 - Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
- EG30 - Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors

However, these most promising groups exhibited differences with respect to the three challenge criteria, with EG23 posing relatively lower development and deployment challenges than the other two due to the recycle of U/Pu as compared to U/TRU. When considering both benefit and challenge, another

[3] Note: U= uranium; Pu = plutonium; TRU = transuranic elements, i.e., atomic number higher than uranium (Neptunium, Plutonium, Americium, Curium, etc.); Th=thorium; the term "U/Pu" indicates that uranium and Pu are recycled together , similarly the term "U/TRU" indicates that uranium and TRU are recycled together.

Evaluation Group was included as a most promising option that has comparable development and deployment challenge to EG23:

- EG29 - Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors

None of these fuel cycles are ready to be deployed today, and R&D is required to develop the appropriate implementing technologies. The EST examined the current state of knowledge and experience to identify the R&D needs for each part of the fuel cycle. The R&D required to support these fuel cycles, along with some requirements for implementing technologies in order to achieve the benefits attributed to the fuel cycles, are as follows:

Reactor Development

– Fast critical reactors since these reactors facilitate effective consumption of actinide elements and efficient use of uranium fuel resources (which may also include intermediate spectrum reactors since these were grouped with fast reactors in the Study)

Separations / Reprocessing Development

– Separations technologies for recovery of U/Pu or U/TRU from irradiated fuel to make them available for recycle

Fuel Development

– Recycle fuel development to facilitate use of separated U/Pu or U/TRU as fuel

In addition, for any fuel cycle, an R&D goal should be to reduce waste generation throughout the fuel cycle, including developing waste forms that reduce the volume of any HLW since HLW volume can be an important factor for deep geologic disposal.

Additional Potentially Promising Fuel Cycles and Their R&D Needs

The EST identified eleven additional *potentially promising groups of fuel cycles* that provide beneficial improvements that are not quite has high as for the four groups listed above. While it is again a matter of judgment by DOE decision-makers and others whether the improvements offered by these groups would be considered both important and substantial, each of these groups perform better than the current U.S. fuel cycle when almost any, but not all, combinations of criteria are considered. (Evaluation Groups are listed in numerical order, with a short description indicative of the fuel cycles included in each Evaluation Group):

- EG06 - Once-through using Th fuel to very high burnup in thermal EDS
- EG07 - Once-through using natural-U fuel to very high burnup in thermal or fast EDS
- EG08 - Once-through using Th fuel to very high burnup in fast EDS
- EG09 - Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors
- EG26 - Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors
- EG28 - Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors
- EG33 - Continuous recycle of U/Pu with new natural-U fuel in both fast EDS and thermal critical reactors
- EG34 - Continuous recycle of U/TRU with new natural-U fuel in both fast EDS and thermal critical reactors
- EG37 - Continuous recycle of ^{233}U/Th with new enriched U/Th fuel in both fast and thermal critical reactors
- EG38 - Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors

- EG40 - Continuous recycle of $^{233}U/Th$ with new Th fuel in fast EDS and thermal critical reactors

While the R&D listed for the four most promising options would support development of some of these fuel cycles, other (different or additional) R&D is needed to support development of some of these promising options in order to achieve the benefits attributed to these fuel cycles, as follows:

Reactor Development

– Thermal critical neutron reactors since some of these reactors facilitate efficient conversion of thorium to usable fuel

– R&D on externally-driven systems (EDS) because subcritical reactors can provide an external source of neutrons to facilitate conversion of fertile materials to more fissionable materials

Separations / Reprocessing Development

– Separations technologies for recovery of $^{233}U/Th$ from irradiated fuel to make it available for recycle

Fuel Development

– Recycle fuel development to facilitate use of separated $^{233}U/Th$ as fuel

– Very high burnup fuel to facilitate greater resource utilization

Other Potentially Promising Fuel Cycles and Their R&D Needs

In addition to the fuel cycle groups listed above, the EST identified a few additional lesser performing fuel cycles that may be potentially promising depending on the relative importance of the underlying evaluation metrics, again if the improvements are considered both important and substantial by DOE decision-makers and others (Evaluation Groups are listed in numerical order, with a short description indicative of the fuel cycles included in each Evaluation Group):

- EG04 - Once-through using natural-U fuel to very high burnup in fast critical reactors
- EG10 - Limited recycle of $^{233}U/Th$ with new Th fuel in fast and/or thermal critical reactors
- EG14 - Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors

The R&D requirements already listed above are sufficient to support development of these fuel cycles.

Insights about Fuel Cycles

Based on the promising fuel cycles identified by the evaluation and screening process, the EST identified certain fuel cycle characteristics that provide beneficial performance improvements with respect to the evaluation metrics, criteria and scenarios:

– Continuous recycle of actinide elements – the actinide elements (thorium, protactinium, uranium, plutonium, neptunium, americium, curium, and so on) are major contributors to the long-lived hazard from irradiation of nuclear fuel, and can be a source of energy, some directly as fuel and others by conversion to usable fuel. Recycling the actinide elements benefits two of the evaluation criteria related to efficient use of fuel resources and reduction of nuclear waste generation.

– Fast neutron irradiation – fast neutron fission has a much more favorable fission-to-absorption ratio for neutrons for certain isotopes, greatly increasing fissioning of isotopes such as ^{240}Pu and enhancing fissioning of ^{239}Pu, reducing the buildup of long-lived highly radioactive higher actinide isotopes.

- Critical reactors – use of reactors that are capable of sustaining fission without the need for an external source of neutrons lowers development risk, lowers safety challenges, and lowers overall costs as compared to externally-driven systems.
- High-internal conversion – efficient conversion of fertile fuel materials to more easily fissionable isotopes allows efficient use of fuel without the need for uranium enrichment for continued operation, increasing resource utilization and reducing waste generation. Fast neutron fission also produces more excess neutrons per fission than thermal fission, facilitating the high-internal conversion needed for self-sustaining fuel cycles.
- Nuclear fuels – irradiating uranium-based fuels in the fast spectrum provides higher internal conversion capability than thorium-based fuels in either a thermal or fast spectrum, facilitating effective resource utilization as long as uranium enrichment is not required for continued operation, as evidenced by the four most promising options identified in the Study. However, even though uranium may be more readily used to achieve greater resource utilization, potentially promising options were also identified for fuel cycle options using thorium-based and uranium/thorium-based fuels, as listed above.
- Safety – promising fuel cycles are capable of safe deployment, with many having safety challenges comparable to the current U.S. fuel cycle. Enhanced safety is not provided by choice of fuel cycle, but may be provided by the choice of implementing technologies and facility design

In addition to these specific fuel cycle characteristics, the EST evaluated other more general concepts applicable to many or all fuel cycles for potential benefit:

- Extended decay storage (SNF and/or UNF[4] , products, or wastes) can slowly lower radiation level by radioactive decay to potentially reduce worker exposure or shielding requirements. It can also, favorably affect recycle of some actinide elements such as curium but may adversely affect recycle of other actinide elements such as plutonium. Decay storage slowly lowers decay heat at the time of disposal for SNF, facilitating handling and emplacement, but is most effective for the HLW from recycle fuel cycles where most of the content is fission products with a relatively short radioactive half-life.
- Processing of spent fuel prior to disposal, not for recycle (for once-through or limited recycle fuel cycles only) to separate the uranium or thorium from the fission products and any long-lived highly-radioactive elements may also greatly reduce the amount of materials requiring isolation such as that provided by deep geologic disposal. However, the uranium and/or thorium separated and recovered during processing still need to be disposed as waste, in contrast to recycle fuel cycles where such materials can be reused to reduce overall waste generation from the fuel cycle and increase utilization of fuel resources.
  - If the separated uranium or thorium can be disposed with much lower isolation requirements, then processing of SNF prior to disposal can reduce the amount of waste requiring geologic isolation, e.g., HLW, by a factor of 10 or more.
  - If the disposal requirements for the recovered uranium and/or thorium are comparable to those for SNF or HLW, then there would appear to be no benefit from processing SNF prior to disposal.
- Minor actinide separation and recycle in addition to uranium/plutonium recycle (TRU recycle) may provide beneficial improvement by further reducing waste generation and increasing resource utilization as compared to uranium/plutonium recycle, although no improvement was noted in this Study for the most promising options of continuous recycle in fast reactors. The EST also noted that there would be no difference in potential benefit for TRU recycle whether all

[4] Note: SNF denotes spent nuclear fuel, which is irradiated fuel destined for disposal. UNF, used nuclear fuel, denotes irradiated fuel that is reprocessed.

of the minor actinide elements are recycled individually in different fuels, as a single group in one fuel, or in combination with fuel containing plutonium. Thorium-based fuel cycles have little minor actinide content in the irradiated fuel and would not have substantial benefit from minor actinide separation and transmutation.

Challenges for Fuel Cycle Development and Deployment

The criteria indicating the challenges associated with developing and deploying an alternative fuel cycle identified several commonalities among essentially all of the promising fuel cycle options:

- Two of the most promising fuel cycles have estimated total development costs in the range of $2 - $10 billion (EG23, EG29), while the other two (EG24, EG30) are in the range of $10 - $25 billion, as are most of the other promising fuel cycles, and estimated development times in the range of 10 to 25 years to bring all enabling implementing technologies and facilities to successful demonstration at engineering scale. The government has historically been the major source of funding for such R&D activities.
- Following completion of the technology development, the promising options have an estimated initial total deployment cost in the range of either $10 - $25 billion (EG06, EG07, EG08, EG23) or $25 - $50 billion (the remaining promising options) to continue development from engineering demonstration through the deployment of first-of-a-kind commercial facilities. Cost-sharing between industry and government may be expected for such development. Fully deploying an alternative fuel cycle to replace the current U.S. fuel cycle would likely require several hundred billion dollars or more, comparable to the cost of continuing with the current fuel cycle replacing existing reactors as they are retired with new similar reactors.
- The market disincentives and barriers to commercial implementation of nearly all of the promising options are expected to be very significant, such that Federal government intervention in the form of direct investment, mandates, or changes in law in order to establish and sustain market drivers will likely be required for full-scale implementation of a new fuel cycle. A fee based on energy production provides a disincentive for waste reduction because for a given amount of energy production, the disposal fee is the same regardless of waste amount.
- Based on the Study results for the estimated levelized cost of electricity at equilibrium (LCAE), many of the promising options may be expected to have electricity production costs that are similar to, or close to, the estimated LCAE for the current U.S. fuel cycle, and that the dominant fuel cycle cost contributor is for the reactors. It was observed that more complex fuel cycles could cost more to build and operate, but can have offsetting lower costs elsewhere in the fuel cycle. For example, a recycle fuel cycle adds costs for reprocessing and recycling, but will have lower fuel resource costs and may eliminate enrichment costs.

Summary

In summary, through this Study, a "framework" (a logical structure and process which includes sets of data, methods and tools) was developed to support nuclear fuel cycle R&D decision making. The Evaluation and Screening is not a fuel cycle design tool, but a means for identifying fuel cycles with the potential for substantial improvement as compared to the current U.S. fuel cycle. This Study was not intended to produce a map to develop an optimum fuel cycle that is perfect for the future. The Study did produce identification of benefits, limitations and challenges of fuel cycle choices and documented all of the reasons for these results, considering the entire range of possible fuel cycle performance.

Use of this evaluation and screening framework identified four most promising options and the R&D required for these fuel cycles to inform DOE in support of their R&D decisions. These four options are all continuous recycle fuel cycles using fast reactors with uranium-based fuel, a result that is consistent with earlier fuel cycle studies. While this result is not necessarily new, the comprehensiveness of the fuel cycles considered allowed this study to make this determination in the context of considering the entire range of possible fuel cycle performance indicates that these fuel cycles are the best among all possible fuel cycles. However, as stated above, it must be emphasized that this R&D must be in addition to efforts to develop and open a repository in the U.S.

The Study also identified fourteen other potentially promising fuel cycles that can provide performance improvement, but not quite as high as for the four most promising. The approach and data used for the Evaluation and Screening study are contained in the computer software developed for the Study (SET, available for download on the INL website along with this report), allowing users to either reproduce the results, or to conduct their own evaluations using the software and data provided.

CONTENTS

FIGURES

TABLES

ACRONYMS

AAA	Advanced Accelerator Applications
ADS	Accelerator-Driven System
CANDU	CANadian Deuterium Uranium [reactor]
D&D	Decontamination and Decommissioning
DOE	Department of Energy
DOE-NE	Department of Energy - Office of Nuclear Energy
DU	Depleted Uranium
E&S	Evaluation and Screening
EDS	Externally-Driven System
EG	Evaluation Group
EST	Evaluation and Screening Team
ESST	The Evaluation and Screening Support Team
FCRD	Fuel Cycle Research and Development
FEFC	Front End of the Fuel Cycle
FFH	Fusion-Fission Hybrid
FOAK	First Of A Kind
FP	Fission Products
Gen IV	Generation IV
GNEP	Global Nuclear Energy Partnership
HLW	High Level Waste
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
INFCE	International Nuclear Fuel Cycle Evaluation
IRT	Independent Review Team
IND	Improvised Nuclear Device
HLW	High-Level Waste
LCAE	Levelized Cost of electricity At Equilibrium
LLW	Low-Level Wastes
LWR	Light Water Reactor
MA	Minor Actinide
MIT	Massachusetts Institute of Technology
MSR	Molten Salt Reactor
MTHM	Metric Ton Heavy Metal
NASAP	Nonproliferation Alternative Systems Assessment Program
NWM	Nuclear Waste Management
PEIS	Preliminary Environmental Impact Statement
PWR	Pressurized Water Reactor
R&D	Research and Development
RDD	Radiological Dispersal Device
RTh	Recovered Thorium
RU	Recovered Uranium
SET	Screening and Evaluation Tool
SNF	Spent Nuclear Fuel
SWU	Separative Work Unit
TRU	Trans-Uranium

NUCLEAR FUEL CYCLE EVALUATION AND SCREENING – FINAL REPORT

1. Introduction

In late 2011, the U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) chartered a study on the evaluation and screening of nuclear fuel cycle options, referred to as the Evaluation and Screening Study, or simply, "Study", to provide information about the potential benefits and challenges of nuclear fuel cycle options and to identify a relatively small number of promising fuel cycle options with the potential for achieving substantial improvements compared to the current nuclear fuel cycle in the United States.[1] This Study is part of an overall effort supported by DOE-NE towards achievement of Objective 3 "*Develop sustainable nuclear fuel cycles*" in the DOE Nuclear Energy Research and Development Roadmap,[2] and follows the recently completed pilot demonstration of an evaluation and screening process.[3] As directed by the Charter, this Study will also address feedback from internal and external reviews of the pilot demonstration which identified the required areas of refinement and improvement of the process.[4]

The Study Charter specified that the evaluation and screening consider the entire fuel cycle, i.e., the complete nuclear energy system from mining to disposal including both once-through and recycle fuel cycles. The results of this Study are intended to strengthen the basis for prioritization of the research and development (R&D) activities undertaken by the DOE-NE Offices of Fuel Cycle Technology and Nuclear Reactor Technologies, as shown in Figure 1.

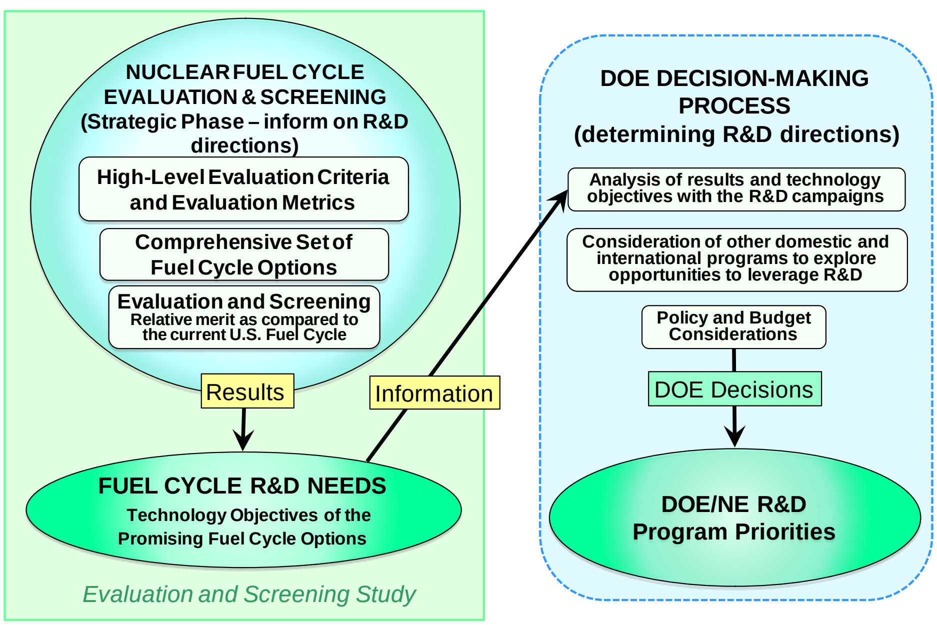

Figure 1. Nuclear Fuel Cycle Evaluation and Screening Provides Input to the DOE Decision-Making Process.

DOE established an Evaluation and Screening Team (EST) to conduct the Study. The EST consisted of national laboratory and industry experts in nuclear fuel cycles, financial risk and economics, and decision analysis. Experts from industry, universities, and others both within and outside of DOE-NE also provided input to this Study to build consensus on the fuel cycles considered, the scope of the evaluations, and the evaluation metrics developed for the Study. The EST used a systematic and independently reviewed evaluation process in a transparent manner to provide information about the potential benefits and challenges of fuel cycle options as described in detail in Appendix A. Under contract with DOE, Northwind LLC established an Independent Review Team (IRT), with members from national laboratories, industry, and universities to review all aspects of this Study, including the final report draft; see Appendix H.

1.1 Fuel Cycle Evaluation Criteria

To achieve the objectives of the Study, the Charter specified that the improvement potential of the promising fuel cycle options would be measured in terms of broadly defined economic, environmental, safety, non-proliferation, security, and sustainability goals. The Study Charter specified nine high-level evaluation criteria used in previous studies and in the Pilot Study, with the first six criteria related to the potential for benefit and the last three reflecting the challenges for developing and deploying a new fuel cycle. The criteria are summarized here, with detailed definitions of the criteria provided in Appendix C.

Nine DOE-Specified Evaluation Criteria

- Nuclear Waste Management (Study considered waste generation only)
- Proliferation Risk
- Nuclear Material Security Risk
- Safety
- Environmental Impact
- Resource Utilization
- Development and Deployment Risk
- Institutional Issues
- Financial Risk and Economics

Nuclear Waste Management Criterion –The premise for this Study used by the EST was that all disposal paths required for the use of nuclear power would be available. Some nuclear fuel cycles may generate less waste than others, but all fuel cycles create similar wastes, both low-level and high-level radioactive wastes. Consequently, all nuclear fuel cycles require waste disposal capabilities, including the need for long-term isolation of some wastes. As a result, the Study focused on the quantity and characteristics of the radioactive wastes generated by the different fuel cycles, including the current U.S. fuel cycle, not on the details of waste disposal such as geologic disposal environments.

Proliferation Risk Criterion – In general, assessing proliferation risk is a complex and challenging endeavor, primarily because it involves both technical and socio-political considerations, with the dominant factor being facility location. Since most of these factors are beyond the scope of the E&S Study, there was no attempt at an assessment of proliferation risk in the E&S Study, and efforts focused only on the evaluation of technical differences between fuel cycle options at the physics-based functional level (this study did not consider any specific implementing technologies as described in below, in Appendix A, and in Appendix B).

Nuclear Material Security Risk Criterion – The comparison of nuclear material security risk between nuclear energy system options includes an evaluation of the potential target materials as they exist for normal operations. Further, the other aspects of physical protection relevant to nuclear material security risk are a function of specific facility designs and operations, including physical barriers and assumptions made about the protective force and adversary force capabilities. These were not considerations in this E&S Study of fuel cycles, and as a consequence, it was not possible to evaluate nuclear material security risk; the E&S Study could only inform on the materials available from the fuel cycle.

Safety Criterion – the EST considered whether a fuel cycle could be safely deployed and the relative challenges in addressing safety hazards for an alternative fuel cycle in comparison to the current U.S. fuel cycle for all of the facilities required for each fuel cycle. The EST did not consider general questions on the acceptability of the current safety of nuclear power as deployed in the U.S.

Environmental Impact Criterion – the EST considered the environmental impacts from the routine operations of a nuclear fuel cycle focusing on impacts from fuel acquisition and nuclear power generation. Environmental impacts from accidents at fuel cycle facilities are not included in this criterion since these are part of the Safety criterion. Similarly, the EST did not consider the environmental impacts of waste disposal under this criterion since they are represented, directly or indirectly, by the metrics in the Nuclear Waste Management criterion. The information in this Study is only about the relative changes in such impacts between fuel cycle options, and not about whether such impacts are ultimately acceptable.

Resource Utilization Criterion – the EST only considered the natural resources required for nuclear fuel (i.e., uranium and thorium), not resources in general.

Development and Deployment Risk Criterion – the EST considered technology development needs for fuel cycle options including what would be necessary for maturing the technologies and factors that would affect deployment of a first-of-a-kind facility and integration of all parts of the entire fuel cycle.

Institutional Issues Criterion – the EST considered issues such as the existing infrastructure, current regulations, and market conditions and any different supporting needs that alternative fuel cycles would have as potential challenges to the deployment of a fuel cycle.

Financial Risk and Economics Criterion – the EST considered the relative differences in financial risk and economics among nuclear fuel cycle options. However, the EST did not consider the overall economic viability of nuclear power in the U.S.

1.2 Historical Perspective

For a perspective on the relationship of this Study to past similar efforts, the following table, Table 1, provides a brief summary of some of the previous studies conducted over the past 40 years. As described in Table 1, all of these previous studies were limited in some manner, either by the scope of the criteria used for evaluating fuel cycles or by the range of fuel cycles considered. These studies provided background information as well as insights that contributed to the approach and conduct of this Evaluation and Screening Study. The current Study reflected a broad range of issues relevant to the present time, and considered the entire range of potential fuel cycle performance. As a consequence of the requirements from the Charter as stated above, when compared to previous fuel cycle studies, this Study emphasized the identification and assessment of a comprehensive set of fuel cycle options and evaluated a broad range of fuel cycle issues on both performance benefits and development challenges.

Table 1. Examples of Past Studies of Nuclear Fuel Cycles.

Study	Objective and Outcome
Nonproliferation Alternative Systems Assessment Program (NASAP) [5] 1980	A U.S. study that assessed the proliferation resistance of civilian nuclear power, with the intent of providing recommendations for the development and possible deployment of “more proliferation-resistant” civilian nuclear power systems. (Proliferation resistant was defined as the capability of the nuclear energy system to slow or stop the diversion of associated fuel cycle materials or facilities from civilian to military use).
International Nuclear Fuel Cycle Evaluation (INFCE) [6] 1980	An international study of nuclear fuel cycles that could be used to meet the world’s energy requirements. Fuel cycle issues such as fuel and heavy water availability, enrichment availability, assurance of long-term supply of technology, reprocessing and plutonium handling and recycle, fast breeders, waste management and disposal, relationship to proliferation risk, and advanced fuel cycle and reactor concepts, were considered. The INFCE study included the entire fuel cycle, a limited number of fuel cycle options, and the national and international boundary conditions and perspectives of that time. The results of NASAP were used to provide U.S. inputs to this evaluation.
Candidate Approaches for an Integrated Nuclear Waste Management Strategy [7] 2001	A U.S. study that evaluated and contrasted the performance of a multi-tier approach to traditional, single-tier transmutation systems based on fast-spectrum reactors or accelerator-driven subcritical (ADS) systems. A few selected systems were evaluated using four high-level goals of (1) improved public safety, (2) benefits to the repository program, (3) reduced proliferation risk from plutonium in commercial spent fuel, and (4) improved prospects for nuclear power. The study aimed to provide a top-level understanding of the major consequences of technology choices with respect to the ability of the various approaches to meet the criteria of the Advanced Accelerator Applications (AAA) Program.

Study	Objective and Outcome
Gen IV Nuclear Energy Systems [8] **2002**	An international effort designed to identify future generation nuclear energy systems that can be deployed by 2030, while satisfactorily addressing nuclear safety, waste, nonproliferation, and public perception concerns. A detailed evaluation of nuclear systems was performed to determine which of the systems were worthy of future R&D to support deployment. The effort focused mainly on advanced reactor technologies, rather than the overall fuel cycle, even though fuel cycle metrics were used in the assessment.
Massachusetts Institute of Technology (MIT) Study on Future of Nuclear Power [9] **2003**	This was an MIT interdisciplinary study that assessed what is required to retain nuclear power as a significant option for reducing greenhouse gas emissions and meeting growing needs for electricity supply. Three representative fuel cycles were considered: (1) conventional thermal reactors operating in a "once-through" mode, (2) thermal reactors with reprocessing in a "closed" fuel cycle (limited recycle), (3) fast reactors with reprocessing in a balanced "closed" fuel cycle (the fast reactors used to balance LWRs). The fuel cycles were rated using evaluation criteria including economics, waste management, nonproliferation, and reactor and fuel cycle safety.
Global Nuclear Energy Partnership (GNEP) Draft Preliminary Environmental Impact Statement (PEIS) [10] **2008**	The GNEP PEIS included an assessment of a limited number of fuel cycle systems using criteria of resource consumption, waste management, public health, and transportation metrics.
DOE-NE Options Study Phases I and II [11,12] **2009, 2010**	The purpose of these studies was to evaluate the potential of alternative integrated nuclear fuel cycles to address the issues associated with a continuing or expanding use of nuclear power in the United States, and to provide information that could be used in identifying potential directions for research and development on nuclear fuel cycle options. The study focused on high-level characteristics of fuel cycles and identified those fuel cycles that could favorably impact nuclear power issues.
International Atomic Energy Agency (IAEA) Advanced Reactor Transmutation Technology Options Study [13] **2009**	The study was designed to increase the capability of interested member states in developing and applying advanced technologies in the area of long lived radioactive waste transmutation. A comparative assessment of the transient behavior of various transmutation systems (called DOMAINs) was performed, though not a direct comparison relative to a reference system. The nuclear systems in the study were limited to fast reactors, ADS, molten salt, and fusion-fission hybrids. Limited effort was expended on evaluation criteria and metrics or ranking of systems.
MIT Study on The Future of the Nuclear Fuel Cycle [14] **2010**	This study was performed by MIT and other experts, and was also informed by an Advisory Committee of senior decision and policy makers of the energy industry. The study considered relatively few nuclear fuel cycle options for evaluation and was specifically focused on fuel cycle dynamics and transition issues, and reactor designs that would not require fast reactor technologies. The fuel cycle performance characteristics of these options were compared to a fuel cycle containing only LWRs, for the balance of the 21st century.

1.3 Use of this Report

The report consists of this Main Report summarizing the Study approach and results identifying potentially promising fuel cycles, the corresponding R&D needed to develop implementing technologies, and insights into beneficial fuel cycle characteristics. A series of Appendices provide the details supporting the Study results, with each Appendix focused on a specific aspect of the Study. Each Appendix contains a separate Table of Contents to aid in locating specific information about any aspect of the Study. The report is arranged as follows:

Main Report – Study Overview and Results Summary

Appendix A – Evaluation and Screening Approach – describes the process used to conduct the study, including a detailed description of each step and of the method used to combine metrics and criteria to yield insights on promising fuel cycles.

Appendix B – Comprehensive Set of Fuel Cycle Options – describes development of the comprehensive set of fuel cycle options considered in the Study, and identification of the 40 Evaluation Groups that were evaluated in detail and screened.

Appendix C – Evaluation Criteria and Metrics – each of the nine Evaluation Criteria identified in the Charter are defined and one or more Evaluation Metrics developed for each criterion.

Appendix D – Metric Data – the Metric Data are determined for the 40 Evaluation Groups, and then used to identify one or more sets of potentially promising Evaluation Groups for metrics where improvement is noted. The R&D needs are also identified.

Appendix E – Evaluation Criteria Results – results are provided for each criterion and the 40 Evaluation Groups, identifying one or more sets of potentially promising Evaluation Groups for each criterion where improvement is noted, along with the R&D needs.

Appendix F – Scenario Results – results are provided for multiple combinations of criteria, referred to as scenarios in this Study, identifying one or more sets of potentially promising Evaluation Groups for each scenario where improvement is noted, along with the R&D needs.

Appendix G – Evaluation and Screening Team – identification and background of the members.

Appendix H – Review Comments and Resolution – Independent Review Team and U.S. DOE – the final report from the IRT is included and the resolution of comments is discussed**.**

To facilitate locating information related to each Evaluation Criterion and the supporting Evaluation Metrics, Table 2 lists the locations in the report where the relevant information is located.

Table 2. Report Location for Evaluation Metrics, Metric Data, Criteria Results and Potentially Promising Options for Each Metric and Criterion.

Evaluation Criterion	**Definition and Metric Development**	**Determination of Metric Data and Potentially Promising Options for each Metric**	**Potentially Promising Options for each Criterion**
Nuclear Waste Management	Appendix C Section C-1	Appendix D Sections D-2.1 to D-2.5	Appendix E Section E-1
Proliferation Risk	Appendix C Section C-2	Appendix D Sections D-2.6	Appendix E Section E-2
Nuclear Material Security	Appendix C Section C-3	Appendix D Sections D-2.6 and D-2.7	Appendix E Section E-3
Safety	Appendix C Section C-4	Appendix D Sections D-2.8 and D-2.9	Appendix E Section E-4
Environmental Impact	Appendix C Section C-5	Appendix D Sections D-2.10 to D-2.13	Appendix E Section E-5
Resource Utilization	Appendix C Section C-6	Appendix D Sections D-2.14 and D-2.15	Appendix E Section E-6
Development and Deployment Risk	Appendix C Section C-7	Appendix D Sections D-2.16 to D-2.21	Appendix E Section E-7
Institutional Issues	Appendix C Section C-8	Appendix D Sections D-2.19 to D-2.21	Appendix E Section E-8
Financial Risk and Economics	Appendix C Section C-9	Appendix D Sections D-2.22	Appendix E Section E-9

At the conclusion of the Study, DOE-NE also requested that the technical experts on the EST provide opinions on what they considered a significant improvement for each of the Evaluation Metrics. This information is provided in Appendix E, Section E-10 for all of the Evaluation Criteria.

The summary of results provided in the Main Report identifies potentially promising options based on improvement with respect to metrics, criteria, and scenarios. The information presented in Table 2 directs the reader to the sections containing the detailed information on the performance improvements that cause an Evaluation Group to be identified as containing potentially promising fuel cycle options.

2. Study Approach, Principles, and Fuel Cycle Analyses

In consideration of the guidance provided by the Charter and the approach tested in the pilot study [3], the EST developed the approach to conduct the Evaluation and Screening, as discussed in detail in Appendix A. During the development of the approach, there were several key concepts that affected both the course of the Study and the overall scope of the considerations.

2.1 Evaluation and Screening Process

Figure 2 shows the systematic logical framework developed and used by the EST to compare fuel cycle options. Metrics for the nine DOE-specified evaluation criteria facilitated the comparative assessment of the performance of the Evaluation Groups. The metric data developed by the EST for each Evaluation Group assumed that each fuel cycle was implemented "well", i.e., making development and deployment choices for technologies and facility designs that would favorably affect the evaluation metrics. Poorly-implemented fuel cycles would not achieve the same performance as well-implemented fuel cycles. The EST used the metric data to evaluate and subsequently screen the fuel cycles to identify the promising options based on the potential for improvement with respect to the evaluation criteria for the six benefit criteria. Simultaneous consideration of multiple criteria using 11 sets of weighting factors and additional parametric variations reflected the range of possible policy guidance and illustrated the effects of specific policy choices. The required functional characteristics of the promising fuel cycle options provided the basis for identifying the R&D needs and identifying specific technical objectives for the essential enabling technologies.

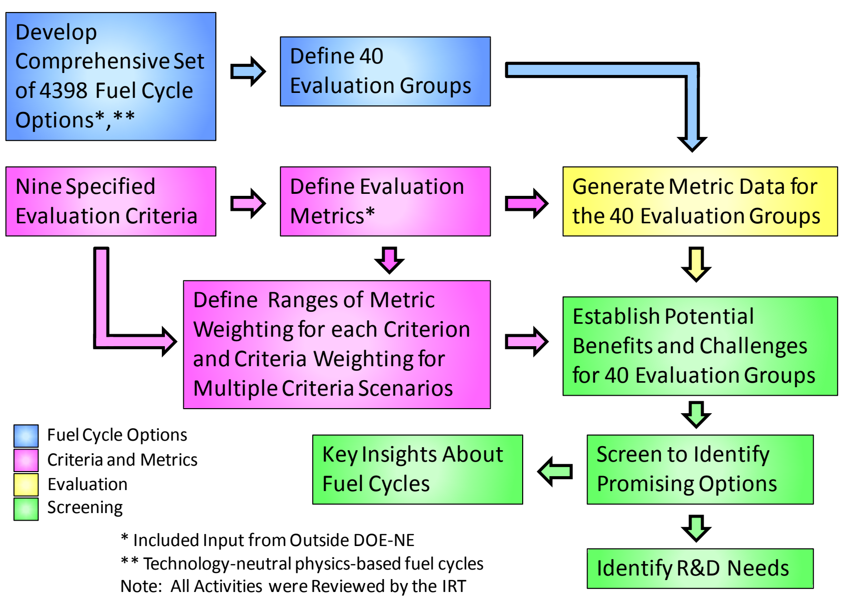

Figure 2. Nuclear Fuel Cycle Evaluation and Screening Process.

The EST focused the Study on technical and other indicators of fuel cycle performance as the basis for identifying promising fuel cycles with the ability to provide substantial improvements compared to the current U.S. fuel cycle. The key concepts used in this Study to achieve this objective are discussed in detail in the following Appendices:

- Using descriptions of fuel cycle options based on the fundamental physics characteristics rather than specific implementing technologies to allow a comprehensive representation of all fuel cycle performance – Sections 2.2, 2.3, and Appendices A and B
- Dividing the Evaluation Criteria into two categories, "benefit" Criteria and "challenge" Criteria, which allowed separate consideration of the potential benefits of promising fuel cycle options and consideration of both the potential benefit and the challenge in developing such fuel cycles – Section 2.4 and Appendix E
- Developing Evaluation Metrics that focused on the fuel cycle performance issues for each Evaluation Criterion – Section 2.4 and Appendix C
- Using an Analysis Example for each Evaluation Group to provide initial estimates for the Metric Data based on calculated performance, placing the results into bins for the Metric Data, and subsequently considering the range of fuel cycles in each Evaluation Group to identify the bin that would represent the best potential for each Evaluation Group for each Evaluation Metric – Section 2.5.2 and Appendix D
- Using the insight from the Evaluation Metric results and the corresponding bins to inform on the thresholds for identifying potentially promising Evaluation Groups at the criterion level – Section 3 and Appendix E
- Using the multiple criteria scenarios, identify any promising Evaluation Groups (sets of fuel cycle options), always expressed as a conditional statement "if this level of improvement is considered substantial, then these are the Evaluation Groups that would be considered promising," leaving judgments about the significance of those improvements to the DOE decision-makers and others – Section 3 and Appendix F
- Using a range of value judgments to explore the sensitivity of the identification of the promising Evaluation Groups to changes in perspectives on the relative importance of the Evaluation Metrics and Evaluation Criteria, providing an indication of "robustness" of the set of promising Evaluation Groups to changes in opinion or perspective – Section 3 and Appendices E and F
- Developing a screening and evaluation tool (SET) using commonly available software (Microsoft® Excel™) to support the Study, which not only facilitated conduct of the Study and documentation of the results, but which established a capability that can be provided to anyone interested in fuel cycle performance. SET includes the Metric Data, the Evaluation Criteria, the Scenarios, and the sets of value judgments used in this Study (which can also be altered in any manner by the user to provide complete flexibility in exploring fuel cycle evaluations).

2.2 Functional Level Evaluation

This Study evaluated and screened nuclear fuel cycles <u>only</u> at what is termed the "functional" level, using the fundamental physics characteristics of each step in a fuel cycle (i.e., the physics principles defining *what* happens at each fuel cycle step, not the technologies for *how* it is accomplished) both to enable creation of a comprehensive set and to provide flexibility for future R&D directions into specific technology choices. For example, a pressurized-water reactor (PWR) is a specific technology for implementing the function of thermal neutron irradiation. Similarly, reprocessing using PUREX to isolate and recover uranium and plutonium is a specific technology for implementing the function of recovering uranium and plutonium from irradiated fuel for reuse (which does not necessarily require isolating plutonium). The EST conducted this Study at such a functional level, e.g., thermal neutron irradiation, plutonium recovery, and many other possible fuel cycle functions, and as a consequence the study did not evaluate or screen either specific technology options or implementation / deployment options. A few important aspects of the functional level evaluation are:

- The definition of a nuclear fuel cycle used in the Study started with mining, and ended with the generation of wastes requiring disposal. Consideration of specific disposal environments required technology specifications and repository designs that were beyond the scope of the Study.
- For the list of fuel cycle options to be comprehensive in terms of fuel cycle performance, the EST identified options based on the fundamental physics principles that determine fuel cycle performance, not on choices for technology or implementation. The study considered the possible range for each physics principle, e.g., thermal, intermediate, or fast neutron spectrum. All combinations of the resulting possibilities for the physics principles resulted in the comprehensive set.
- Fuel cycle options with similar physics-based performance with respect to the benefit criteria and metrics (e.g., waste generation and resource use) were collected into groups called Evaluation Groups, and the resulting evaluation and screening was applied to each group of fuel cycle options (the 40 Evaluation Groups described below in Section 2.3). As a result, even though having similar physics-based performance, the fuel cycles within each Evaluation Group span a range of overall performance. To appropriately inform on the potential of each group, the EST identified the Metric Data bin (with a range of performance, as discussed below) representing the best performance potential for each Evaluation Group and each Evaluation Metric.

The application of the functional level approach for defining fuel cycles is discussed in more detail in the next section, and in Appendix B.

2.3 Comprehensive Set of Fuel Cycle Options

The set of fuel cycle options considered in the Study was to be as comprehensive as possible with respect to potential fuel cycle performance. As described above, and in Appendices A and B, the EST based the approach developed for the Study on the fundamental physics characteristics of nuclear fuel cycles rather than the specific fuel cycle implementation technologies, e.g., specifying a thermal reactor for thermal neutron irradiation rather than a light-water reactor or gas-cooled reactor. As part of the process of developing a comprehensive set of fuel cycles, a survey was conducted to identify any potential constraints that may exist on the types of fuel cycles that could be considered in this Study, with the result that all fuel cycles were potentially usable in the United States.[15] Appendix B describes the creation of such a comprehensive set which included once-through and recycle fuel cycles; thermal, intermediate and fast neutron reactors; critical and sub-critical (externally-driven systems, or EDS) reactors; and uranium and/or thorium for fuel along with other distinguishing fuel cycle features. Part of the process was the collection of fuel cycles with similar physics-based performance for the benefit criteria into 40 Evaluation Groups that maintained the comprehensive nature of the set with regards to performance, although it was also recognized that some of the collected fuel cycles in each Evaluation Group may be relatively poorer performers overall when compared to the best fuel cycles in the group.

Representing the Comprehensive Set of Fuel Cycle Options with a Finite Set of Groups

- Although there can be an almost endless set of Fuel Cycle Options when all technology and fuel cycle option choices are considered, there is only a relatively smaller set of Fuel Cycle Option Groups based on fundamental physics principles.
- Defining the finite set of groups requires consideration only of the physics principles.
- Accounting for the similarities among options, 40 distinct groups were identified as sufficient to represent possible fuel cycle options for the Evaluation Criteria specific to this study.

2.3.1 Fundamental Fuel Cycle Characteristics

While an almost endless variety of nuclear fuel cycles is possible given the technology choices for all of the activities in a nuclear fuel cycle, the EST defined a comprehensive set for the Study by considering the fundamental functional characteristics of a nuclear fuel cycle that potentially affecting the fuel cycle performance, the Evaluation Metrics, and in turn, the Evaluation Criteria, as follows:

1. "Once-Through" or "Recycle" where recycle includes limited recycle and continuous recycle
   - Limited recycle fuel cycles are those that only recycle once or a limited number of times before SNF is disposed along with high level waste generated from the recycle processes
   - Continuous recycle fuel cycles are those that always reprocess irradiated fuel for recycle and only high-level waste (HLW) is disposed
2. Irradiation system
   - Self-sustaining (critical reactor)
   - Externally-driven (sub-critical reactor)
3. Neutron spectrum (as defined in Appendix B, Section 2.4)
   - Thermal
   - Intermediate
   - Fast
4. Nuclear Fuel
   - Uranium
   - Thorium and Thorium/Uranium
5. Isotopic Enrichment
   - Uranium enrichment
   - No Uranium enrichment
6. Recycled Elements
   - One or more of the following: U (includes ^{233}U bred from Th); Pu; minor actinides (MA); All transuranic elements (TRU); Th; fission products (FP)

The EST considered other principles generically, such as processing spent fuel before disposal, or extended storage to allow for radioactive decay, since they could be applied to most or all fuel cycle options. As described above, since the characteristics listed above identify a fuel cycle at a "functional" level, i.e., only the fundamental physics characteristics were specified, not any of the specific technologies that would be needed to implement a fuel cycle in practice. This approach not only allowed a comprehensive list to be generated for use in this Study, but it facilitates the future consideration of any suitable technology for R&D as long as the functional requirements are satisfied.

As described in detail in Appendix B, the permutations of these functional characteristics resulted in 4398 potentially viable Fuel Cycle Option Groups. Starting with this set of Fuel Cycle Option Groups, the EST combined many of these groups into larger groups using a series of operations based on the similarity of their expected physics-based performance with respect to the Evaluation Metrics for the benefit criteria. At the end of this process, 40 groups of fuel cycles, called Evaluation Groups, were obtained that were sufficient to comprehensively represent all fuel cycle options to inform on their potential for providing substantial improvement:

- 8 Once-through Evaluation Groups
- 10 Limited recycle Evaluation Groups
- 22 Continuous recycle Evaluation Groups

As stated above, even though the fuel cycles were collected based on similarity of physics-based performance, the overall performance would not necessarily be equal for all fuel cycles in an Evaluation Group. The EST recognized that some of the collected fuel cycles in each Evaluation Group may actually be relatively poorer performers overall when compared to the best fuel cycles in the group. Further analyses of each promising Evaluation Group after completion of the Study would determine whether any of the Fuel Cycle Option Groups included in that Evaluation Group could be eliminated from further consideration.

To aid in interpretation of the results, Table 3 contains short descriptions for the 40 Evaluation Groups indicative of the fuel cycle options included in each Evaluation Group based mainly on the characteristics of the Analysis Examples (but are not complete descriptions of the Evaluation Group in most cases).

Appendix B provides detailed definitions of all of the Evaluation Groups and the included fuel cycles. Evaluation Group EG01 served as the "Basis of Comparison", representing the current U.S. fuel cycle as it would be completely implemented including disposal of the spent nuclear fuel.

Table 3. The 40 Evaluation Groups.

Evaluation Group	Short Description Indicative of Fuel Cycles in the Evaluation Group (Detailed Description of Each Evaluation Group is in Appendix B)
Once-through	
EG01	Once-through using enriched-U fuel in thermal critical reactors
EG02	Once-through using enriched-U fuel to high burnup in thermal or fast critical reactors
EG03	Once-through using natural-U fuel in thermal critical reactors
EG04	Once-through using natural-U fuel to very high burnup in fast critical reactors
EG05	Once-through using enriched-U/Th fuel in thermal or fast critical reactors
EG06	Once-through using Th fuel to very high burnup in thermal EDS
EG07	Once-through using natural-U fuel to very high burnup in thermal or fast EDS
EG08	Once-through using Th fuel to very high burnup in fast EDS
Limited Recycle	
EG09	Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors
EG10	Limited recycle of ^{233}U/Th with new Th fuel in fast and/or thermal critical reactors
EG11	Limited recycle of ^{233}U/Th with new enriched-U/Th fuel in fast or thermal critical reactors
EG12	Limited recycle of U/Pu with new natural-U fuel in fast and/or thermal critical reactors
EG13	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors
EG14	Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors
EG15	Limited recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors
EG16	Limited recycle of U/Pu with new enriched-U fuel in thermal critical reactors and fast EDS
EG17	Limited recycle of Pu/Th with new enriched-U/Th fuel in thermal critical reactors
EG18	Limited recycle of ^{233}U/Th with new enriched-U/Th fuel in thermal critical reactors
Continuous Recycle	
EG19	Continuous recycle of U/Pu with new natural-U fuel in thermal critical reactors
EG20	Continuous recycle of U/TRU with new natural-U fuel in thermal critical reactors
EG21	Continuous recycle of U/Pu with new enriched-U fuel in thermal critical reactors
EG22	Continuous recycle of U/TRU with new enriched-U fuel in thermal critical reactors
EG23	Continuous recycle of U/Pu with new natural-U fuel in fast critical reactors
EG24	Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
EG25	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in thermal critical reactors
EG26	Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors
EG27	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in fast critical reactors
EG28	Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors
EG29	Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors
EG30	Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors
EG31	Continuous recycle of U/Pu with new enriched-U fuel in both fast and thermal critical reactors
EG32	Continuous recycle of U/TRU with new enriched-U fuel in both fast and thermal critical reactors
EG33	Continuous recycle of U/Pu with new natural-U fuel in both fast EDS and thermal critical reactors
EG34	Continuous recycle of U/TRU with new natural-U fuel in both fast EDS and thermal critical reactors
EG35	Continuous recycle of U/Pu with new enriched-U fuel in both thermal critical reactors and fast EDS
EG36	Continuous recycle of U/TRU with new enriched-U fuel in both thermal critical reactors and fast EDS
EG37	Continuous recycle of ^{233}U/Th with new enriched-U/Th fuel in both fast and thermal critical reactors
EG38	Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors
EG39	Continuous recycle of ^{233}U/Th with new enriched-U fuel in both thermal critical reactors and fast EDS
EG40	Continuous recycle of ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

Note: EDS = externally-driven systems (subcritical reactors), and ^{233}U/Th indicates recycle of uranium that is predominantly ^{233}U with thorium.

The EST conducted the Study by comparing the performance of the 40 Evaluation Groups for the Evaluation Metrics, the Evaluation Criteria, and combinations of Evaluation Criteria. The IRT reviewed both the approach for creating the comprehensive set and the resulting Evaluation Groups.

2.4 Evaluation Metrics

The EST developed the Evaluation Metrics as directed by the Study Charter for the nine specified Evaluation Criteria, coordinated with input from DOE, industry, universities, and others through collaborations, meetings and reviews. This activity resulted in one or more Evaluation Metrics for each Evaluation Criterion along with the justification for each metric and the methods to be used to calculate or estimate the metrics. Appendix C discusses the development and use of the Evaluation Metrics.

Table 4 shows the metrics for the nine Evaluation Criteria. The EST noted that the first six Criteria represented opportunities for improvement (or "benefit") when compared to the current U.S. fuel cycle, while the other three are related to the "challenges" associated with developing and implementing any new fuel cycle. The EST also recognized that the current U.S. fuel cycle would likely perform best for the “challenge” criteria relating to development and deployment since this fuel cycle is already in use, with the exception of SNF disposal (but disposal capabilities such as those required for SNF are needed by all fuel cycles for managing SNF and HLW). The IRT also reviewed the approach for creating the Evaluation Metrics and the set of metrics, with subsequent approval by DOE-NE.

Table 4. Evaluation Criteria and Evaluation Metrics.

"Benefit" Criteria	
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
Environmental Impact	Land use per energy generated
	Water use per energy generated
	Radiological exposure - total estimated worker dose per energy generated
	Carbon emission - CO_2 released per energy generated
Resource Utilization	Natural Uranium required per energy generated
	Natural Thorium required per energy generated
"Challenge" Criteria	
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
	Existence of market incentives and/or barriers to commercial implementation
Financial Risk and Economics	Levelized Cost of Electricity at Equilibrium

2.5 Fuel Cycle Analyses

Analysis of the fuel cycles represented by the Evaluation Groups provided the basis for the Metric Data for the Evaluation Metrics. The EST used several principles as discussed in the following sections.

2.5.1 Steady-State Analysis and Transition

> **Steady-State Nuclear Fuel Cycle Analysis**
>
> - Analysis of the deployed mature fuel cycle determined if there were any potential benefits from using an alternative fuel cycle with respect to most of the Evaluation Criteria.
> - Development and initial deployment issues were specifically considered by two of the Evaluation Criteria.

For the purposes of calculating the amount of fuel materials used, wastes produced, and other quantities, this evaluation considered the nuclear energy system as it would perform for such a "steady-state" or "equilibrium state" of deployment. That is, for each nuclear energy system, all of the facilities were being continually built, operated, and decommissioned as needed to support the power generation needs, reflecting the useful lifetime of such facilities. This situation occurs after all initial deployment issues were resolved and costs stabilized, as would be expected after a sufficient number of each facility was built. The EST used this assumption of nuclear energy systems at equilibrium to assess whether an alternative to today's use of nuclear power would offer any significant benefits as compared to continuation of the current U.S. fuel cycle and to explain and quantify the benefits. The EST noted that some benefits identified in this Study would be obtained when a decision is made to implement a new fuel cycle, e.g., if the new fuel cycle involves recycle, the spent fuel would no longer be destined for disposal, but reprocessed and there would only be disposal of the smaller amount of HLW. Other benefits would accrue during transition, such as any reduction in fuel resources required by the new fuel cycle.

Some of the issues that may arise in replacing today's infrastructure with such an alternative, including deployment issues and introduction costs, are reflected in the Evaluation and Screening by two of the Evaluation Criteria, informing on the anticipated effort and difficulties in developing and implementing a nuclear energy system different from the current U.S. nuclear power infrastructure. However, the detailed deployment of the new fuel cycle to replace the existing U.S. infrastructure, designated as the "transition" phase, including choices on timing of facility construction and options for accelerating or delaying such a transition, was not part of this Study.

Figure 3 is a schematic that associates the metrics for the three challenge criteria (Development and Deployment Risk, Institutional Issues, and Financial Risk and Economics) to the development, initial deployment, and transition phases for implementing an alternative fuel cycle. Note that the transition phase extends from the time at which the first-of-a-kind (FOAK) systems have been developed and deployed to that when the new fuel cycle has completely replaced the current fuel cycle system, i.e., replacing today's once-through LWR fleet with something else. As shown on Figure 3, this transition occurs after the decision to replace the current nuclear energy system. Appendix A provides further analysis of the issues and implications of transition.

Appendix C, Section C-7 describes the development of the metrics shown in Figure 3 for the Development and Deployment Risk and Institutional Issues criteria, with the results provided in Appendix D, Sections D-2.16 to D-2.21. The metrics of development time and cost apply to the initial R&D phase where after decisions are made by DOE to proceed with R&D, technologies are developed to the point of an engineering scale demonstration. The next phase is the initial deployment culminating in FOAK commercial facilities. The metric of Deployment Cost from Prototypic Validation to FOAK Commercial estimates the costs for this phase. At this time, a decision is required to proceed with the transition phase where part or all of the current U.S. fuel cycle infrastructure is replaced by the new fuel cycle. At the end of the transition phase, with the new fuel cycle fully deployed, the metric for the Financial Risk and Economics criterion, the Levelized Cost of Electricity (LCAE) provides an estimate of the electricity production costs from the new fuel cycle. Appendix C-9 describes the LCAE metric and the calculation methodology, with the results presented in Appendix D, Section D-2.22.

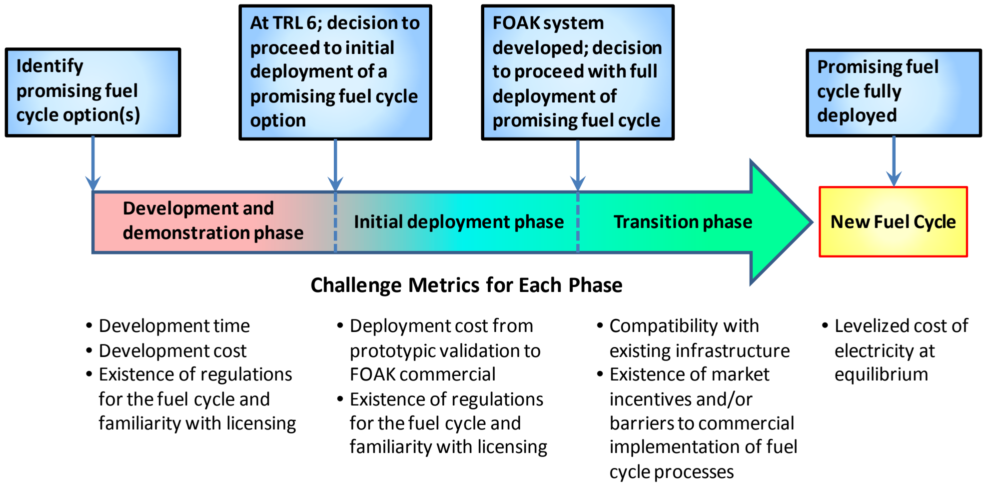

Figure 3. Fuel Cycle Development and Transition.

2.5.2 Analysis Examples and Metric Data

> **Use of Analysis Examples**
> - An Analysis Example is used to provide quantitative data or to otherwise inform the development of the Metric Data.
> - The Analysis Example only specifies technologies for irradiation of nuclear fuel, with all other parts of the fuel cycle being described at the functional level. Therefore, the Analysis Example is not a specific nuclear fuel cycle option as defined for this Study.

Determination of the Metric Data required detailed information about fuel cycle performance. To support the development of the Metric Data, an Analysis Example was identified for each Evaluation Group by specifying the irradiation environment and fuel type for the Fuel Cycle Option Group, e.g., a PWR using uranium oxide fuel as the thermal reactor in a fuel cycle, since this level of detail was necessary to obtain accurate information on the effects of irradiation on fuel resource needs, nuclear fuel composition, and spent fuel characteristics. Note that an Analysis Example is not a specific nuclear fuel cycle option as the term is used in the Study Charter (defined in the Glossary) since only the irradiation and fuel technologies were specified, and all other fuel cycle activities are only specified at the functional level. The Analysis Example was only used for calculating detailed reactor physics-based material mass balance information and other necessary information that provided an initial estimate of the performance of the Evaluation Group. For this Evaluation and Screening, the EST specifically chose the Analysis Examples to reflect a wide variety of possible irradiation systems to convey the broad scope of the Evaluation and Screening, not knowing a priori if the selected irradiation system represented the best performing system for each Evaluation Group. The EST performed the Evaluation and Screening on the Evaluation Groups, not on the Analysis Examples or their Fuel Cycle Option Group.

As described in Appendices C and D for each metric, the EST divided the potential range of the data into a small number of "bins", typically 5 to 7, with each bin covering a part of the entire data range. Using the results provided by an Analysis Example, the EST identified the bin containing that information as the initial determination of the Metric Data for that Evaluation Group. The EST then considered all of the Fuel Cycle Option Groups within the Evaluation Group to determine if the bin identified for each metric represented the potential performance of the best options within that Evaluation Group. In almost all cases, there was no need to make any changes from this initial determination. However, in some cases, once all of the results were available for the Analysis Examples, the choice of irradiation system did not represent the best potential of the Evaluation Group. In those few cases, the EST used information for a better choice of irradiation system (available from the Analysis Examples of other, similar, Evaluation Groups) to guide and justify identification of the appropriate bin for the best potential of that Evaluation Group. The details of this process are discussed in Appendix D for all cases where this was required.

The EST recognized that this process of identifying the bin representing the best performance potential for each metric could result in a set of Metric Data for an Evaluation Group that may not be achievable by any fuel cycle in the group, i.e., performing well on some metrics may be to some degree incompatible with simultaneously performing well on others. This is part of the issue that prevented justifiable identification of an Analysis Example a priori that excelled with respect to all Evaluation Metrics. However, since the purpose of the evaluation and screening was to inform on the potential of fuel cycles with respect to all metrics and criteria without regard to their relative importance, the EST considered each metric and criterion independently, and treated the relative importance of the Evaluation Metrics and Criteria parametrically within the Study. Examination of the promising Evaluation Groups has not identified any such incompatibilities in performance, resulting in the conclusion that viable fuel cycle options in the promising Evaluation Groups could be developed that have the capability to perform as indicated by the Metric Data.

2.5.3 Treatment of Uncertainties

The EST recognized that any assessment of fuel cycle performance would be subject to uncertainties from a variety of sources, including uncertainty about the Evaluation and Screening process itself, the grouping of fuel cycles into Evaluation Groups, the use of the Analysis Examples, and the accuracy of input data and accuracy of calculation. There is also the additional technical uncertainty about how yet-to-be developed technologies will perform many years in the future.

As stated above, a goal of the Study was to identify the potential for fuel cycles to provide substantial improvement with respect to the current U.S. fuel cycle. To achieve this goal, it was only necessary for the Metric Data to represent the best potential for all of the fuel cycles included in each Evaluation Group, not the performance of all fuel cycles in the group. As described in the previous section, the EST divided entire data range for each Evaluation Metric into a small number of bins. This process facilitated the handling of analysis uncertainty since the range of each bin represented the Metric Data, not specific values associated with a particular choice of technologies. As a result, the importance of uncertainty for calculating Metric Data was reduced to any effect such uncertainty would have in determining the proper bin for the best performance for an Evaluation Group for each metric. By representing the best potential in the evaluation group, the EST ensured that no potentially promising Evaluation Groups were eliminated, but as described above, also recognized that this approach may “carry along” fuel cycles that are less promising if they happen to be in an Evaluation Group with at least one high-performing fuel cycle.

2.5.4 Use of Value Judgments and Scenarios to Identify Promising Options

For the purpose of identifying the promising Evaluation Groups (which would contain one or more promising fuel cycle options), the EST considered the potential for improved performance as measured by the metrics, criteria, and groups of criteria, called scenarios in the study. The EST recognized that the value of an improvement for each metric, criterion, and scenario would be a judgment based on the viewpoint of the decision-maker, as is the amount of improvement that would be considered substantial. For this Study, the EST used a range of value judgments to explore the sensitivity of the identification of promising Evaluation Groups. These value judgments took the form of:

- Value functions indicating the relative importance of a change in the metric over a data range of interest, called "shape functions" in the Study;
- Sets of weighting factors called "metric tradeoff factors" for combining the Evaluation Metrics to inform on each Evaluation Criterion;

– Sets of weighting factors called "criteria tradeoff factors" for exploring the effects of the relative importance of Criteria when multiple criteria were being considered, each case called a "Scenario" as described above.

The result of applying the shape functions was a "utility" indicating the relative merit of the Evaluation Group performance for each metric. Use of the tradeoff factors provided the utility values for each criterion and scenario. Further details on the development of the value judgments and the application of decision analysis concepts to the Evaluation and Screening Study are given in Appendix A. The interactive software tool, SET (Screening & Evaluation Tool), provides the capability for a user to explore any value judgment desired.

The EST used the Metric Data to rank the Evaluation Groups from the highest performing to the lowest to develop an understanding of the potential for performance improvement from an alternative fuel cycle. The Basis of Comparison was Evaluation Group EG01 representing the current U.S. fuel cycle. The performance improvement of the Evaluation Groups with respect to the Basis of Comparison provided information on the benefit potential for each metric. The results are expressed as "conditional," i.e., stated in terms of "if this amount of improvement or greater is considered substantial, then these are the Evaluation Groups that have the potential for providing a significant improvement." For metrics where more than one "bin" of improvement over the Basis of Comparison was possible, several sets of Evaluation Groups were identified, based on which bin was used to denote a significant improvement. Appendix D describes these results in detail.

The EST followed the same process for the benefit criteria, using the utility calculated for each Evaluation Group based on the Metric Data and application of the value judgments and the metric tradeoff factors, to develop an understanding of the potential of an alternative fuel cycle to improve performance for the criterion. The EST again characterized the results as "conditional" based on the level of improvement that could be considered significant, and conditional on the particular value judgments used for the metrics in each criterion. An additional step related the potential improvement in performance for the benefit criteria with the challenge of developing and deploying the fuel cycle, as represented by the Development and Deployment Risk criterion. Appendix E describes these results in detail.

The EST developed 11 multiple criteria scenarios to represent a variety of different perspectives about the relative importance (weight, or tradeoff factor) of changes in four of the six benefit criteria (Nuclear Waste Management, Resource Utilization, Environmental Impact, and Safety) and to investigate the sensitivity of the results to changes in those perspectives, and grouped the scenarios into three categories:

- Scenario 1 – Changes in the four listed benefit criteria were of equal importance.
- Scenarios 2 through 5 – These four scenarios each emphasized changes in a single benefit criterion with respect to a balance of the three remaining criteria.

Six other scenarios were defined, each exploring an emphasis on a sub-set of these four benefit criteria, each defined to reflect one of a variety of perspectives. These scenarios were defined as:

- Scenario 6 - emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management, Resource Utilization, and Environmental Impact criteria– to focus on the direct physical impacts of producing nuclear power and the potential to reduce the impacts by choice of fuel cycle.
- Scenario 7 - de-emphasize the importance of differences between Evaluation Groups on the Environmental Impact criterion, focusing instead on the potential for improvement in Nuclear Waste Management, Resource Utilization, and Safety Criteria based on choice of fuel cycle.
- Scenario 8 - de-emphasize the importance of differences between Evaluation Groups on the Resource Utilization criterion– to explore the potential impact of expanded fuel resource

availability (such as uranium from seawater) and its effect on the relative benefits of fuel cycles. This scenario also provides insight on whether Resource Utilization as a separate criterion adds a different perspective to the results.

- Scenario 9 - de-emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management criterion – to explore, in combination with Scenarios 1, 7 and 8, any potential overlap between the Nuclear Waste Management and the Resource Utilization criteria and the potential impact on the choice of fuel cycle.
- Scenario 10 - emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management and Resource Utilization criteria – to focus on long-term and large-scale sustainability issues and the potential impact of the choice of fuel cycle.
- Scenario 11 - emphasize the importance of differences between Evaluation Groups on the Nuclear Waste Management and Safety criteria– to explore a perspective reflecting the most prominent current concerns and the potential impact of the choice of fuel cycle.

For the scenarios, the EST used the same process to identify the potentially promising Evaluation Groups, both for each scenario and for all scenarios. The performance improvement of the Evaluation Groups provided information on the benefit potential for each scenario, again expressed as a conditional statement. As with the criteria, an additional step related the potential improvement in performance for the benefit criteria with the challenge of developing and deploying the fuel cycle, as represented by the Development and Deployment Risk criterion. The EST explored the sensitivity of the identification of the promising Evaluation Groups to the range of value judgments by subsequent parametric variation of the functions and tradeoff factors, ultimately resulting in the sets of promising Evaluation Groups. Appendix F provides the detailed results for the scenario studies, summarized in the following section.

3. Key Results

This report, including all Appendices, provides the results of the Study and the supporting analyses. As discussed in the previous section, Table 5 highlights and summarizes what this Study does and does not do, consistent with the purpose stated in the Study Charter of providing information for R&D prioritization.

Table 5. Scope of the Nuclear Fuel Cycle Evaluation and Screening.

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 cycles 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 R&D needs	Investigate the transition from the current U.S. fuel cycle to a fully deployed alternative fuel cycle

This report provides performance data for the 40 Evaluation Groups of fuel cycles on the evaluation metrics, the nine evaluation criteria, and for 11 scenarios, where the scenarios consider multiple criteria simultaneously, assigning varying degrees of relative importance to the changes possible for each criterion to explore a potential range of policy guidance. This report identifies those Evaluation Groups where improvement with respect to the current U.S. fuel cycle is possible. Recognizing that what constitutes a "substantial improvement" as stated in the Study Charter is a judgment that may vary considerably among decision-makers, the report identifies multiple sets of potentially promising Evaluation Groups based on the amount of improvement. Using this approach, decision-makers can find the appropriate promising Evaluation Groups corresponding to their view of what constitutes a substantial level of improvement. The report also provides the corresponding development and deployment challenges for all Evaluation Groups, allowing decision-makers to consider both the potential benefits and the associated challenges. The report then identifies the associated R&D that would be required to develop the fuel cycles in the promising Evaluation Groups.

The information in the report allows the reader to examine the results for each metric, criterion, and scenario to see when the choice of fuel cycle makes a difference and when it does not, what fuel cycle characteristics make such improvement possible, and why certain R&D directions support development of the fuel cycle options in the promising Evaluation Groups. The evaluation and screening software (the Evaluation and Screening Tool, SET) and metric data are also available for download and use on the INL website along with this report, allowing exploration of any desired combination of metrics and criteria.

The EST evaluated and screened nuclear fuel cycles only at what is termed the "functional" level, using the fundamental physics characteristics of each step in a fuel cycle (i.e., the physics principles defining *what* happens at each fuel cycle step, not the technologies for *how* it is accomplished) both to enable creation of a comprehensive set and to provide flexibility for future R&D directions into specific technology choices. The EST evaluated the alternative fuel cycles by comparing them to the current U.S. fuel cycle assuming successful implementation of all disposal paths. It is recognized that DOE-NE's first priority is developing and opening a geologic repository in the U.S., given that no alternative fuel cycle can eliminate the need for such a repository, although an alternative fuel cycle may make more efficient use of such a repository. The EST identified several promising Evaluation Groups that have the potential for improved performance relative to the current U.S. fuel cycle for three of the benefit criteria as follows:

– *Nuclear Waste Management Criterion*: On a per unit energy generated basis, reduction in generation of fuel cycle waste materials requiring geologic disposal by as much as a factor of 10 or more, reduction in long-term activity corresponding to a reduction in long-term radiation hazard by as much as a factor of 10 or more, and reduction in uranium (depleted from the enrichment process or recovered from reprocessing) and/or thorium (recovered from reprocessing) disposal needs by a factor of 100 or more, and without a large increase in low-level waste generation (up to about 50% higher).
– *Resource Utilization Criterion*: On a per unit energy basis, reduction in the amount of fuel resources needed by a factor of 100 or more.
– *Environmental Impact Criterion*: On a per unit energy basis, reduction in the amount of land required and in the amount of CO_2 emitted (always much lower for nuclear power than for fossil-based generation) by about a factor of 2.
– *Proliferation Risk Criterion*: For the purpose of this E&S Study, which is to inform the R&D investment prioritization for the DOE Office of Nuclear Energy, the result for this criterion is that no promising options were identified, and that all of the Evaluation Groups were evaluated as capable of being comparable to the current U.S. fuel cycle at the physics-based functional level as far as material attractiveness is concerned.
– *Nuclear Material Security Risk Criterion*: For the purpose of this E&S Study, which is to inform the R&D investment prioritization for the DOE Office of Nuclear Energy, the result for this criterion was that all of the Evaluation Groups were assessed as comparable to the current U.S. fuel cycle at the physics-based functional level as far as material attractiveness for usefulness in INDs is concerned. All Evaluation Groups also contain highly radioactive spent fuel and/or HLW,

providing targets with activity comparable to the current U.S. fuel cycle in usefulness for RDDs / REDs. As a consequence, no promising options were identified.

– *Safety Criterion*: The Study results demonstrate that addressing the safety hazards identified for alternative fuel cycles in the most promising Evaluation Groups and for many of the potentially promising Evaluation Groups was comparable in difficulty. As a result, the EST concluded that it would be possible to safely deploy at least one of the fuel cycles in each Evaluation Group. The EST also concluded that the ability to provide enhanced safety compared to the current U.S. facilities was not affected by the choice of fuel cycle, but depended on decisions that would be made for implementing the fuel cycle, such as technology choices and facility design decisions.

For the three evaluation criteria related to the challenge of developing and deploying a fuel cycle alternative to the current U.S. fuel cycle, the following summarizes the challenges identified by the Study:

– *Development and Deployment Risk*: Alternatives to the current U.S. fuel cycle in the promising Evaluation Groups require R&D to bring the enabling technologies up to the level of successful engineering demonstration including pilot-scale facilities, which the Study results indicate as requiring several billion dollars over 10-25 years. Similarly, further development up to the first-of-a kind commercial facilities would require an additional several billion dollars. Any transition to a new fuel cycle would take decades to achieve, although some fuel cycle performance benefits such as wastes destined for deep geologic disposal would accrue more quickly. Fully deploying an alternative fuel cycle would likely require several hundred billion dollars or more, comparable to the cost of continuing with the current U.S. fuel cycle as new reactors replace existing reactors. Other metrics for development and deployment risk also inform on the Institutional Issues, and are discussed next.

– *Institutional Issues*: Any of the alternative fuel cycles in the promising Evaluation Groups faces several institutional issues, including lack of supporting infrastructure, lack of regulations and licensing experience, and market barriers to commercial implementation.

– *Financial Risk and Economics*: Estimates of the electricity production cost for fuel cycles in the most promising Evaluation Groups and many of the promising Evaluation Groups are similar to, or close to, those for continuing with the current U.S. fuel cycle.

3.1 Identification of Promising Fuel Cycles

The goal of this Evaluation and Screening Study was to identify promising fuel cycle options, defined as those that offer the potential for significant improvement over the currently deployed fuel cycle in the United States, to support decision-making about directions for DOE Nuclear Energy related research and development. As described throughout this report, different fuel cycle options might be considered promising by decision-makers or stakeholders who have different priorities or values. The EST used a wide range of perspectives to represent this variability in decision-maker preferences, and the sensitivity analyses for each scenario identified Evaluation Groups that are robust to different perspectives, i.e., those that exceed the promise threshold for many of the perspectives considered. Appendix F provides the detailed discussion of the process for identifying the promising options and organizing them into three sets: most promising options, additional potentially promising options, and other potentially promising options. An example of the results obtained for a scenario is shown in Figure 4, which shows the results for the scenario where the four benefit criteria of Nuclear Waste Management, Resource Utilization, Environmental Impact, and Safety were given equal criteria tradeoff factors.

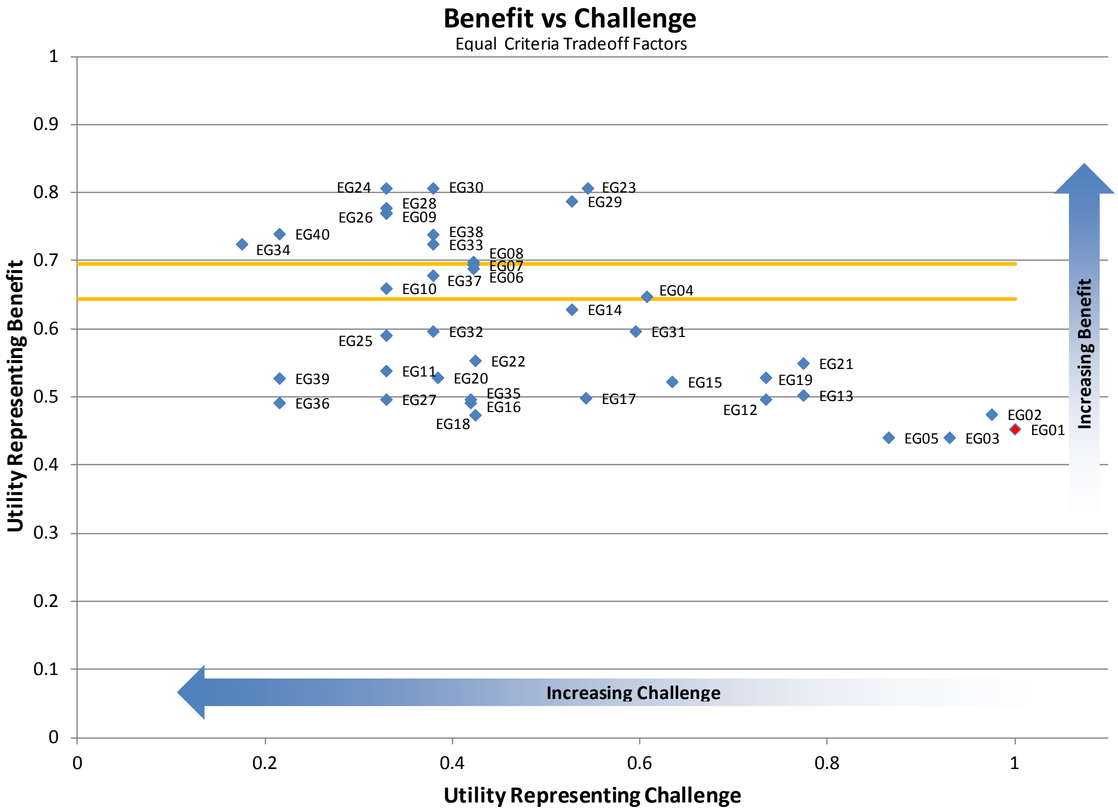

Figure 4. Benefit versus Challenge for the 40 Evaluation Groups for Scenario 1.

Figure 4 shows the potential for improved performance, represented by a non-dimensional benefit utility on the y-axis, and the relative challenge of development and deployment of fuel cycles providing this improved performance, represented by a non-dimensional utility on the x-axis. As the arrows on Figure 4 indicate, higher utility on the y-axis indicates higher benefit, while lower utility on the x-axis indicates greater challenge. The current U.S. fuel cycle is plotted with a red symbol on the right of the figure, with benefit utility slightly greater than 0.5 and challenge utility of 1.0 (no challenge for development since this fuel cycle is already implemented). The two orange lines indicate thresholds of performance improvement that might be considered as providing substantial, or significant, improvement by decision makers. The figure shows 13 Evaluation Groups above the higher orange line, and four more Evaluation Groups above the lower orange line, showing varying levels of potential improvement and varying degrees of challenge in developing and deploying fuel cycles in these groups.

The EST evaluated 11 specific scenarios in detail using these four benefit criteria, but clearly many other scenarios *could* be defined. To provide a further check on the robustness of the results of the study, the EST conducted a set of sensitivity analyses, exploring a very wide range of potential scenarios through two simulation studies. The sensitivity analyses considered a wide range of perspectives, varying both the metric tradeoff factors and the criteria tradeoff factors randomly. For the sensitivity analysis shown in Figure 5, 10 simulations of 1,000,000 iterations each were run (see Appendix F-3.2). These results represent a large sample of any result that might be obtained considering the shape functions and metric tradeoff factors defined for this study, and any combination of criteria tradeoff factors for the four benefit criteria. While this approach will necessarily include sets of criteria tradeoff factors that represent very extreme views, Evaluation Groups that have high utility values under a large majority of these simulations, even for extreme views, are highly robust to different perspectives on the relative importance of changes across the criteria.

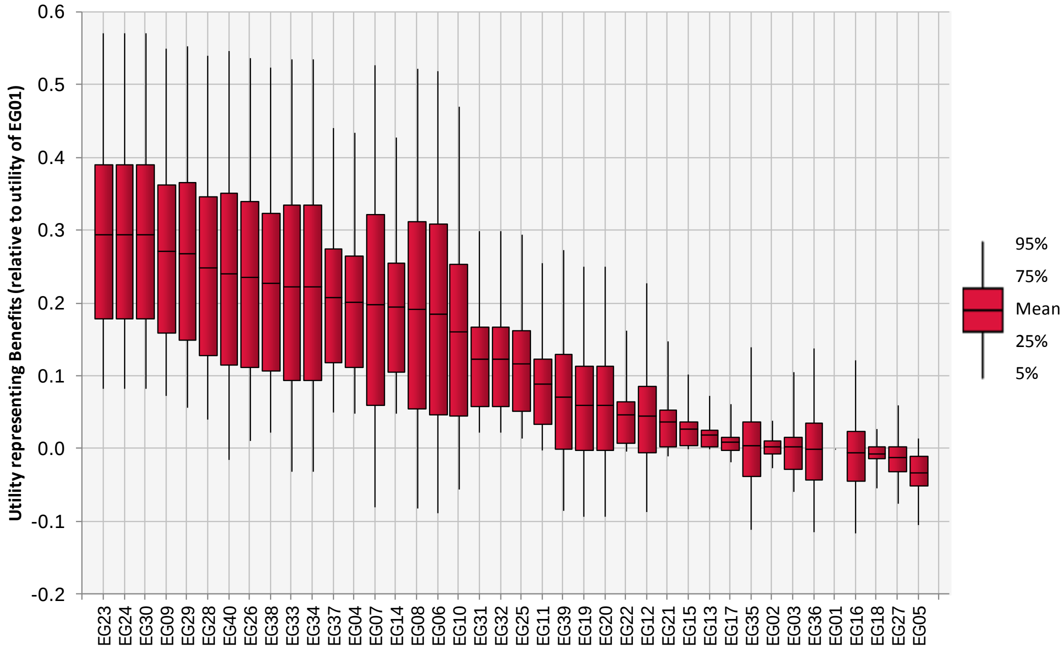

Figure 5. Sensitivity Results Considering 10 Simulations of 1,000,000 Iterations with Different Sets of Criteria Tradeoff Factors and Metric Tradeoff Factors, Considering All Defined Sets of Shape Functions.

Figure 6 presents these results in the same format used to show the sensitivity or robustness results for each scenario in Appendix F. An arbitrary threshold of an incremental benefit utility of 0.15 was chosen. This Figure shows 17 evaluation groups exceed this threshold for more than 50% of all perspectives.

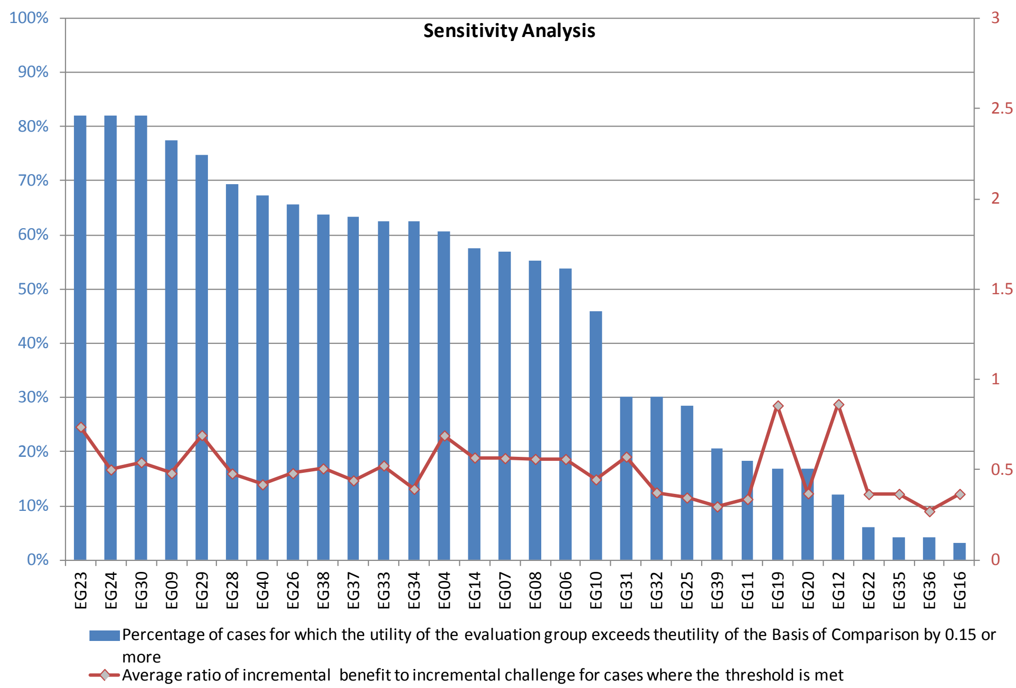

Figure 6. Scenario-level Sensitivity Results: Percentage of Simulation Runs Where the Incremental Utility Exceeds a Threshold of 0.15, and the Ratio of Incremental Benefit to Incremental Challenge for those Evaluation Groups Exceeding the Threshold.

3.2 Most Promising Fuel Cycles and Their R&D Needs

The multiple criteria scenarios and parametric variations of the metric and criteria weighting factors were used to identify the promising Evaluation Groups and to determine the robustness of the identification with respect to changing perspectives on the relative importance of the benefit criteria. Among all options, three groups of fuel cycles consistently provided the highest improvements compared to the current fuel cycle in the U.S. (e.g., as on Figure 4), regardless of the perspective on the relative importance of the benefit criteria. Note that the Evaluation Groups (EGs) are listed in numerical order, with a short description indicative of the fuel cycles included in each Evaluation Group:

- EG23 - Continuous recycle of U/Pu[5] with new natural-U fuel in fast critical reactors
- EG24 - Continuous recycle of U/TRU with new natural-U fuel in fast critical reactors
- EG30 - Continuous recycle of U/TRU with new natural-U fuel in both fast and thermal critical reactors

Table 6 provides a summary of the Metric Data for the six benefit criteria for these three Evaluation Groups and the Evaluation Group representing the current U.S. fuel cycle, EG01. The highlighted metric data are those for which potentially substantial improvement is possible with the most promising options.

Table 6. Summary of Metrics for the Benefit Criteria for the Best-Performing Evaluation Groups.

	Once-through	**Continuous Recycle**		
Fuel Cycle Option	**EG01 – Current U.S. Fuel Cycle**	**EG23 – U/Pu Recycle, Fast Systems**	**EG24 – U/TRU Recycle, Fast Systems**	**EG30 – U/TRU Recycle, Fast and Thermal Systems**
Nuclear Waste Management Criterion				
Mass of SNF+HLW, t/GWe-yr	12-36	< 1.65	< 1.65	< 1.65
Activity @100 years, MCi/GWe-yr	1.05-1.60	0.67-1.05	0.67-1.05	0.67-1.05
Activity @100,000 years, MCi/GWe-yr	0.001-0.0023	0.0005-0.001	0.0005-0.001	0.0005-0.001
Mass of DU+RU+RTh, t/GWe-yr	120-200	<1	<1	<1
Volume of LLW, m^3/GWe-yr	252-634	252-634	252-634	252-634
Proliferation Risk Criterion				
Material attractiveness – normal operating conditions	Unattractive	Unattractive	Unattractive	Unattractive
Nuclear Material Security Risk Criterion				
Material attractiveness – normal operating conditions	Unattractive	Unattractive	Unattractive	Unattractive
Activity @10 years per energy generated	Highly radioactive	Highly radioactive	Highly radioactive	Highly radioactive
Safety Criterion				
Challenges of addressing safety hazards	Reference	Similar	Similar	Similar
Safety of the deployed system	Yes	Yes	Yes	Yes
Environmental Impact Criterion				
Land use, km^2/GWe-yr	0.1 - 0.2	< 0.1	< 0.1	< 0.1
Water use, ML/GWe-yr	15000 - 30000	15000-30000	15000-30000	15000-30000
CO_2 emission, kt/GWe-yr	30-60	< 30	< 30	< 30
Radiological exposure, person-Sv/GWe-yr	0.5 - 5	0.5 - 5	0.5 - 5	0.5 - 5
Resource Utilization Criterion				
Uranium resources, t/GWe-yr	> 145	< 3.8	< 3.8	< 3.8

[5] Note: U= uranium; Pu = plutonium; TRU = transuranic elements, i.e., atomic number higher than uranium (Neptunium, Plutonium, Americium, Curium, etc.); Th=thorium; the term "U/Pu" indicates that uranium and Pu are recycled together, similarly the term "U/TRU" indicates that uranium and TRU are recycled together.

Note that these three Evaluation Groups all have the same Metric Data, providing the same amount of potential improvement over the current U.S. fuel cycle. These 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 (since as noted above, choice of fuel cycle for most of the remaining criteria did not result in any improvement or differentiation), a judgment made by DOE decision-makers and others.

As shown on Figure 4, these most promising Evaluation Groups exhibited differences with respect to the challenge criteria, with EG23 posing relatively lower development and deployment challenges than the other two. When considering both benefit and challenge, Figures 4 and 6, the EST considered another group as also being most promising that has slightly less improvement but lower challenge compared to EG24 and EG30:

- EG29 - Continuous recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors

The sensitivity studies described above and in detail in Appendix F confirm that these four Evaluation Groups are the best performing groups across a very broad range of value judgments, indicating that they are robust to different perspectives about the relative value of improvements in the Evaluation Metrics and Criteria. These four fuel cycles can be implemented without uranium enrichment other than perhaps for initial startup of a reactor. All of these fuel cycles can reduce the waste requiring long-term isolation by a factor of 10 or more, where the amount of waste is represented in the Study by the mass of spent nuclear fuel and High Level Waste (HLW, but without any waste form matrix mass). These fuel cycles also reduce the amount of depleted uranium disposed by a factor of 100 or more, with very little change in the volume of low-level waste from the entire fuel cycle as compared to the current U.S. fuel cycle. The reduction in natural uranium resources required by the fuel cycle can be greater than a factor of 100.

None of these fuel cycles are ready to be deployed today. R&D must be conducted to develop the appropriate implementing technologies. The EST examined the current state of knowledge and experience to identify the R&D needs for each part of the fuel cycle. The R&D required to support these fuel cycles, along with some requirements for implementing technologies in order to achieve the benefits attributed to the fuel cycles, are as follows:

Reactor Development

- R&D on fast critical reactors because these reactors facilitate effective consumption of actinide elements and efficient use of uranium fuel resources (which may also include intermediate spectrum reactors since these were grouped with fast reactors in the Study; fast subcritical reactors are also in this Evaluation Group with similar physics-based performance but face greater challenges than critical reactors, including for LCAE, so the supporting R&D is not listed)
    - The reactors must have conversion of fertile materials to more fissionable materials sufficient to sustain operation without the need for ongoing supplies of enriched uranium

Separations / Reprocessing Development

- R&D on separation of U/Pu or U/TRU from irradiated fuel to make them available for recycle
    - The separations processes should have total nominal product losses of about 1% or less to waste disposal; smaller losses may not be of further benefit

Fuel Development

- R&D on recycle fuel development to facilitate use of recovered U/Pu or U/TRU as fuel
    - The fuel should have irradiation capability comparable to or greater than today's fuel

In addition, for any fuel cycle, an R&D goal should be to reduce waste generation throughout the fuel cycle, including developing waste forms that reduce the volume of any HLW since HLW volume can be an important factor for deep geologic disposal.

3.3 Additional Potentially Promising Fuel Cycles and Their R&D Needs

Recognizing that organizing the promising Evaluation Groups into sets of similar potential benefit is somewhat arbitrary, the EST used the thresholds on Figure 4 (Scenario 1, equal criteria tradeoff factors) and Figures 5 and 6 as guides to identify eleven additional *potentially promising groups of fuel cycles* that provide somewhat lower, but still potentially substantial, beneficial improvements than the four discussed above. While it is again a matter of judgment by DOE decision-makers and others whether the improvements offered by these groups are considered both important and substantial, each of these groups perform better than the current U.S. fuel cycle when almost any, but not all, combinations of criteria are considered. (Evaluation Groups are listed in numerical order, with a short description indicative of the fuel cycles included in each Evaluation Group):

- EG06 - Once-through using Th fuel to very high burnup in thermal EDS
- EG07 - Once-through using natural-U fuel to very high burnup in thermal or fast EDS
- EG08 - Once-through using Th fuel to very high burnup in fast EDS
- EG09 - Limited recycle of U/TRU with new natural-U fuel to very high burnup in fast critical reactors
- EG26 - Continuous recycle of ^{233}U/Th with new Th fuel in thermal critical reactors
- EG28 - Continuous recycle of ^{233}U/Th with new Th fuel in fast critical reactors
- EG33 - Continuous recycle of U/Pu with new natural-U fuel in both fast EDS and thermal critical reactors
- EG34 - Continuous recycle of U/TRU with new natural-U fuel in both fast EDS and thermal critical reactors
- EG37 - Continuous recycle of ^{233}U/Th with new enriched U/Th fuel in both fast and thermal critical reactors
- EG38 - Continuous recycle of ^{233}U/Th with new Th fuel in both fast and thermal critical reactors
- EG40 - Continuous recycle of ^{233}U/Th with new Th fuel in fast EDS and thermal critical reactors

Again, the sensitivity analyses presented above and described in detail in Appendix F confirm the robustness of these Evaluation Groups to alternative value functions: they are in a set defined by a similar upper threshold value across a very wide range of judgments about the relative value of improvements in Evaluation Metrics and Criteria.

While the R&D listed for the four most promising options would also support some of these fuel cycles, other, different or additional, R&D is needed to support development of some of these promising options, as follows:

Reactor Development

– R&D on thermal critical neutron reactors because these reactors facilitate efficient conversion of thorium to usable fuel
  - The reactors must have conversion of fertile thorium materials to more fissionable materials sufficient to sustain operation without the need for ongoing supplies of fissile materials such as enriched uranium

– R&D on externally-driven systems (EDS) because subcritical reactors can provide an external source of neutrons to facilitate conversion of fertile materials to more fissionable materials (although the greater challenges for such systems, including LCAE, should be recognized)

  - The reactors must have conversion of fertile thorium and/or uranium materials to more fissionable materials sufficient to support operation without the need for ongoing supplies of fissile materials such as enriched uranium
  - The additional safety challenges identified for EDS compared to critical reactors should be addressed

Separations / Reprocessing Development

- R&D on separation of $^{233}U/Th$ from irradiated fuel to make it available for recycle
  - The separations processes should have total nominal product losses of 1% or less to waste disposal; larger losses may be acceptable while still preserving sufficient benefits, but smaller losses may not be of further benefit

Fuel Development

- R&D on recycle fuel development to facilitate use of separated $^{233}U/Th$ as fuel
  - The fuel should have irradiation capability comparable to or greater than today's fuel
- R&D on very high burnup fuel to facilitate greater resource utilization
  - The fuel should have irradiation capability several times higher than today's fuel and even well beyond experimentally-demonstrated capability for advanced fuel

3.4 Other Potentially Promising Fuel Cycles and Their R&D Needs

In addition to the Evaluation Groups listed above, using the lower threshold in Figure 4 and the sensitivity analyses described above for Figures 5 and 6, and in Appendix F, a few additional lesser performing fuel cycles were identified that may be potentially promising depending on the relative importance of the criteria and the underlying metrics, again if the improvements are considered both important and substantial by DOE decision-makers and others (Evaluation Groups are listed in numerical order, with a short description indicative of the fuel cycles included in each Evaluation Group):

- EG04 - Once-through using natural-U fuel to very high burnup in fast critical reactors
- EG10 - Limited recycle of $^{233}U/Th$ with new Th fuel in fast and/or thermal critical reactors
- EG14 - Limited recycle of U/Pu with new natural-U fuel in both fast and thermal critical reactors

The R&D requirements already listed above are sufficient to support development of these fuel cycles.

3.5 Insights about Fuel Cycles

Based on the promising fuel cycles identified by the evaluation and screening process, the EST identified certain fuel cycle characteristics that provide beneficial performance improvements with respect to the evaluation metrics, criteria and scenarios:

- Continuous recycle of actinide elements – the actinide elements (thorium, protactinium, uranium, plutonium, neptunium, americium, curium, and so on) are major contributors to the long-lived hazard from irradiation of nuclear fuel, and can be a source of energy, some directly as fuel and others by conversion to usable fuel. Recycling the actinide elements benefits two of the evaluation criteria related to efficient use of fuel resources and reduction of nuclear waste generation.
- Fast neutron irradiation – fast neutron fission has a much more favorable fission-to-absorption ratio for neutrons for certain isotopes, greatly increasing fissioning of isotopes such as ^{240}Pu and enhancing fissioning of ^{239}Pu, reducing the buildup of long-lived highly radioactive higher actinide isotopes.

- Critical reactors – use of reactors that are capable of sustaining fission without the need for an external source of neutrons lowers development risk, lowers safety challenges, and lowers overall costs as compared to externally-driven systems.
- High-internal conversion – efficient conversion of fertile fuel materials to more easily fissionable isotopes allows efficient use of fuel without the need for uranium enrichment for continued operation, increasing resource utilization and reducing waste generation. Fast neutron fission also produces more excess neutrons per fission than thermal fission, facilitating the high-internal conversion needed for self-sustaining fuel cycles.
- Nuclear fuels – irradiating uranium-based fuels in the fast spectrum provides higher internal conversion capability than thorium-based fuels in either a thermal or fast spectrum, facilitating effective resource utilization as long as uranium enrichment is not required for continued operation, as evidenced by the four most promising options identified in the Study. However, even though uranium may be more readily used to achieve greater resource utilization, potentially promising options were also identified for fuel cycle options using thorium-based, and uranium/thorium-based fuels, as listed above.
- Safety – promising fuel cycles are capable of safe deployment, with many having safety challenges comparable to the current U.S. fuel cycle. Enhanced safety is not provided by choice of fuel cycle, but may be provided by the choice of implementing technologies and facility design

In addition to these specific fuel cycle characteristics, the EST evaluated other more general concepts applicable to many or all fuel cycles for potential benefit:

- Extended decay storage (SNF and/or UNF[6], products, or wastes) can:
    - slowly lower radiation level by radioactive decay to potentially reduce worker exposure or shielding requirements, but the remaining radiation is sufficient to still require remote handling of the materials
    - favorably affect recycle of some actinide elements such as curium, but may adversely affect recycle of other actinide elements such as plutonium
    - slowly lower decay heat at the time of disposal for SNF, facilitating handling and emplacement, but is most effective for the HLW from recycle fuel cycles where most of the content is fission products with a relatively short radioactive half-life.
- Processing of spent fuel prior to disposal, not for recycle (for once-through or limited recycle fuel cycles only) to separate the uranium or thorium from the fission products and any long-lived highly-radioactive elements may also greatly reduce the amount of materials requiring isolation such as that provided by deep geologic disposal. However, the uranium and/or thorium separated and recovered during processing still need to be disposed as waste, in contrast to recycle fuel cycles where such materials can be reused to reduce overall waste generation from the fuel cycle and increase utilization of fuel resources.
    - If the separated uranium or thorium can be disposed with much lower isolation requirements, then processing of SNF prior to disposal can reduce the amount of waste requiring geologic isolation, e.g., HLW, by a factor of 10 or more.
    - If the disposal requirements for the recovered uranium and/or thorium are comparable to those for SNF or HLW, then there would appear to be no benefit from processing SNF prior to disposal.
- Minor actinide separation and transmutation

[6] Note: SNF denotes spent nuclear fuel, which is irradiated fuel destined for disposal. UNF, used nuclear fuel, is used to denote irradiated fuel that is going to be reprocessed.

- Minor actinide separation and recycle in addition to uranium/plutonium recycle (i.e., TRU recycle) may provide beneficial improvement by further reducing waste generation and increasing resource utilization as compared to uranium/plutonium recycle although no improvement was noted for the metrics used in this Study for the most promising options of continuous recycle in fast reactors. However, at the fuel cycle level, the EST also noted that there would be no difference in potential benefit for TRU recycle whether all of the minor actinide elements are recycled individually in different fuels, as a single group in one fuel, or in combination with fuel containing plutonium. Thorium-based fuel cycles have little minor actinide content in the irradiated fuel and therefore would not have substantial benefits from minor actinide separation and transmutation.

3.6 Challenges for Fuel Cycle Development and Deployment

The criteria indicating the challenges associated with developing and deploying an alternative fuel cycle identified several commonalities among essentially all of the promising fuel cycle options:

- Two of the most promising fuel cycles have estimated total development costs in the range of $2 - $10 billion (EG23, EG29), while the other two (EG24, EG30) are in the range of $10 - $25 billion, as are most of the other promising fuel cycles, and estimated development times in the range of 10 to 25 years to bring all enabling implementing technologies and facilities to successful demonstration at engineering scale. The government has historically been the major source of funding for such R&D activities.
- Following completion of the technology development, the promising options have an estimated initial total deployment cost in the range of either $10 - $25 billion (EG06, EG07, EG08, EG23) or $25 - $50 billion (the remaining promising options) to continue development from engineering demonstration through the deployment of first-of-a-kind commercial facilities. Cost-sharing between industry and government may be expected for such development. Fully deploying an alternative fuel cycle to replace the current U.S. fuel cycle would likely require several hundred billion dollars or more, comparable to the cost of continuing with the current fuel cycle replacing existing reactors as they are retired with new similar reactors.
- The market disincentives and barriers to commercial implementation of nearly all of the promising options are expected to be very significant, such that Federal government intervention in the form of direct investment, mandates, or changes in law in order to establish and sustain market drivers will likely be required for full-scale implementation of a new fuel cycle. A fee based on energy production provides a disincentive for waste reduction because for a given amount of energy production, the disposal fee is the same regardless of waste amount.

Based on the Study results for the estimated levelized cost of electricity at equilibrium (LCAE), discussed in detail in Appendix D, many of the promising options may be expected to have electricity production costs that are similar to, or close to, the estimated LCAE for the current U.S. fuel cycle as shown in Figure 7 where the difference is given in mils per kW-hr.

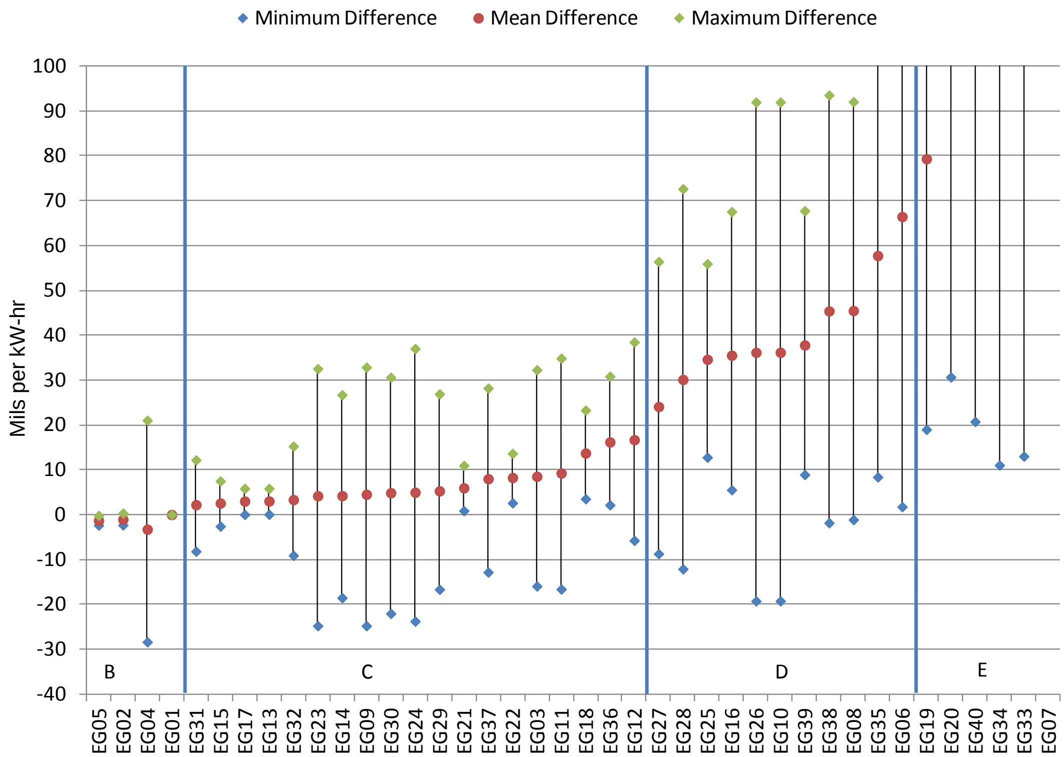

Figure 7. Difference in LCAE in mils per kW-hr for the Analysis Example of each Evaluation Group and the Analysis Example of EG01, Ordered by Increasing Positive Difference.

The four most promising options, EG23, EG24, EG29,and EG30, all have a mean estimated LCAE within 5 mils per kW-hr of the cost of continuing with the current U.S. fuel cycle, which has an LCAE of about 50 mils per kW-hrs. The EST observed that more complex fuel cycles could cost more to build and operate, but could have offsetting lower costs elsewhere in the fuel cycle, and the dominant fuel cycle cost contributor is for the reactors. For example, a recycle fuel cycle adds costs for reprocessing and recycling, but may have lower fuel resource costs and may eliminate enrichment costs.

Since the EST did not group the LCAE with the other challenge criteria but provided the information separately as additional information, it is instructive to examine the differences in LCAE for the best performing Evaluation Groups. Figure 8 shows the main cost contributions to the estimated mean LCAE for Analysis Examples EG23, EG24, EG29 and EG30 and compared directly to the cost contributions of EG01. The Analysis Examples EG23 and EG24 are fast reactors operating on a closed U/Pu and U/TRU cycle, respectively, which are self-sufficient due to Pu and TRU production. The Analysis Examples EG29 and EG30 are, respectively, net Pu and TRU producing fast reactors that breed sufficient excess fissile to supply thermal reactors so that uranium enrichment is not needed. While the O&M costs are about the same for all 5 systems, the charges for capital cost recovery are, as expected, higher for EG23 and EG24 which use only fast reactors. Evaluation Groups EG29 and EG30, which involve a combination of fast and thermal reactors, have capital cost recovery charges that are proportional to the fraction of each reactor type utilized in the system. Further details on LCAE are given in Appendix D.

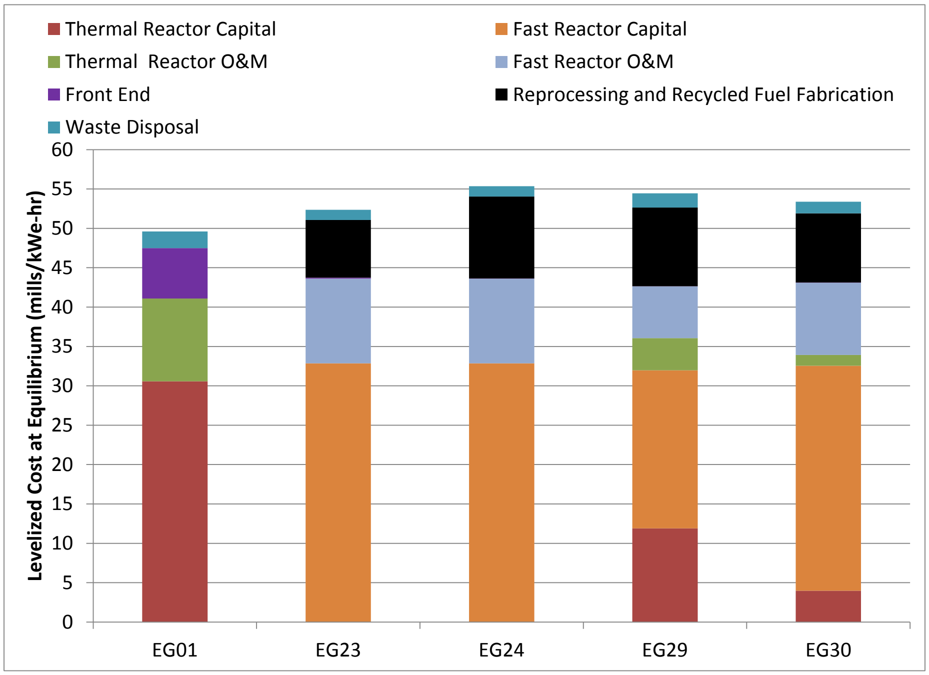

Figure 8. Comparison of the Levelized Cost of Electricity at Equilibrium Cost Breakdown for EG01, EG23, EG24, EG29 and EG30 Using Averages of the Calculated Values.

4. Conclusions

The EST developed a systematic analysis framework for conducting the fuel cycle evaluation and screening that was transparent and reproducible. The EST created the comprehensive list of fuel cycle options specifically for this use of the framework, as well as defined evaluation metrics for the evaluation criteria. The EST conducted the evaluation and screening to identify promising fuel cycle options and the associated R&D. With the software and data developed to support this evaluation and screening of nuclear fuel cycles, others can use the entire process to either repeat this evaluation or to explore other evaluations of nuclear fuel cycles.

Specifically, the Evaluation and Screening Study provided:

- a systematic and traceable method for evaluating nuclear fuel cycle options supported by a reusable framework, data, and software
- fuel cycle performance evaluations compared to the current U.S. fuel cycle including the limitations of alternative fuel cycles
- identification of the R&D needs for fuel cycles screened for potentially substantial performance advantages, and of challenges for developing and deploying them
- documentation of the basis for the evaluations to facilitate understanding why certain fuel cycles should be explored for further development
- interactive screening software using a well-known and widely-available application (Excel)

The EST intends the products of this Study to enhance the ability of the DOE-NE program to achieve its mission of identifying and developing sustainable nuclear fuel cycles as called for in the "NE Roadmap". The supporting R&D needs are clearly identified and associated with the potential improvements. These R&D needs can inform DOE-NE in developing a focused program with R&D targeted towards enabling the fuel cycles that provide specific benefits, as identified in this Study. The evaluation framework, software and data also give decision makers a means to explore how to adapt the program should future policy changes occur.

The Evaluation and Screening is not a fuel cycle design tool, but a means for identifying fuel cycles with the potential for substantial improvement as compared to the current U.S. fuel cycle. This Study was not intended to produce a map to develop an optimum fuel cycle that is perfect for the future. The Study did produce identification of benefits, limitations and challenges of fuel cycle choices and documented all of the reasons for these results, considering the entire range of possible fuel cycle performance.

4.1 Questions Posed in the Charter

The following questions were posed in the Study Charter, with answers to be provided by this Study:

Which nuclear fuel cycle system options have the potential for substantial beneficial improvements in nuclear fuel cycle performance, and what aspects of the options make these improvements possible?

Which nuclear material management approaches can favorably impact the performance of fuel cycle options, e.g., extended decay storage (spent or used fuel, products, or wastes), specific disposal environments, processing of used fuel, minor actinide separation and transmutation, etc.?

Where is DOE R&D investment needed to support the set of promising fuel cycle system options and nuclear material management approaches identified above, and what are the technical objectives of associated technologies?

The information presented in Section 3 provides the answers to these questions, including which fuel cycles might offer substantial improvements and the characteristics of these fuel cycles that make such improvements possible, as follows:

- **Continuous recycle of actinides** – the actinides are both a source of energy in a reactor and a contributor to the long-lived hazard of spent fuel. Recycling the actinides benefits both of these aspects.
- **Fast neutron irradiation** – the desirability of fast neutrons for fission is based on the much more favorable fission-to-absorption ratio for neutrons, where fissioning of isotopes such as ^{240}Pu greatly reduces the buildup of the higher actinide isotopes that are highly radioactive with some being long-lived
- **Self-sustaining reactors** – use of reactors that are capable of sustaining fission without the need for an external source of neutrons simplifies reactor design and lowers development risk, safety challenges, and overall costs as compared to externally-driven systems.
- **High-internal conversion** – allows efficient resource utilization without the need for uranium enrichment for continued operation, although enrichment may be needed for the first fuel load in the reactor

Fuel cycle options including these characteristics have the potential to benefit the Nuclear Waste Management, Resource Utilization, and Environmental Impact criteria without necessarily adversely affecting the Safety criterion. Any promising fuel cycle option using these characteristics has a need for development of the supporting technologies, with total development costs estimated in excess of $10B and development time in excess of 10 years.

The associated R&D for the promising fuel cycles is also identified in Section 3, along with those technical objectives that were derived from the promising Evaluation Groups.

4.2 Use of the Evaluation and Screening Results

In summary, through this Study, a “framework” (a logical structure and process which includes sets of data, methods and tools) was developed to support nuclear fuel cycle R&D decision making. Use of this evaluation and screening framework identified four most promising Evaluation Groups and the R&D required for these fuel cycles to inform DOE in support of their R&D decisions. The fuel cycles contained within these four most promising Evaluation Groups are all continuous recycle fuel cycles using fast reactors with uranium-based fuel, a result that is consistent with earlier fuel cycle studies. While this result is not necessarily new, this Study provides extensive documentation justifying the identification of these fuel cycles. The comprehensiveness of the fuel cycles considered allowed the EST to make this determination in the context of considering the entire range of possible fuel cycle performance, indicating that these fuel cycles are the best among all possible fuel cycles. However, as stated above, it must be emphasized that this R&D must be in addition to efforts to develop and open a repository in the U.S.

The EST also identified fourteen other promising fuel cycles with the potential for substantial, but somewhat lesser, performance improvement, along with their corresponding R&D needs. The approach and data used for the Evaluation and Screening study are contained in the computer software (SET, available for download on the INL website along with this report), allowing users to either reproduce the study results, or to conduct their own evaluations using the software and data provided.

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GLOSSARY

Analysis Example - obtained by specifying the irradiation environment for the Fuel Cycle Option Group in each Evaluation Group to provide an example that represents the focus of the Evaluation Group, e.g., a PWR as the thermal reactor in a fuel cycle, since this was necessary to obtain accurate information on the effects of irradiation on the nuclear fuel composition. Note that an Analysis Example is not a Nuclear Fuel Cycle Option since only the irradiation technologies and fuel materials are specified, but all other fuel cycle activities are only specified at the functional level. The Analysis Example was used for calculating detailed reactor physics-based material mass balance information and other information as appropriate for informing the Evaluation and Screening. In general, it was not necessary to specify a fuel fabrication or processing technology, only the technical functions and specifications. For this Evaluation and Screening, the Analysis Examples were specifically chosen to reflect a wide variety of possible irradiation systems to convey the broad scope of the Evaluation and Screening. It is also important to reiterate that the Evaluation and Screening itself is performed on the Evaluation Groups, not on the Analysis Examples or their Fuel Cycle Option Group.

Evaluation Criterion – One of the nine DOE-specified criteria used for the evaluation and screening of fuel cycle options in this Study.

Evaluation Group – the group of Fuel Cycle Option Groups created by considering the similarities in physics-based performance between Fuel Cycle Option Groups. Each Evaluation Group consists of one or more Fuel Cycle Option Groups, as shown in Figure 9, and results from the process of combining groups based on the principles of similarity of resource requirements, fuel mass usage and compositions, and disposal needs. These Evaluation Groups are also appropriate for representing the differences between Fuel Cycle Options for the Evaluation Criteria, given the principle of ensuring that promising options would be identified by the Evaluation and Screening, but that no promising option would be inadvertently screened out by being placed in a lesser performing Evaluation Group. The resulting set of 40 Evaluation Groups provides a comprehensive representation of all possible nuclear fuel cycles.

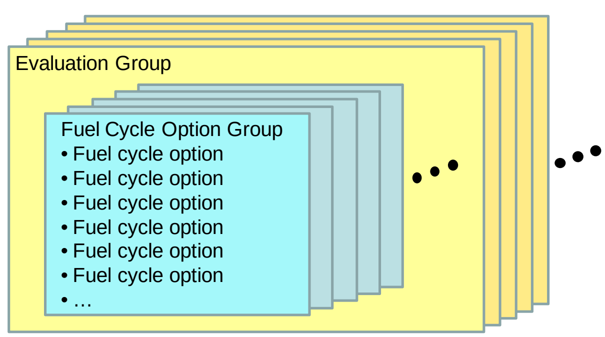

Figure 9. Nuclear Fuel Cycle Options, Fuel Cycle Option Groups, and Evaluation Groups.

Fuel Cycle – the complete nuclear energy system from mining to disposal including both once-through and recycle fuel cycles, as shown in Figures 10-13.

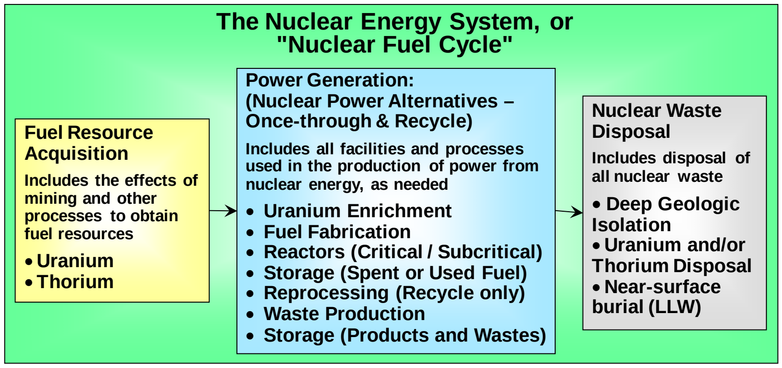

Figure 10. The Nuclear Energy System, also known as the Nuclear Fuel Cycle.

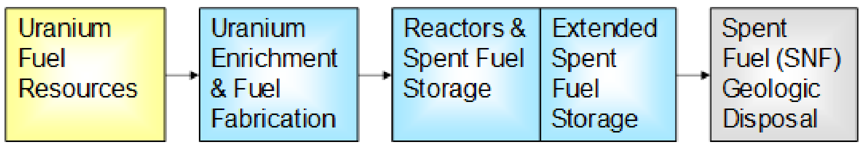

Figure 11. The "Once-Through" Fuel Cycle using Enriched Uranium for Nuclear Fuel.

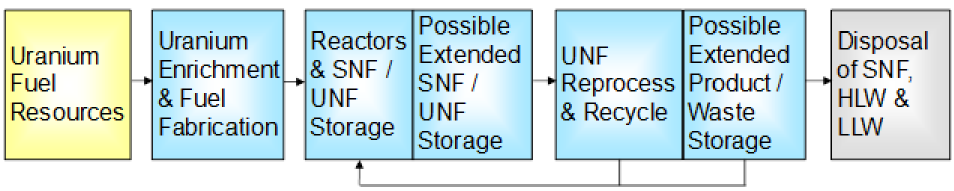

Figure 12. A Limited Recycle Fuel Cycle Example using Enriched Uranium for New Fuel.

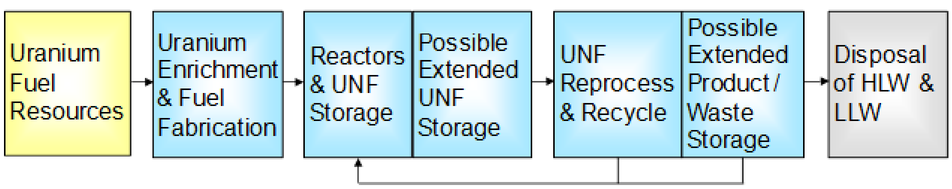

Figure 13. A Continuous Recycle Fuel Cycle Example using Enriched Uranium for New Fuel.

Fuel Cycle Option Group – a group of one or more Nuclear Fuel Cycle Options (functional level description of a fuel cycle) with similar fundamental physics principles and fuel cycle characteristics as defined in Section 2.3, such as once-through vs. recycle, thermal vs. fast neutron irradiation, uranium vs. thorium as fuel materials, and so on. For example, a fuel cycle option group could be a once-through fuel cycle using enriched uranium fuel in critical thermal reactors. The existence of fundamental principles that define the similarities between Fuel Cycle Options allowed identification of the comprehensive set of groups instead of attempting to identify all possible individual Specific Nuclear Fuel Cycle Options. These principles were the critical aspect of the Evaluation and Screening Study that made a comprehensive evaluation of fuel cycle options possible. The distinguishing physics principles and characteristics of each fuel cycle function between fuel cycle option groups allowed each Fuel Cycle Option Group to be defined by specifying only these functional principles and characteristics.

Metric Data – the performance of an Evaluation Group for an Evaluation Metric as defined in Section 2.5.2. The Metric Data is a bin with a range of performance, and represents the best potential performance of the Fuel Cycle Options in an Evaluation Group.

Nuclear Energy System – also known as the Nuclear Fuel Cycle, or Fuel Cycle as defined above.

Specific Nuclear Fuel Cycle Option - a specific implementation of the complete nuclear energy system as shown in Figure 10, including all technologies required for the production of electricity using nuclear energy, from obtaining natural resources for nuclear fuel to the disposal of radioactive wastes. For this Study, each fuel cycle option (or nuclear energy system) was divided into three parts:

1. Fuel Resources – obtaining the raw materials from natural resources that are used to make nuclear fuel. Currently, only uranium and thorium are considered as fuel resources.
2. Nuclear Power Alternative – the part of the fuel cycle that uses nuclear fuel to generate power, and
3. Nuclear Waste Disposal – all facilities and processes required for the disposal of radioactive wastes.

For example, one Specific Fuel Cycle Option could be the surface mining of natural uranium, uranium enrichment using gas centrifuges, fabrication of oxide fuel using sintered pellets, energy generation in a pressurized water reactor (PWR) using Zircaloy-clad fuel, temporary on-site storage of used fuel in spent fuel pools and dry casks, and disposal of spent fuel in a geologic repository.

Specific Technology – to implement a nuclear fuel cycle, specific technologies have to selected, developed, and deployed. The nuclear fuel cycle with all technologies specified is referred to in this study as a Specific Nuclear Fuel Cycle Option, defined above. Examples of specific technologies are gas centrifuge uranium enrichment, sintered uranium oxide fuel, PWRs, PUREX reprocessing, sodium-cooled fast reactors, and high-temperature gas reactors.

TRU – trans-uranium or transuranic elements – chemical elements with atomic number higher than uranium (Neptunium, Plutonium, Americium, Curium, etc.).

Utility – a non-dimensional measure of the performance of an Evaluation Group. Utility is used for each benefit criterion and for each scenario as well as for the Development and Deployment Risk criterion representing the challenge.