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Promising Fuel Cycle Options for R&D- Results, Insights, and Current Activities

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Abstract – *The Fuel Cycle Options (FCO) campaign in the U.S. DOE Fuel Cycle Research & Development Program recently completed a detailed evaluation and screening of nuclear fuel cycles (report available at www.inl.gov). The comprehensive study identified promising fuel cycle options that offer the potential for substantial improvement compared to the current U.S. fuel cycle. This paper describes insights from the study and the use of the results for current fuel cycle analysis activities. The insights obtained from the study prompted questions about the usefulness of minor actinide recycle and the relative potential of thorium-based fuel cycles compared to uranium-based fuel cycles. The FCO campaign is conducting analyses exploring these issues as well as the potential transition to such fuel cycles to identify the challenges and the timing for critical decisions that would need to be made, including investigation of concerns such as the effects of a temporary lack of recycle fuel resources or supporting infrastructure. These studies are part of an overall analysis approach designed to provide information to the U.S. DOE Office of Nuclear Energy decision-making process for R&D directions.*

I. INTRODUCTION

The U.S. Department of Energy, Office of Nuclear Energy (DOE-NE) chartered a study on the Evaluation and Screening (E&S) of nuclear fuel cycle options, i.e., the complete nuclear energy system from mining to disposal, which was recently completed.[1] The study used an objective and independently reviewed evaluation process to provide information about the potential benefits and challenges that could be used to strengthen the basis and provide guidance for the activities undertaken by the DOE-NE Fuel Cycle Technology Program Office, shown in Figure 1. DOE-NE 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. The set of fuel cycle options was to be as comprehensive as possible with respect to potential fuel cycle performance. The Charter specified the following questions to be answered:

1. 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?

2. Which nuclear material management approaches can favorably impact the performance of fuel cycle options?

3. Where would research and development (R&D) investment be 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?

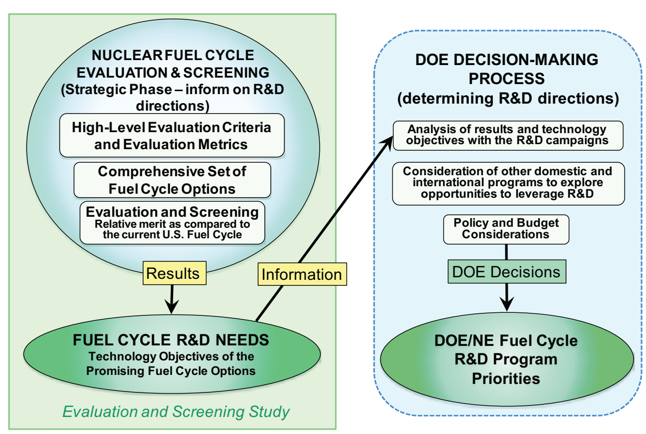

Fig. 1. Nuclear Fuel Cycle Evaluation and Screening Informing the DOE Decision-Making Process.

The comparative assessment of fuel cycle options was conducted by an Evaluation and Screening Team from the U.S. DOE national laboratories, DOE, and industry, and used a systematic logical framework that required development of suitable evaluation metrics for the specified evaluation criteria. Relevant stakeholders from industry, universities, and the government provided input to the metric development process. The metric descriptions in the report include justification for each metric and the associated calculation or estimation methodology.[1]

As mentioned above, for this study, the set of fuel cycle options was required to be comprehensive with respect to potential fuel cycle performance. An approach based on the fundamental characteristics of nuclear fuel cycles rather than on specific fuel cycle technologies allowed creation of such a comprehensive set and included once-through and recycle fuel cycles, thermal and fast reactors, critical and sub-critical externally–driven systems (EDS), and uranium and/or thorium for fuel along with other distinguishing fuel cycle features, resulting in almost 4400 options. Part of the process was to group fuel cycle options with similar characteristics and performance into 40 Evaluation Groups, and to provide the metric data calculated or estimated for each group of fuel cycles.

The metric data developed for each Evaluation Group provided the information required to evaluate and subsequently screen the fuel cycle options to identify the most promising alternatives based on the potential for improvement with respect to the current U.S. fuel cycle. For criteria with multiple evaluation metrics, the sensitivity of the results to the relative importance of each metric was investigated. The process used to identify those fuel cycle options with potential for improvement included varying the relative importance of the evaluation criteria when considering multiple criteria simultaneously, resulting in promising fuel cycles that were relatively insensitive to viewpoints on the importance of the evaluation criteria.[1] The required characteristics of the promising fuel cycle options provide the basis for establishing specific technical objectives for the R&D on the essential supporting technologies.

II. PROMISING FUEL CYCLE OPTIONS

As described above, the scenarios considering multiple criteria simultaneously 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. Fig. 2 shows an example of a multiple criteria scenario, where the various methods used for identifying promising options are also indicated. Fig. 2 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 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 in this example 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.

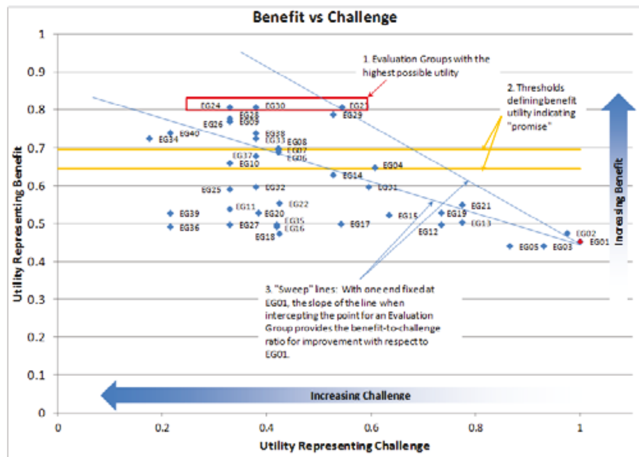

Fig. 2. An Example of the Benefit versus Challenge Results and the Methods Used for Identifying the Promising Options.

The example in Fig. 2 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 these fuel cycles.

Among all options, Fig. 2 shows the three Evaluation Groups that consistently had the highest improvements compared to the current fuel cycle in the U.S., regardless of the perspective on the relative importance of the benefit criteria. These Evaluation Groups each have the same metric data bin values for the 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, a judgment made by DOE decision-makers and others.

Eleven specific scenarios were studied in detail using these four benefit criteria, but clearly many other scenarios could be defined. A set of sensitivity analyses was conducted to provide a further check on the robustness of the results of the study, 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, 10 simulations of 1,000,000 iterations each were run. 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.

II.A. The Most Promising Fuel Cycle Options

As noted above, three Evaluation Groups perform as well as, or better than, any other Evaluation Group. The Evaluation Groups (EGs) are listed in numerical order, each with equivalent performance, with a short description indicative of the fuel cycles included in each group:

- 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
- 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 estimated with lower development and deployment challenges than the other two due to the use of U/Pu recycle as compared to U/TRU recycle. When considering both benefit and challenge, another Evaluation Group was included as a most promising option that has comparable development and deployment challenge to EG23 and almost the same potential benefit:

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

These four Evaluation Groups were identified in the study as the most promising fuel cycle options.

It should be noted that none of these fuel cycles are ready to be deployed today, and R&D is required to develop the appropriate implementing technologies.

II.B. Additional Potentially Promising Options

Eleven additional potentially promising groups of fuel cycles were seen to provide beneficial improvements that are not quite has high as for the four groups listed above but still representing what may be considered to be substantial improvements. 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 below in numerical order, not in order of potential performance improvement, 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,

II.C. Other Potentially Promising Fuel Cycle Options

In addition to the fuel cycle groups listed above, a few additional lesser performing fuel cycles that may be potentially promising were identified, 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 again listed below in numerical order, not in order of potential performance improvement, 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.

III. INSIGHTS AND QUESTIONS

Most of the promising options share a number of characteristics, including continuous recycle of the actinide elements, fast neutron irradiation in critical reactors, high internal conversion of fertile nuclear materials to fissile, and no need for uranium enrichment once the fuel cycle has been established. For the criteria and metrics used in the Study, the best performing fuel cycles (with respect to the performance of all possible fuel cycles) have the following characteristics:

- Continuous recycle of actinides (U/Pu or U/TRU)
- Fast neutron-spectrum critical reactors
- High internal conversion (of fertile to fissile)
- No uranium enrichment required once established

The key attributes derive mainly from the use of recycle and fast spectrum irradiation.

The use of fast-spectrum irradiation is beneficial compared to the thermal spectrum irradiation currently used in the U.S. fuel cycle because of the more favorable fission / absorption ratio for isotopes of many of the higher actinide elements as shown in Fig. 3. Isotopes where fission probability is substantially higher are highlighted.

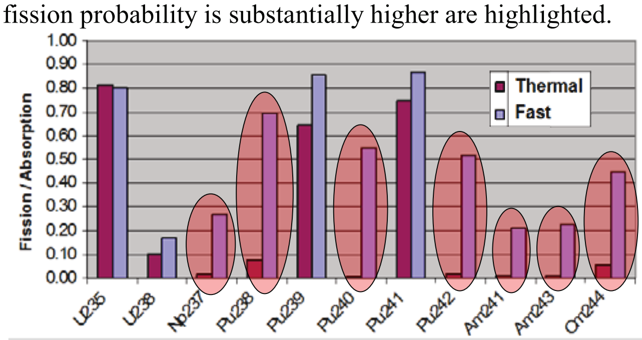

Fig. 3. Fission to Absorption Ratio for Selected Actinide Isotopes.

High internal conversion is also facilitated by the use of fast neutron irradiation, as shown in Fig. 4. In the fast neutron energy range (greater than 1 x 10^5 eV), the higher value of η (the average number of neutrons emitted in fission per neutron absorbed) shows that more neutrons are available as compared to the thermal energy range, where η is just over 2.0, the minimum required for breeding sufficient fissile for the reactor to be self-sustaining.

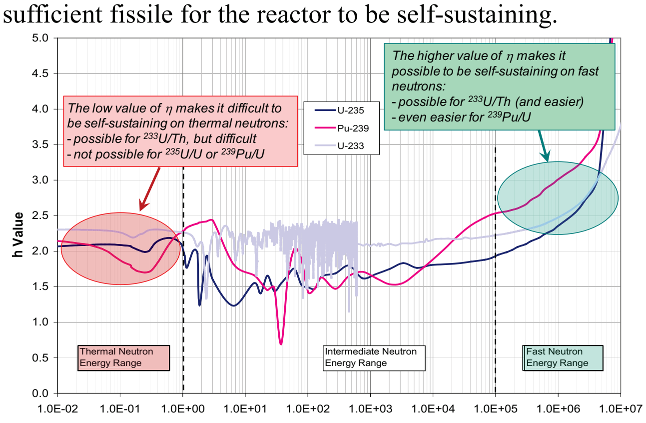

Fig. 4. Average Number of Neutrons Emitted per Neutron Absorbed as a Function of Neutron Energy

However, examination of the implications of these results raised several questions concerning the relative potential for benefit among the promising options. For example, it was observed that there were fuel cycle options that provided equivalent potential benefits, but which have potentially widely differing amounts of development and deployment challenge.

III.A. Minor Actinide Recycle

Among the most promising options, equivalent potential performance improvement was obtained for either U/Pu or U/TRU (Pu plus the minor actinides) recycle in fast reactors, yet the development and deployment challenges were different. The metric data for the most promising groups are summarized in Table I for some of the benefit metrics and in Table II for the challenge metrics for two of the most promising Evaluation Groups, EG23 and EG24, compared to the current U.S. fuel cycle, EG01. Both EG23 and EG24 use continuous recycle in fast reactors, with no thermal reactors. Metric data for each Evaluation Group is not a single value for each metric, but assigned to a bin with a range of value, consistent with the technology-neutral approach for defining the fuel cycles and indicating that the expected performance of the best performing fuel cycles in each Evaluation Group would be within the data range listed. The uncertainty in data for any specific metric was smaller than the data ranges used.

TABLE I

Benefit Metric Performance - the Most Promising Options

Metric	EG01	EG23 (U/Pu)	EG24 (U/TRU)
Mass of SNF+HLW disposed per energy generated, t/GWe-yr	12 to < 36	< 1.65	< 1.65
Activity of SNF+HLW (@100 years) per energy generated, MCi/GWe-yr	1.05 to < 1.60	0.67 to < 1.05	0.67 to < 1.05
Activity of SNF+HLW (@100,000 years) per energy generated , kCi/GWe-yr	1.0 x10^{-3} to < 2.3 x10^{-3}	5.0 x10^{-4} to < 1.0 x 10^{-3}	5.0 x10^{-4} to < 1.0 x 10^{-3}
Mass of DU+RU+RTh disposed per energy generated, t/GWe-yr	120 to < 200	<1	<1
Volume of LLW per energy generated, m^3/GWe-yr	252 to < 634	252 to < 634	252 to < 634
Natural Uranium required per energy generated	≥ 145.0	< 3.8	< 3.8

As seen in Table I, the benefits are from the reduction in the mass of highly radioactive wastes requiring geologic isolation, both SNF (for EG01) and HLW (for EG23 and EG24), from the reduction in mass of depleted uranium (DU) and recovered uranium (RU) requiring disposal, and the reduction in the amount of uranium required per energy generated. However, the benefits are the same whether U/Pu or U/TRU is recycled, possibly questioning the desirability of developing U/TRU recycle. Examination of the analysis examples used in the study for which detailed numerical results are available also indicate little difference between U/Pu and U/TRU recycle for these metrics.

As shown in Table II, the estimated costs for developing and deploying U/TRU recycle in fast reactors are greater than for U/Pu recycle in fast reactors.

TABLE II

Challenge Metric Performance - the Most Promising Options

Metric	EG23 (U/Pu)	EG24 (U/TRU)
Development time, years	10 to 25	10 to 25
Development cost	\$2B to \$10B	\$10B to \$25B
Deployment cost from prototypic validation to FOAK commercial	\$10B to \$25B	\$25B to \$50B
Compatibility with the existing infrastructure	Requires Almost Entirely New Infrastructure	Requires Almost Entirely New Infrastructure
Existence of regulations for the fuel cycle and familiarity with licensing	No U.S. Regulations/Familiarity	No Regulations/Familiarity
Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes	Markets weak, incentives required	Markets weak, incentives required
Levelized Cost of Electricity at Equilibrium	Likely to be similar to the current U.S. fuel cycle	Likely to be similar to the current U.S. fuel cycle

Activities are already underway in the FCO campaign to further investigate any potential for U/TRU recycle to offer advantages compared to U/Pu recycle by considering specific technologies for parts of the fuel cycle, including potential HLW waste forms and the effects of candidate waste disposal environments.

Analyses are also being performed for the other two most promising Evaluation Groups, EG29 and EG30, which include recycle in thermal reactors along with fast reactors, with the fast reactors providing the source of fissile material for the thermal reactors to avoid ongoing uranium enrichment. The answer to the question on the benefit of minor actinide recycle, U/TRU as compared to U/Pu, could have significant impact on R&D decisions since U/Pu recycle is already being conducted on an industrial scale in thermal reactors with experimental data available for fast reactor recycle, while the technologies to support U/TRU recycle in fast reactors will require substantial development.

III.B. Thorium-Based Recycle Fuel Cycles

As listed above, there were several Evaluation Groups identified as potentially promising that used a thorium-based fuel cycle. These fuel cycles also used recycle, but in this case the recycle was mainly the ^{233}U created from thorium. In principle these fuel cycles could be implemented using either thermal or fast reactors, but as shown on Fig. 4, recycle using fast reactors was evaluated as being easier to implement. The benefits for such thorium-based recycle fuel cycles were not quite as great as for uranium-based fuel cycles, but the differences were confined to only a few metrics as listed in Table III, which compares a best-performing group EG23 (U/Pu recycle in fast reactors) with EG26 and EG28, ^{233}U/Th recycle in thermal or fast reactors, respectively.

TABLE III

Benefit Metric Performance - the Most Promising Options

Metric	EG23 (U/Pu)	EG26 (^{233}U/Th)	EG28 (^{233}U/Th)
Mass of SNF+HLW disposed per energy generated, t/GWe-yr	< 1.65	< 1.65	< 1.65
Activity of SNF+HLW (@100 years) per energy generated, MCi/GWe-yr	0.67 to < 1.05	1.05 to < 1.60	1.05 to < 1.60
Activity of SNF+HLW (@100,000 years) per energy generated , kCi/GWe-yr	5.0×10^{-4} to < 1.0×10^{-3}	5.0×10^{-4} to < 1.0×10^{-3}	2.3×10^{-3} to < 5.0×10^{-3}
Mass of DU+RU+RTh disposed per energy generated, t/GWe-yr	<1	<1	<1
Volume of LLW per energy generated, m^3/GWe-yr	252 to < 634	≥ 1592	634 to < 1592
Natural Uranium required per energy generated	< 3.8	< 3.8 (0)	< 3.8 (0)
Natural Thorium required per energy generated	< 3.8 (0)	< 3.8	< 3.8

From Table III it can be seen that the thorium-based recycle fuel cycles perform as well as the most promising options except for the higher activity at 100 years, the higher activity at 100,000 years, and the increased generation of low-level waste (LLW). However, the time-dependent behavior of activity for the HLW from the thorium-based fuel cycles EG26 and EG28 varies from that of uranium-based fuel cycles such as EG23, generally having lower activity for the first 10,000 years or so, and then higher activity out to about a million years, but the differences are not large as listed in Table III. Whether the thorium-based fuel cycles would have higher or lower activity than uranium-based fuel cycles depends on the times selected for evaluating activity, but a more important question is whether these differences would be of concern, either for repository performance or to a decision-maker.

The metric of activity at 100 years was intended to reflect the relative difficulty in handling materials as well as the decay heat generation from these materials since that can impact repository operations and area loading. While the activity for the thorium-based fuel cycles was higher as shown in Table III, the decay heat was comparable to the uranium-based recycle fuel cycles. This was caused by higher fission product content of certain isotopes since fissioning of ^{233}U doesn't result in the same fission product distribution as fissioning of ^{239}Pu. Whether the difference in activity at 100 years is important would depend on the relative importance of activity and decay heat, and analysis of this situation is currently ongoing.[2]

The activity at 100,000 years was intended to inform on the relative long-lived hazard of the materials placed in geologic disposal. The hazard from geologic disposal is from elements that may be released from the repository and transported to the inhabited environment, which is affected by the release and transport characteristics of those hazardous elements and their radiotoxicity. Further analysis of the importance of this difference is also underway.[2]

Overall, depending on the importance of these metrics to the decision-maker, the thorium-based recycle fuel cycles may be viewed more or less favorably with respect to the uranium-based fast reactor recycle fuel.

III.C. Transition to an Alternative Fuel Cycle

All of the fuel cycle evaluations in the E&S study were performed for the fully deployed and implemented fuel cycle to allow comparison with the performance of the current U.S. fuel cycle. However, once the results of the study were obtained, it was clear that an alternative fuel cycle that had the potential for significant performance improvement compared to the current U.S. fuel cycle would likely have a very different infrastructure, as listed in Table II.

As a consequence, transition analysis studies are being conducted in the FCO campaign. As a first activity, these studies are exploring the likely or possible transition to the most promising fuel cycles, all of which involve recycle in fast reactors. If it is assumed that a decision is made to develop and implement one of the most promising fuel cycles as an alternative fuel cycle in the U.S., one of the major boundary conditions for transition to a new fuel cycle is the anticipated lifetime of the existing nuclear reactor infrastructure. In the U.S., if it is assumed that the existing reactors all have lifetime extended to 60 years, and lifetime is not further extended to 80 years, the retirement of these reactors will begin in about 2030, 15 years from now. The reactors retire at a more or less steady rate over the next 20 years until they are all retired by about 2050. This can create issues for the substitution of an alternative fuel cycle since as listed in Table II, the development time was estimated to be in the range of 10-25 years, and that is only the the level of engineering-scale demonstration. Additional time is required for maturing the technologies to commercialization and for the initial deployment, especially given the need for recycle capabilities.

The transition analyses are exploring the effects of different times at which the new fuel cycle would be ready for deployment. Some of the most promising fuel cycles are also systems that use both thermal and fast reactors, indicating that at least some LWRs could be an ongoing part of a most promising fuel cycle. The limitation in this case is whether the LWRs can be sustained by fissile created in the fast reactors, or whether the percentage of LWRs is too high and continuing use of uranium enrichment is needed, adversely affecting both resource utilization and waste generation.

IV. CONCLUSIONS

The comprehensive evaluation and screening of nuclear fuel cycles identified those fuel cycles and their characteristics that had the potential to provide significant improvement with respect to the current U.S. fuel cycle.[1] The results from this study provided insights about how the choice of fuel cycle may be able to improve fuel cycle performance but also raised questions about some of the choices that could be made, such as choosing between U/Pu and U/TRU recycle in fast reactors when there appears to be no difference in benefit but the challenge for developing and deploying U/TRU recycle is greater, or whether or not to pursue thorium-based recycle fuel cycles. These questions are now being investigated by the FCO campaign for the purpose of informing DOE-NE as part of their decision-making process on R&D directions.

The lack of much common infrastructure between the current U.S. fuel cycle and the most promising options has also prompted investigation of the issues concerning transition to a new fuel cycle by the FCO campaign. Several issues, including the projected lifetime of the current reactors, affect the timing and effect of critical decisions regarding development of such promising fuel cycles if they are to have an impact in the 21st century.

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