Analysis of fuel cycle strategies and U.S. transition scenarios

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Abstract

The nuclear fuel cycle Evaluation and Screening (E&S) study that was completed in October 2014 [1] enabled the identification of four fuel cycle groups that are considered most promising based on a set of nine evaluation criteria: (a) six benefit criteria of Nuclear Waste Management, Proliferation Risk, Nuclear Material Security Risk, Safety, Environmental Impact, Resource Utilization, and (b) three challenge criteria of Development and Deployment Risk, Institutional Issues, Financial Risk and Economics. The E&S study was conducted at a level of analysis that is "technology-neutral," that is, without consideration of specific technologies, but using the fundamental physics characteristics of each part of the fuel cycle. The study focused on the fuel cycle performance benefits at the fuel cycle equilibrium state, with only limited consideration of transition and deployment impacts. Common characteristics of the four most promising fuel cycle options include continuous recycle of all U/Pu or U/TRU, the use of fast-spectrum reactors, and no use of uranium enrichment once fuel cycle equilibrium has been established. The high-level wastes are mainly from processing of irradiated fuel, and there would be no disposal of any spent fuel.

Building on the findings of the E&S study, additional studies have been conducted in the last two years following the information exchange meeting, the 13th IEMPT, which was held in Seoul, the Republic of Korea in 2014. Insights are presented from the recent studies on the benefits and challenges of recycling minor actinides, and transition considerations to some of the most promising fuel cycle options.

Introduction

The U.S. Department of Energy, Office of Nuclear Energy (DOE-NE), chartered a study of nuclear fuel cycle options, called the Nuclear Fuel Cycle Evaluation and Screening (E&S) study, which was completed in October, 2014 [1]. DOE-NE specified nine fuel cycle evaluation criteria representing broadly defined economic, environmental, safety, non-proliferation, security and sustainability goals to allow identification of promising fuel cycle options that have the potential for achieving substantial improvements as compared to the current nuclear fuel cycle in the United States. Six criteria addressed the potential for benefits with respect to fuel cycle performance, while the other three criteria addressed potential challenges for fuel cycle development and deployment.

DOE-NE also specified that the set of fuel cycle options to be evaluated in the E&S study was to be as comprehensive as possible with respect to potential fuel cycle performance. An approach based on the fundamental physics-based characteristics of nuclear fuel cycles rather than on fuel cycle examples using specific implementing technologies was developed to enable the creation of such a comprehensive set, which represented the performance of all once-through and recycle fuel cycles, and included thermal and fast reactors, critical and sub-critical systems, and uranium and/or thorium for fuel along with other distinguishing fuel cycle features. The entire set of possible fuel cycle options was reduced to a set of 40 Evaluation Groups (EGs) by collecting fuel cycles with similar characteristics and performance into each EG. The E&S study considered the complete nuclear energy system from mining to disposal, and provided information about the potential benefits and challenges of nuclear fuel cycles that could be used to strengthen the basis of, and provide guidance for, the R&D activities undertaken by DOE-NE. The performance of each EG was assessed by using metrics developed for each evaluation criterion.

The process used to identify those fuel cycle options with potential for improvement included varying the relative importance of the six benefit criteria when considering multiple criteria simultaneously, resulting in promising fuel cycles that were relatively insensitive to viewpoints on the importance of the benefit criteria. The E&S study identified four groups of fuel cycles as being “most promising” for R&D, listed in Table 1 by their Evaluation Group (EG) number, based on the potential for performance improvement with respect to the benefit criteria provided by DOE-NE for the E&S study. The descriptions in Table 1 are only indicative of the fuel cycles included in each group, and the term "new natural uranium fuel" indicates that enrichment is not needed for either new uranium fuel resources or for the recycled uranium.

Table 1: Most Promising Fuel Cycle Groups from the E&S Study

Evaluation Group	Most Promising Fuel Cycle Groups
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
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

Note: U= uranium; Pu = plutonium; TRU = transuranic elements, i.e., atomic number higher than uranium (neptunium, plutonium, americium, curium, etc.); 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.

These four most promising Evaluation Groups share 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 steady-state conditions are established

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. The fast spectrum also has more favorable internal conversion of fertile ^{238}U to ^{239}Pu, facilitating the use of uranium without enrichment to sustain the fuel cycle.

The results of the E&S study have been used to identify the subsequent studies conducted in the past two years. This paper summarizes the results and insights from several of these studies.

Minor Actinide Recycle – Benefits and Challenges

In considering the four groups of most promising fuel cycles, it was observed that both U/Pu and U/TRU recycle in fast reactors appeared to provide comparable potential benefits for the criteria and metrics used in the study, as shown by some examples in Table 2, where the performance of the current once-through U.S. fuel cycle using thermal reactors (EG01) is compared to the performance of two of the most promising fuel cycles. However, these most promising groups exhibited differences with respect to the three challenge criteria, with fuel cycles in EG23 and EG29 estimated to have lower development and deployment challenges than those in EG24 and EG30 due to the use of U/Pu recycle as compared to U/TRU recycle.

TABLE 2: Fuel Cycle Performance for Selected Evaluation Metrics

Evaluation 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	1.0×10^{-3} to < 2.3×10^{-3}	5.0×10^{-4} to < 1.0×10^{-3}	5.0×10^{-4} to < 1.0×10^{-3}
Mass of DU+RU 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

Note: HLW= High Level Waste; DU = Depleted Uranium; RU = Reactor Recovered Uranium; SNF = Spent Nuclear Fuel; LLW -= Low-Level Waste.

A study was conducted that compared the performance of U/Pu and U/TRU recycle in greater detail, going beyond the evaluation criteria and metrics used in the E&S study, to determine if there were any additional potential benefits associated with U/TRU recycle, and to further explore the nature of the development and deployment differences, that would help to justify the greater development and deployment challenges [2]. The basic difference between U/Pu recycle and U/TRU recycle is that the minor actinides (MA) are recycled along with the Pu in U/TRU recycle, while they are disposed with U/Pu recycle. In common with the E&S study, this study also compared the performance at an assumed "steady-state", where a fuel cycle is completely deployed and continuously operated.

Overall, the results of the study showed that both U/Pu and U/TRU recycle fuel cycles could each provide benefits with respect to the other depending on where the minor actinides are in the fuel cycle, as summarized in Table 3.

TABLE 3. Relative Benefits and Challenges of U/Pu and U/TRU Recycle

Fuel Cycle Activity	EG23 (U/Pu)	EG24 (U/TRU)
Recycle fuel fabrication and handling	Potentially lower shielding requirements due to lower activity	Requires remote (hot cell) activities
In-reactor fuel behavior	Substantial experience with U/Pu fuel	Little experience with U/TRU fuel, especially for heterogeneous recycle, and development challenges have been identified
Used fuel handling	Determined by fission products in the used fuel	Determined by fission products in the used fuel; heterogeneous recycle may provide greater challenges
Used fuel reprocessing	Only uranium and plutonium are recovered	Uranium and the TRU are recovered, likely to be more complex and requiring greater development
HLW fabrication and handling	HLW will have minor actinides, increasing radioactivity and decay heat, potentially complicating HLW form development	HLW has lower activity and decay heat
HLW disposal (decay heat)	Higher initial decay heat due to presence of ^{241}Am	Recycle of all TRU greatly lowers minor actinide content in the HLW
HLW disposal (radiotoxicity and long-term repository performance)	Long-term radiotoxicity is mainly determined by plutonium and uranium isotopes, which are in the HLW at process loss amounts in both cases. As a result, minor actinide content of HLW may not be relevant for long-term geologic repository performance. Mobile releases are fission product elements for many geologies.	

For U/Pu recycle fuel cycles, whether only fast reactors are used (EG23) or if fast reactors provide the fissile materials to operate thermal reactors (EG29), the minor actinides are intentionally part of the high-level waste (HLW) and would only potentially be present in the rest of the fuel cycle as a contaminant from reprocessing activities. Implementing a fuel cycle that recycles U/Pu allows the use of fuels with a significant experience base, and these fuels could be fabricated and handled with less shielding than is needed when the minor actinides are in the fuel as is the case with U/TRU recycle. The irradiated U/Pu fuel also has lower decay heat than when U/TRU is recycled, allowing handling and shipping sooner with fewer shipments to processing facilities. Reprocessing technologies for recovering U/Pu are available that are similar to those that have been deployed industrially, potentially reducing R&D needs. However, at the same time, even though the presence of the minor actinides in the HLW is accommodated by existing waste form technologies, the minor actinides could complicate advanced waste form development and affect the durability of an advanced waste form due to the higher α radiation, potentially increasing R&D needs in this area. In addition, the HLW minor actinide content, especially ^{241}Am, adds decay heat that needs to be managed during handling and storage, and which may either increase the size of a geologic repository due to the potential for requiring an increased area for disposal of HLW with higher decay heat, or pose greater engineering and operational challenges to manage the decay heat.

In contrast, recycle of the minor actinides in U/TRU recycle fuel cycles, whether only fast reactors are used (EG24) or if fast reactors provide the fissile materials to operate thermal reactors (EG30), keeps the minor actinides out of the HLW except for processing losses. This would allow the use of existing waste form technologies and has the potential to simplify advanced waste form development. The lower HLW decay heat may enable more compact disposal, reducing the size requirements for a geologic repository. However, these benefits also come with the development challenges associated with keeping the minor actinides within the fuel cycle. As mentioned above, U/TRU recycle fuels will require more shielding for handling and fuel fabrication, there is little to no experience with such U/TRU recycle fuels in a reactor, and the handling and storage of the irradiated fuel must deal with the higher decay heat associated with the minor actinides. Reprocessing technology also needs to be developed, and R&D has been ongoing to achieve U/TRU recovery.

It is also possible to consider recycle of just one or more of the minor actinides rather than all of them together. Prior studies and the considerations show that such approaches can modify the relative benefits and challenges between fuel cycle options but do not change the conclusions of the study [3]. For example, if americium is recycled along with the U/Pu, the decay heat from the americium is kept out of the HLW, potentially benefitting the space required for waste disposal, but there may still be complications for advanced waste form development due to α damage, mainly from curium. At the same time, the presence of americium in the recycle fuel increases the decay heat, affecting storage and handling, and there is little to no experience with such fuels although challenges related to the recycle of americium have been identified in other studies. This example illustrates that such partial recycle of the minor actinides may move specific benefits and challenges between the different parts of the fuel cycle but they will always be present.

Overall, this examination of the relative benefits and challenges of U/Pu and U/TRU recycle fuel cycles confirmed that either approach has both benefits and challenges. It appeared that the benefits are associated with the parts of the fuel cycle that do not contain significant amounts of minor actinides, and the R&D challenges we associated with the parts of the fuel cycle where the minor actinides are present. Given that both U/Pu and U/TRU recycle fuel cycles have both benefits and challenges, any preference for either U/Pu or U/TRU recycle would depend on the preferences for R&D either on waste forms or on recycle fuel fabrication, operation, and reprocessing, respectively. At this time, no further assessment was made of the relative difficulty of the R&D choices, and a strategy that pursued both U/Pu and U/TRU recycle options would appear to be the logical approach until such time that the results of R&D begin to differentiate the development and deployment challenge, if that should occur, with all four most promising groups from the E&S study as potential candidates for development.

Transition Studies

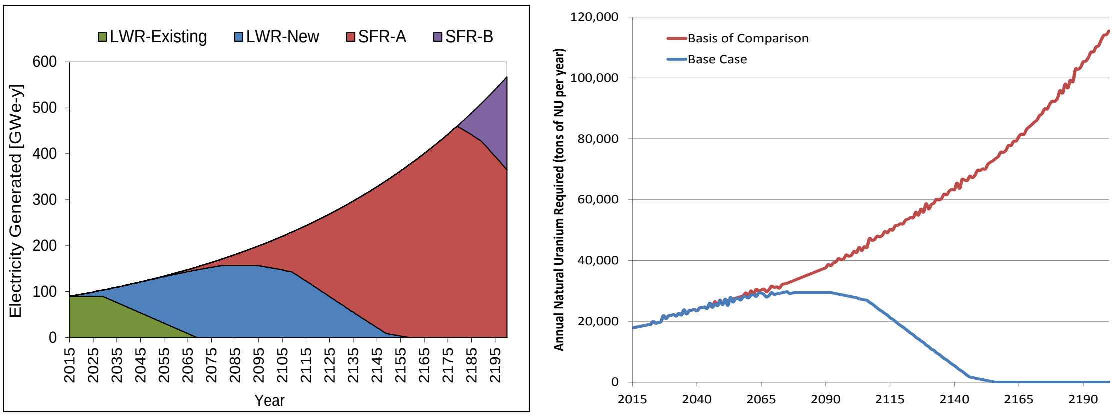
While the recycle of fuel would have benefits identified by the E&S study, particularly in the steady-state implementation of such a fuel cycle, changing to such a fuel cycle would introduce practical issues that need to be addressed in the transition. Transition scenario studies have been conducted for the most promising fuel cycle options to develop an understanding of the requirements for a successful transition from the currently operating fuel cycle in the U.S. to an alternative fuel cycle, especially identifying any issues or constraints that would inhibit or prevent such a transition. The scenario studies explored a range of effective transition strategies, with the goal of developing an understanding of transition issues, times, costs, and constraints in order to enable development of effective transition strategies; to identify robust transition pathways that consider economic conditions, energy demand, etc., and; to identify the decisions that need to be made, the time frame for such decisions, and the effects of delaying decisions. This ultimately requires consideration of a broad range of possible implementing technologies and future conditions to inform decision makers.

Transition to U/Pu Recycle in Fast Reactors (EG23)

A base case was defined assuming U.S. nuclear energy production growing at an annual rate of 1%, and where all LWR Used Nuclear Fuel (UNF) produced beginning in 2015 is recycled and used to support deployment of fast reactors [4]. The transition simulations start in 2015 and extend to 2200. This growth rate is thought to be representative of nuclear energy roughly maintaining its current market share of electricity based on a projection of current electricity demand growth rates in the U.S. The base case assumes that existing inventories of UNF generated prior to 2015 will be disposed as spent nuclear fuel (SNF). The base case also included defining when each reactor in the current fleet is expected to shut down. For these analyses, the assumed lifetime of the existing fleet is that in terms of energy generation, half would operate for 60 years and half would have their lifetime extended to 80 years. It was additionally assumed that the implementing technologies for EG23 are sodium-cooled fast reactors (SFRs), off-site aqueous reprocessing of UNF, and glove-box fabrication of the recycled metallic fuel. The SFRs are assumed to be available for commercial deployment beginning in 2050. Prior to that, all demand for new or replacement generation to maintain the 1% growth rate is met by constructing new light-water reactors (LWRs) with lifetimes of 80 years.

A major consideration during transition is having sufficient fissile material for starting the fast reactors before the fast reactor fleet is self-sustaining by recycling its own fuel. As Figure 1 shows, the FR fleet will go through a period of rapid growth as the fast reactor fleet expands from just a few reactors to 100 or more. During this phase, a separate fissile source will be required to supplement the fissile available from recycled fast reactor fuel, either from recycled LWR fuel or LEU, or new LWRs would be built until sufficient fissile is available to support the startup of the fast reactors. As the fast reactor fleet expands, the fraction of fissile that needs to be added from outside the fuel cycle decreases and by the end of transition, the fleet has become self-sufficient, i.e., all new fissile material required will be produced by the fast reactor fleet.

Figure 1: Transition to Fast Reactor Recycle of U/Pu and the Reduction in the Need for Natural Uranium as Compared to the Current U.S. Fuel Cycle



Three pathways were explored in the study. The first pathway is the “Base Case” described above. which uses only plutonium and uranium recovered from light-water reactor (LWR) used nuclear fuel (UNF) of the current fleet, which is referred to as “LWR RU/Pu”, to start up the first fast reactors. As Figure 1 shows, new LWRs need to be deployed after 2050, thereby extending transition. The second pathway involves using low-enriched uranium (LEU) fuel during initial fast reactor deployment to supplement the U/Pu available from recycled LWR fuel. This pathway is designated as the “LEU Support” pathway. The third is the “LEU only” pathway which uses only LEU fuel as the startup fissile source for the fast reactors, and no LWR UNF is recycled, and represents a bounding case intended to inform on the tradeoffs of recycling the LWR UNF since fissile material availability was observed to be a key constraint on the ability to deploy fast reactors during transition. In the analyses, LEU and the necessary natural uranium (NU) and enrichment (SWU) capacity are assumed to be unconstrained, and removes the fissile material availability constraint to starting up fast reactors during transition [5].

The analyses indicated that for all scenarios envisioned, fast reactors need to be deployed as soon as possible in order to maximize the benefits associated with transition to a new fuel cycle. This may be achieved by fueling the fast reactors with LEU when there is insufficient Pu available. In the base case scenario, LWRs may also be deployed during the transition to meet energy demand if fast reactors cannot be started due to insufficient fissile material to fuel them. In addition, existing LWRs shut down before the introduction of FRs must be replaced by new LWRs that are assumed to operate for another 80 years, thereby increasing the cumulative amount of energy generated with LEU fuel and delaying the end of transition to the new fuel cycle.

The study also found that life extension that keeps existing light-water reactors operational until after the fast reactors are available will lead to better transition performance since fewer new LWRs will need to be built. The use of LEU to fuel the fast reactors reduces or perhaps even eliminates the need for LWR UNF recycle technologies. By decoupling the LWR UNF recycle technologies from the deployment of the fast reactors, significant investments in these technologies can be delayed, reduced, or eliminated.

In general, the total amount of fissile material required to sustain the operation of a reactor is the total amount of material that is in the reactor as well as all material that is in storage or held up in processes outside of the reactor including decay storage, separations, fabrication, and transportation. This total time from reactor discharge to recharge as fresh fuel is referred to in the study as the recycle time. The use of technologies or deployment of those technologies in a way that reduces recycle time will significantly reduce the fissile material required to start up and sustain the operation of a fast reactor. Shorter recycle time for the fast reactor fuel makes the fissile material produced in the fast reactors available sooner and reduces the material held up in processes and storage outside of the reactor. This allows for a much more rapid expansion of the fast reactor fleet. For transitions that are constrained by the availability of U/Pu from LWR UNF, there are significant performance benefits that result from a shorter recycle time of the fast reactor UNF. However, there appeared to be no significant benefits from reducing the recycling time of the LWR UNF, since there is already a large inventory of LWR UNF that exists when fast reactor deployment begins.

The study also found that for transitions potentially constrained by the availability of U/Pu from LWR UNF, using LEU to start up the fast reactors results in lower overall natural uranium and enrichment requirements by the end of transition, although there would be a significant increase during the early stages. An LEU-fueled fast reactor requires significantly more natural uranium and a higher enrichment than an LEU-fueled LWR to generate the same energy. However, the fast reactor only requires LEU until sufficient fast reactor recycled fuel is available (on the order of ~10 years depending on the scenario and recycle time) while LWRs require LEU for the entire 80-year lifetime of the plant, resulting in larger lifetime demand. In addition, the use of LEU to start up fast reactors may have large economic benefits during the early part of transition when availability of UNF and demand for recycled material is relatively low compared to the anticipated processing capacity of recycle facilities, potentially resulting in low capacity factors for reprocessing plants for many years. Unfortunately, the scenario that uses LEU to start up fast reactors and eliminates the need for recycle of LWR UNF means that all of the LWR UNF will be disposed, resulting in larger quantities of material requiring geologic disposal, and the properties of these materials will be more challenging (higher activity, heat, and toxicity).

All three FR startup pathways proved to be viable transition approaches, although the characteristics of each pathway affect the resulting performance of the fuel cycle during transition and the challenges of transition, which depend on the scale of the future nuclear energy system and the recycle time of the fast reactor UNF. There are other technology-dependent considerations that will have impacts on transition, but for most of these considerations, what is beneficial for the technology performance is also beneficial for transition performance. For example, the greater thermal efficiency and higher average discharge burnup for the fast reactor will both improve the economics of the fast reactor and the performance of the fuel cycle. However, while higher burnup is also better for LWR performance, less U/Pu would be available in the LWR UNF inventory to support startup of the fast reactors, potentially delaying transition.

Transition to U/TRU Recycle in Fast Reactors (EG24)

The analysis of transition to fuel cycles in EG24 (U/TRU recycle in fast reactors) was built on the knowledge developed in the analysis of EG23. As with EG23, there are four key technologies involved in recycle: 1) fast reactor; 2) fuel fabrication; 3) qualified fuel; and 4) material recovery (separation). As described above, other than the fast reactor, the recycle technologies for EG24 are less developed and there is less experience, potentially requiring more time and investment to advance them to commercial deployment. Additionally, there are challenges related to the recycling of higher heat and radiation emission materials that result from recycling of the MA, e.g., recycle times within the system due to the minimum cooling times for shipment and/or separation.

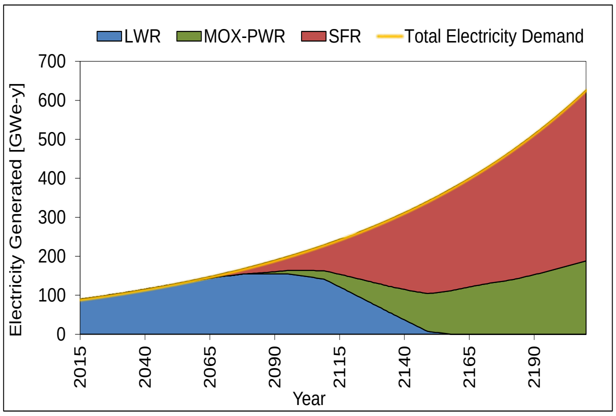
Three pathways were considered, equivalent to those for transition to U/Pu recycle as described in the preceding section, except now it is all TRU elements being recycled. These equivalent pathways are U/TRU from LWR UNF (used nuclear fuel), U/TRU from LWR UNF supplemented by LEU, and LEU only without any LWR UNF recycled. For EG24 relative to EG23, it was found that the inclusion of the MA has little impact on the transition behavior for the aspects driven by fissile material requirements. However, it was noted that achieving a particular recycle time becomes more challenging because of the higher decay heat and radiation emission levels that make shipping and separation more difficult. If a longer recycle time is required, this can significantly delay transition. The evaluation indicated that while homogeneous recycle (recycle of all TRU elements as a group) or heterogeneous recycle (recycle of the TRU elements in two or more groups) are not expected to have significant performance differences at steady state, there are significant differences that could result during transition.

Transition to U/TRU Recycle in Fast and Thermal Reactors Fuel Cycle (EG29)

Recent studies have also included an assessment of the key considerations that affect performance and the challenges of transition from the current U.S. nuclear energy system to a future nuclear energy system in which U/Pu is continuously recycled in critical reactors using both fast and thermal reactors, but enriched uranium is no longer needed (EG29) since all of the fissile required to operate the reactors is created in the fast reactors while the thermal reactors (e.g., advanced light-water reactors (LWRs)) are net burners of fissile. The steady-state fleet after transition is a mix of U/Pu-fueled fast reactors and U/Pu-fueled thermal reactors. The proportion of fast reactors and thermal reactors can vary, with up to about 50% thermal reactors being possible for the maximum breeding ratio in the fast reactors in the case where there is no growth in nuclear power energy generation. Other factors may affect the proportion, such as the relative economics of the fast and thermal reactors, but in all cases, the overall fuel cycle benefits identified in the E&S study are attained. For this study, the assumption was that the objective would be to maximize the share of energy produced by the thermal reactors, which for the analyses performed in the study was about 30% LWRs for the assumed 1% growth rate for nuclear power.

As the results of the E&S study showed, the potential steady-state benefits of EG23 and EG29 are essentially the same since for both systems, there is no disposal of either uranium or spent nuclear fuel, and only minor actinides, fission products, and U/Pu losses are sent to high-level waste. As Figure 2 illustrates, the transition times are quite similar between EG23 and EG29 for the examples shown here (although the transition time for EG23 can be shortened by further optimizing the fast reactor performance). The major differences between the two transitions are in the transition flexibility and the potential benefits of that flexibility since the ratio of thermal and fast reactors can be allowed to vary significantly during transition without necessarily delaying the end of transition. Almost all of the conclusions from the analysis of transition to EG23 can be applied to the transition to EG29. The major difference is the inclusion of the thermal reactors in EG29 as an end-state technology and not a technology to be phased out during transition.

Figure 2: Transition to Fast and Thermal Reactor Recycle of U/Pu



R&D Needs and Opportunities

Transition analyses typically involve significant complexity and consideration of a range of assumptions. The development of reactors and recycle systems designed for transition objectives is a key consideration, and the qualities and performance of reactors that facilitate transition need to be better understood. The design of recycle facilities that can efficiently handle different throughputs and material flows is needed to inform on the tradeoffs, such as those associated with operating at shorter cooling times, higher recovery efficiencies, and different scales of facility sizes.

The economics of transition adds complexity to the challenge of understanding and informing on the economics of future nuclear energy systems. For example, the relationship between fast reactor breeding ratio and the average discharge burnup can affect overall fuel cycle economic performance. In the fast reactor, lower average discharge burnup for the driver fuel increases the reprocessing capacity required in terms of MTIHM/yr, but more fissile remains in the driver fuel and there is lower fission product content. If blanket assemblies are used, lower discharge burnup lowers both fission product content and fissile concentration. These and other relationships result in the economics of transition to a system using both fast and thermal reactors having even more complex cost behavior.

Ongoing activities are designed to improve the understanding of the issues and factors that affect the potential transition to a new fuel cycle using recycle in fast reactors, including identifying the technology characteristics that lead to more favorable transition performance, such as overall time to complete transition, waste generation rates, and annual costs.

Conclusions

The Evaluation and Screening (E&S) study identified the most promising fuel cycle options for R&D within the U.S. DOE Office of Nuclear Energy fuel cycle technologies program for the specified Evaluation Criteria. Subsequent studies building on the results of the E&S study have provided insights on more focused issues associated with the development and deployment of technologies for an advanced fuel cycle system. Results of some of the completed and ongoing studies were discussed in this paper, and included the assessment of the impact of recycling minor actinides in the fuel cycle and the characterization of transition and associated challenges.

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