APPENDIX B

COMPREHENSIVE SET OF FUEL CYCLE OPTIONS

CONTENTS

FIGURES

TABLES

B. COMPREHENSIVE SET OF FUEL CYCLE OPTIONS

This Appendix describes the process and results of identifying a comprehensive set of fuel cycle options for the Nuclear Fuel Cycle Evaluation and Screening (E&S) as stated in the Study Charter [Attachment 1 in Appendix A]. The E&S uses "Evaluation Groups" which represent a grouping of fuel cycle options with similar physics-based performance. The Evaluation Groups and associated Analysis Examples (which are used to generate fuel cycle performance data for the evaluation of metrics) are created through a process that begins with the full universe of fuel cycle options, and groups them using a logical approach so that as a set, the resulting Evaluation Groups represent the potential performance of all fuel cycle options.

Content and Structure of Appendix B:

This Appendix describes the development of the comprehensive list of fuel cycle options, the approach used to develop the list, the process to group options based on their characteristics, the identification of the final set of options to be analyzed for the Evaluation and Screening, and the fuel cycle performance data supporting the determination of Metric Data for the Evaluation Metrics. The EST developed the comprehensive list with input and review from groups external to the study, including government, industry, and universities, as discussed in Appendix A.

The Appendix starts with the principles used to develop the comprehensive list using fundamental characteristics to identify groups of fuel cycles, followed by stating the principles used to combine groups of fuel cycles into a smaller number of groups. Next the final set of groups is described in detail along with the examples for which reactor physics-based analyses were performed. Finally, the analysis results supporting the Metric Data are presented.

Concluding remarks and a descriptive listing of the 40 Evaluation Groups identified for the E&S are given in Section B-6, along with a discussion of the relationship of the present study to the results of the earlier Pilot Study.[B1] Table 3 in the Main Report provides a short description of each Evaluation Group that is indicative of the fuel cycles in the group.

It should be noted that all of the information, in all of the Appendices, is connected and synthesized in the main body of the report. Thus, the "big picture" appears in Appendix A, which describes major concepts used in other Appendices. This Appendix provides the details on the comprehensive set of options.

Definition of the Nuclear Fuel Cycle for the Study

The E&S considers a Nuclear Energy System (NES), also referred to as a "Nuclear Fuel Cycle," to include all the functions required for generating and using nuclear energy, from obtaining fuel resources through disposal of the wastes, and everything in between as shown in Figure B1.

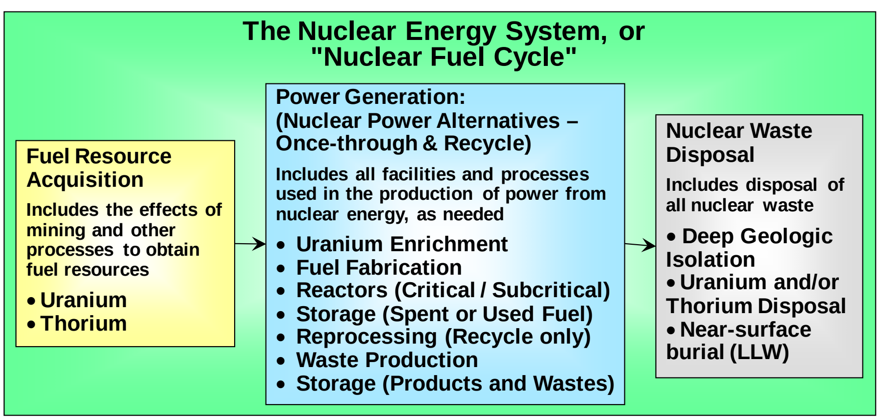

Figure B1. The Nuclear Energy System, also known as the Nuclear Fuel Cycle.

The "everything in between" is referred to as the Nuclear Power Alternative (NPA) of each NES and contains the irradiation devices (critical reactor or sub-critical driven system), with supporting facilities for enrichment (if needed), fuel fabrication, reprocessing (if needed), and used fuel storage. The main function of the NPA is to produce useful energy, and during performance of this function, fuel materials transmute as a result of irradiation. Given that all NES require fuel resources and spent fuel/waste disposal, the differences between NES for the E&S are really differences between the NPA since "fuel resources" and "disposal" are considered generically. As a consequence, in the development of Fuel Cycle Option Groups (discussed below), the differences in the NPA reflect all of the differences between fuel cycle options in the study. For this reason, the NPA is referred to as a "fuel cycle option" in what follows.

The following sections describe the key steps/phases in the development of the Evaluation Groups that are used in the E&S:

- Development of a comprehensive set of Fuel Cycle Option Groups that represents the performance of all possible approaches for generating and using nuclear power based on fundamental reactor physics principles. Each Fuel Cycle Option Group contains one or more specific fuel cycle options, which includes implementing technologies.
- Collection of Fuel Cycle Option Groups into Evaluation Groups based on similarities in expected physics-based performance, and confirmation that these groups are appropriate when all high-level criteria are considered.
- Identification of an Analysis Example for each Evaluation Group for the purpose of performing reactor physics-based analyses to generate data needed for the metrics associated with the high-level criteria. The Analysis Example is defined with implementing technology(s) only for the fuel(s) and irradiation environment(s), as the specification of technologies for the rest of the fuel cycle is not needed for the analyses.

Figure B2 shows the hierarchical structure of the results of this process: (1) specific *Fuel Cycle Options*, (e.g., once-through PWR with LEU fuel) which are collected into (2) *Fuel Cycle Option Groups* (e.g., once-through thermal spectrum reactors with enriched uranium fuel) based on fundamental physics principles, which are (3) collected based on similarities in performance into *Evaluation Groups* (e.g., once-through fuel cycles with enriched uranium with similar uranium utilization).

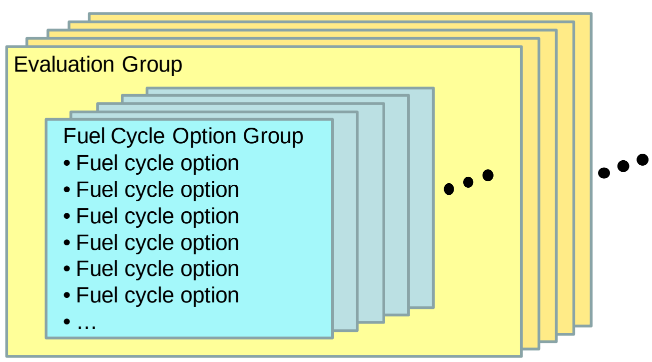

Figure B2. Nuclear Fuel Cycle Options, Fuel Cycle Option Groups, and Evaluation Groups.

B-1. Creation of a Comprehensive Set of Fuel Cycle Options

In considering approaches for creating a set of nuclear fuel cycle options for the Nuclear Fuel Cycle Evaluation and Screening that is comprehensive with respect to fuel cycle performance, the concept for the E&S was to consider specific fuel cycle characteristics that distinguished the performance of one fuel cycle option from another, and to identify the generic Fuel Cycle Option Groups based on these characteristics. As shown in Figure B2, each Fuel Cycle Option Group contains one or more specific fuel cycle options, where a specific fuel cycle option includes the implementing technologies for all parts of the fuel cycle. For example, a Fuel Cycle Option Group could be described as "once-through, thermal neutron irradiation in critical reactors using enriched uranium fuel". Within this group there could be an almost endless variety of fuel cycle options when the implementing technologies are considered, such as "once-through use of LEU in PWRs" or “once-through use of LEU in BWRs/HTGRs/etc.” It is essential to recognize that the Nuclear Fuel Cycle Evaluation and Screening aims at identifying the potential for substantial improvements in fuel cycle performance. Therefore, it is appropriate to include fuel cycle options with similar performance in the same Fuel Cycle Option Group.

Table B1 identifies such performance characteristics as they relate to the nine high-level Evaluation Criteria and correlates them to the relevant fuel cycle "features", e.g., the basic physics characteristics defining the fuel cycle such as once-through vs. recycle, as explained in the subsequent sections. Several of the Evaluation Criteria do not correspond to differences in fuel cycle option performance, e.g., development and deployment risk is assessed for all fuel cycles and differences in development and deployment risk do not create new fuel cycle options as defined by Figure B1.

The fuel cycle features listed in Table B1 are capable of having a direct influence on the fuel cycle characteristics relevant to the criteria, including whether or not the fuel cycle includes recycle, the neutron kinetic energy distribution (“spectrum”) in the nuclear fission system, whether or not the system requires a self-sustaining neutron fission chain reaction (i.e., either critical or subcritical), the fuel material(s) (uranium and/or thorium), whether or not uranium enrichment is needed, and what elements (or their isotopes) are recycled. These form the general basis for identifying the fuel cycle options, while also providing the logical structure to collect fuel cycles together if they have similar performance with respect to the Evaluation Criteria.

Table B1. Evaluation Criteria, Fuel Cycle Characteristics, and Fuel Cycle Features.

Evaluation Criterion	Relevant Fuel Cycle Characteristics	Potential Fuel Cycle Features
Nuclear Waste Management	For all wastes, radionuclide inventory including fission product and actinide content; decay heat; HLW and spent nuclear fuel (SNF) masses, and low level waste (LLW) volume	Once-through / Recycle Critical / Sub-critical Neutron Spectrum Fuel Material(s) Enrichment Recycled Elements Decay Storage
Proliferation Risk	Material attractiveness of new fuel, SNF, and any products or wastes;	Once- through / Recycle Critical / Sub-critical Neutron Spectrum Fuel Material(s) Decay Storage Enrichment Recycled Elements

Evaluation Criterion	Relevant Fuel Cycle Characteristics	Potential Fuel Cycle Features
Nuclear Material Security Risk	Material attractiveness of new fuel, SNF, and any products or wastes; radioactivity of materials	Once-through / Recycle Critical / Sub-critical Neutron Spectrum Fuel Material(s) Decay Storage Enrichment Recycled Elements
Safety	Ability to safely operate facilities and conduct all operations, including storage and transportation	Once-through / Recycle Critical / Sub-critical Neutron Spectrum Fuel Material(s) Recycled Elements
Financial Risk and Economics	Economic aspects of the fuel cycle, including financial risks such as capital costs, operating costs, and revenue.	Once-through/Recycle Critical / Sub-critical Neutron Spectrum Fuel Material(s) Decay Storage Enrichment Recycled Elements
Environmental Impact	Fuel resources (land disturbance, processing to obtain fuel, greenhouse gas emissions, etc.); disposal resources (land use, environmental risk, etc.);	Once-through / Recycle Neutron Spectrum Fuel Material(s) Enrichment Recycled Elements
Resource Utilization	Percentage of fuel resource used in power production, efficiency of power production	Once-through / Recycle Critical/Sub-critical Neutron Spectrum Fuel Material(s) Enrichment Recycled Elements
Development and Deployment Risk	Current state of technology development, fuel cycle technical viability	Once-through/Recycle Critical / Sub-critical Neutron Spectrum Fuel Material(s) Recycled Elements
Institutional Issues	Compatibility with existing nuclear fuel cycles; availability of industrial infrastructure; etc.	Once-through/Recycle Critical / Sub-critical Neutron Spectrum Fuel Material(s) Recycled Elements

The following Section discusses the fuel cycle features, or physics characteristics, considered in developing the Fuel Cycle Option Groups to encompass and divide the entire range of fuel cycle performance.

B-2. Fuel Cycle Features

In the E&S, a comprehensive set of fuel cycle options is represented by an associated comprehensive set of Fuel Cycle Option Groups. In order to ensure that a comprehensive set of Fuel Cycle Option Groups is considered in the E&S, the features (basic physics characteristics) that determine the performance of a Nuclear Energy System (NES) were identified: the materials going in, how they are used, the materials coming out, what, if anything, is recycled, and what is destined for ultimate disposal. The intent was to include all major aspects of a fuel cycle that may affect the content and disposition of all materials.

Several "discriminators" were considered in dividing the range of fuel cycle performance:

1. Once-through or recycle (Sections B-2.1 and B-2.2)
2. Critical or sub-critical systems (Section B-2.3)
3. Neutron spectrum (Section B-2.4)
4. Nuclear fuel (Section B-2.5)
5. Need for enrichment (Section B-2.6)
6. Recycled elements (Section B-2.7)

The nuclear fuel cycle options considered in this study all primarily use neutron fission to produce heat energy, including the hybrid concepts combining nuclear fusion or spallation neutron sources with neutron fission reactions. Other irradiation approaches have been considered, including the use of non-neutron elementary particles (such as protons, electrons, ions, and photons) to induce nuclear fission and other reactions. These were considered impractical for energy production or material transmutation, as they have low efficiencies and low intensities. Therefore, they were not considered in this study. The purpose of each fuel cycle option is to either produce electricity or provide heat energy for other applications. Each fuel cycle option is either a "once-through" or "recycle" fuel cycle, as discussed in the following, and whether to use recycle or not may affect the high-level Evaluation Criteria in a significant manner. For this reason, the choice of "once-through" or "recycle" is a logical ***first discriminator*** for dividing the range of fuel cycle performance.

The nuclear fuel must be capable of sustaining or contributing to fission power, and typically consists of several kinds of chemical elements and isotopes, all of which can potentially affect the composition of the fuel at discharge:

- Fissile materials – in sufficient amounts capable of sustaining fission in the provided neutron environment
- Fertile materials - can capture neutrons in the provided neutron environment to change into new fissile isotopes, called "breeding" if fissile production is greater than fissile consumption
- Neutron poisons - can capture neutrons without creating fissile materials
- Structural and fuel matrix materials - can absorb neutrons to create activation products, i.e., radioactive isotopes of these elements
- Other light elements such as oxygen, carbon, and nitrogen that may be part of the fuel.

As a result of the neutron fission and capture processes, the fuel content continuously changes during irradiation, accumulating fission products, heavier isotopes, and activation products while consuming fissile materials in the fuel and creating new fissile fuel from fertile material. After sufficient irradiation, dictated by system design and the operating conditions, the fuel is removed ("discharged") at the goal "burnup" (typically indicated by the percentage of fuel consumed or energy produced), containing accumulated fission products, activation products, neutron poisons and any unused fissile and fertile materials.

The content of the discharged fuel may affect many of the Evaluation Criteria, as listed in Table B1, and a useful discrimination for fuel cycle performance is between those fuel cycles that dispose of the irradiated fuel and those that reprocess and reuse material recovered from the irradiated fuel, i.e., “recycle”, potentially recovering any usable materials and altering the content of wastes destined for disposal. In this study, two definitions for the irradiated fuel reflect this difference in disposition (these terms are widely used, but not always with the same meanings; it is important to define each as they are used in this study):

- Spent nuclear fuel (SNF) – intact irradiated fuel that is disposed, with the requirement for long-term isolation from the environment, such as that provided by deep geologic disposal
- Used nuclear fuel (UNF) – irradiated fuel that is reprocessed to recover one or more elements for reuse, with the resulting high-level wastes disposed, with the requirement for long-term isolation from the environment, such as that provided by deep geologic disposal

Note that the same irradiated fuel can be either SNF or UNF depending on its use within the fuel cycle, since the definition depends on the disposition of the irradiated fuel, not on the contents or characteristics. This report also defines processing and recycling possibilities as follows (again, these terms are widely used, but not always with the same meanings; these are the definitions used in this study):

- Post-processing - any treatment of irradiated fuel (fuel that is "post-irradiation") that alters the intact fuel form. Primarily applies to treatment of SNF.
- Reprocessing – any post-processing that uses separations technologies (technology that separates one or more of the chemical elements in UNF, either individually or in groups), e.g., separating gaseous fission products from irradiated fuel, or separating the TRU elements from fission products and uranium, with the intention of recycling one or more elements, and disposing of high-level radioactive waste and low-level radioactive waste, HLW and LLW, respectively.
- Recycle – the action of using one or more of the chemical elements separated in reprocessing UNF as part of new nuclear fuel for reuse in a reactor (critical or sub-critical).

The addition of post-processing to the nuclear fuel cycle creates both high-level and low-level radioactive wastes, but can partly or completely eliminate the need to dispose of any intact SNF. However, it is essential to recognize that even with fuel cycles that use reprocessing and recycle, long-term isolation from the environment such as that provided by deep geologic disposal is always necessary to manage long-lived fission products and other long-lived hazardous isotopes in the HLW, such as actinide losses from reprocessing.

B-2.1 Once-through Fuel Cycles

A “once-through” fuel cycle uses nuclear fuel only once in the nuclear fission system, followed by storage and disposal, as shown by the example in Figure B3. As described above, spent fuel contains unused fissile, fertile and/or fuel matrix materials, fission products, activation products, structural materials, and other chemical elements. The Study Charter states that the purpose of the Nuclear Fuel Cycle Evaluation and Screening is 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, but does not define the current U.S. fuel cycle. For the purposes of this study, the once-through fuel cycle shown in Figure B3 is assumed as the current U.S. fuel cycle.

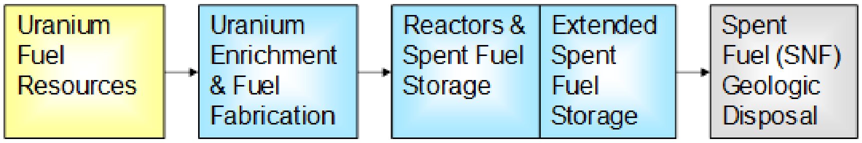

Figure B3. A Once-through Fuel Cycle Example Using Enriched Uranium for New Fuel.

B-2.1.1 Disposal of Spent Fuel

Once-through fuel cycles have disposal of all SNF after discharge from the reactor and following a storage period to allow for decay of shorter-lived radioactive isotopes, which in turn reduces the decay heat and may facilitate handling and disposal. Since all SNF will require long-term isolation from the environment, such as deep geologic disposal that would provide the required isolation from the inhabited environment for the years that the SNF could pose a radiological hazard, disposal usually considers the effects of volume, volumetric heat generation rate, radionuclide content of the SNF, and any other characteristics of the SNF that are relevant to geologic disposal. Fuel cycle features such as neutron energy spectrum and fuel material can affect these characteristics.

B-2.1.2 Processing Prior to Disposal

In principle, any intact SNF can be post-processed for any reason, including waste management purposes, changing the form of the SNF into one or more waste forms for disposal, possibly providing more options for geologic disposal. For a once-through fuel cycle, this would avoid disposal of SNF and substitute disposal of HLW and LLW which may allow the development of waste forms that could provide superior performance in the disposal environments, while also limiting the need for deep geologic disposal to only that part of the spent fuel which poses a radiological hazard requiring such isolation. For example, the shorter-lived isotopes could be separated from the longer-lived ones, since the former affect decay heat issues and the latter affects the risk of exposure for possible releases from the geologic repository. While it is acknowledged that such an approach would add to costs prior to disposal, there may be a potential reduction in disposal cost to offset the effects of post-processing activities. The performance of the nuclear energy system, which includes disposal, may be very different in this case. Such approaches for managing SNF can be applied to any fuel cycle that disposes of SNF, and are viewed in this study as a generic option for such fuel cycles rather than being used as the basis for creating additional Fuel Cycle Option Groups.

B-2.2 Recycle Fuel Cycles

In contrast to the once-through approach, recycle fuel cycles use at least part of the nuclear fuel more than once, as shown by the examples in Figures B4 and B5. Recycle includes reprocessing the UNF, recovering the elements intended for reuse in recycle fuel, fabricating the recycle fuel, and discarding the remainder as waste. There are many variations to a recycle fuel cycle, including recycle back into the same nuclear fission system or recycle into another fission system, and performing the recycle only one or a few times, called “limited recycle” (Figure B4), or recycling indefinitely, called “continuous recycle” (Figure B5). Note that the main difference between limited and continuous recycle is the disposal of SNF with limited recycle. All of the HLW and LLW generated during reprocessing and recycle fuel fabrication must also be disposed. Extended storage is an option at several places in the fuel cycle to allow for decay of shorter-lived isotopes. As noted above, it is important to understand that the recycle back into reactors may use the same reactors or entirely different reactors or nuclear systems, depending on the fuel cycle option. Variations include the elements being recycled (typically one or more actinide elements, and may include some fission products), and the number of different fission systems.

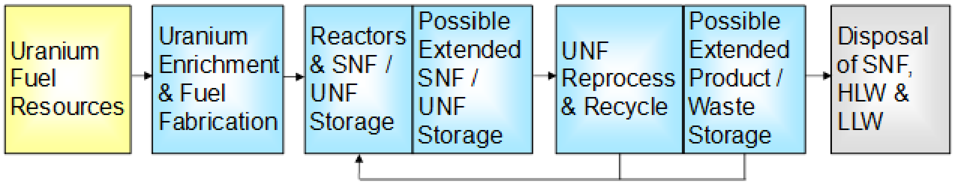

Figure B4. A Limited Recycle Fuel Cycle Example using Enriched Uranium for New Fuel.

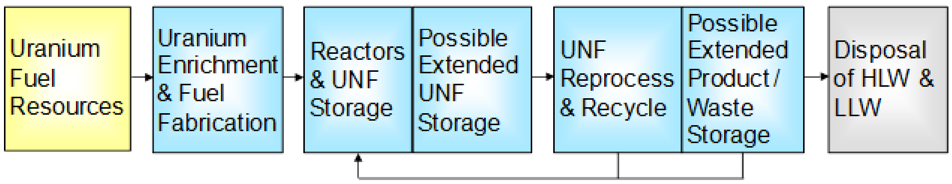

Figure B5. A Continuous Recycle Fuel Cycle Example using Enriched Uranium for New Fuel.

With limited recycle, at some point the irradiated recycle fuel is sent to disposal as SNF. Storage may be used to allow the decay heat of the SNF (and the HLW) to decrease to the desired level prior to placement in repositories, which also alters the content as isotopes decay. Similar to the once-through system, any SNF destined for disposal could be post-processed prior to disposal. This aspect of a fuel cycle can be added to any limited fuel cycle option.

For all recycle fuel cycle options, it is important to note that the content of the HLW from reprocessing includes all of those materials intended for disposal along with processing losses (from reprocessing and recycle fuel fabrication) of elements intended for recycle. The presence of processing losses in HLW means that recycle fuel cycles dispose of all of the same materials as once-through fuel cycles, but the amounts of some materials are greatly reduced since processing losses are typically on the order of 1%.

B-2.3 Critical and Sub-critical Irradiation Environments

Various neutron-based irradiation environments are possible for power production. They include critical reactors that achieve a self-sustaining neutron fission chain reaction, and subcritical reactors that are not able to self-sustain the neutron fission chain reaction, but are driven by neutrons from an external source such as a fusion device or a particle accelerator with a spallation neutron source. The systems can produce power and be an integral part of the electric grid, or be dedicated, non-power producing burners targeted at fissioning specific isotopes to eliminate them from the wastes. Systems that are expected to be sources of power are subject to additional requirements than dedicated burners since they must have sufficient reliability to contribute to, and be integrated with, the electricity grid. The choice of critical or sub-critical system places constraints on other parts of the fuel cycle and may affect many of the resulting fuel cycle characteristics relevant to the high-level criteria, and as a result, this choice is used as the ***second discriminator*** for dividing the range of potential fuel cycle performance.

B-2.3.1 Self-Sustaining Systems (Critical Reactors)

Critical reactor systems have been used for power production and can be used for the transmutation of nuclides. A variety of reactor types (thermal, intermediate or fast spectrum) and fuel materials (uranium-based and/or thorium-based fuels) could be used for both the once-through and recycle strategies, and as a result, numerous systems for once-through, limited and continuous recycle have been proposed in the past. For example, with UNF reprocessing, the transmutation of minor actinides (MA) in recycle fuel becomes an option relative to disposal of MA. All of these variations may have an impact on fuel cycle performance, especially those related to resource utilization and waste management.

The amount of the actinide nuclides destroyed by fission for a given reactor thermal power is the same for all reactor designs, since power production is primarily from the fission process. It is possible to preferentially destroy some nuclides at a higher rate relative to the others by using a different neutron energy spectrum or nuclear fuel composition. For example, plutonium nuclides can be destroyed or utilized for fuels in thermal, intermediate, and fast spectrum reactors. Fundamental physics dictates that fast reactors have more surplus neutrons that can be used for transmutation than thermal reactors, as shown in Figure B6, where the value 'η' represents the number of fission neutrons per absorption. An 'η' value greater than 1 is needed to sustain the chain reaction and values greater than 2 are needed to breed (1 neutron for fission, and 1 neutron for capture). For example, Figure B6 shows that 'η' is higher than 2 in the fast neutron energy range for ^{239}Pu bred from ^{238}U. Figure B6 also shows why ^{233}U bred from thorium may be effectively used with thermal neutrons for breeding while ^{235}U and ^{239}Pu do not breed effectively with thermal neutrons due to the lower value of 'η'.

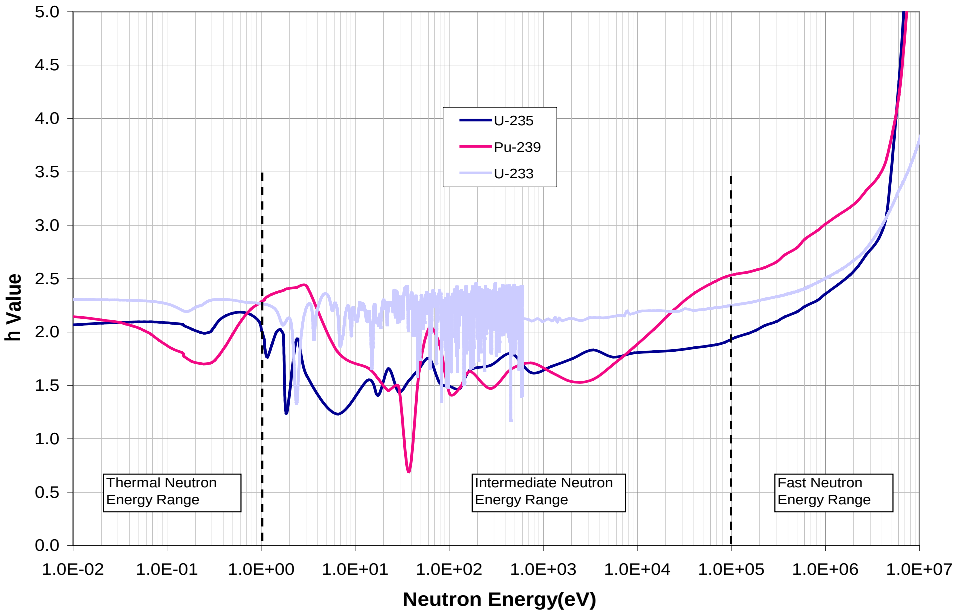

Figure B6. Neutrons Produced from Fission per Neutron Absorbed in Fuel (η).

Fast reactors are more effective for burning of the minor actinides since they have a significantly higher probability of fission versus capture upon neutron absorption as shown in Figure B7, which leads to reduced higher actinide creation in fast neutron spectra. It is important to note the large difference in the fission/absorption ratio for ^{240}Pu, ^{242}Pu, and the americium and curium isotopes, since the much higher fission probability in fast reactors leads to much lower equilibrium content of the higher actinide elements resulting from neutron capture (neutron absorption but not followed by fission). Evaluation of the required neutron consumption for a recycled nuclide, defined as the number of neutrons required to pass from the initial nuclide to a stable nuclide, indicates that it is always possible to have actinide nuclides transmuted into stable lower mass nuclides in a fast spectrum, but is more difficult (i.e. requires more neutrons) in a thermal spectrum due to the stronger competition between neutron capture and fission, as well as poisoning (absorption) by fission products. These effects are typically overcome in a thermal reactor by increasing fuel fissile content.

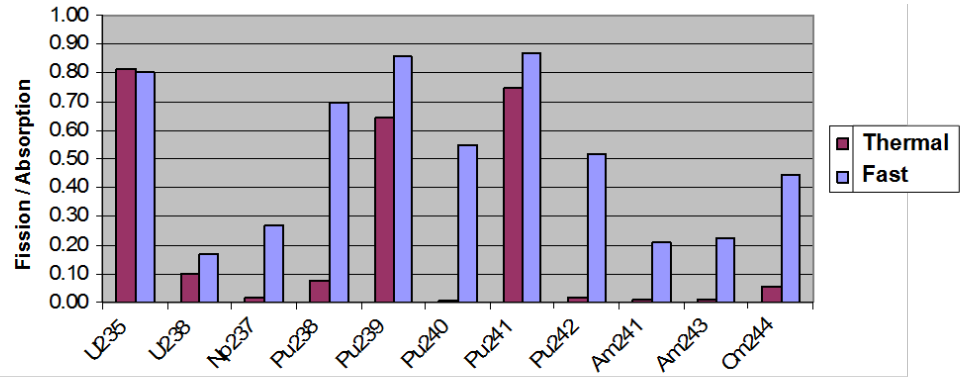

Figure B7. Example Neutron Fission to Absorption Ratio in Thermal and Fast Neutron Spectra.

B-2.3.2 Externally-Driven Systems (Sub-critical Reactors)

The need to self-sustain the nuclear chain reaction could limit the ability of reactors to achieve target burnup since they need sufficient fissile content to maintain criticality. Consequently, the requirement of a self-sustaining nuclear fission reaction has been relaxed for some of the nuclear systems that have been proposed in the past for high burnup of fuel materials or transmutation of wastes, referred to as "sub-critical" reactor systems. This class of systems would require an external neutron source to ensure a sustained neutron reaction. Examples of these externally-driven sub-critical systems include accelerator driven systems (ADS) and fusion-fission hybrids (FFH). These systems have been proposed from nearly the start of the nuclear era, and they have been resurrected in recent times for the claimed purposes of effective material utilization, UNF consumption, and fissile nuclear material production.

In the context of the once-through fuel cycle, these systems typically use an external neutron source device (accelerator-driven spallation neutron or fusion neutron) and significant neutron multiplication in the fission blanket to produce neutrons to drive the high burnup. With limited recycle and continuous recycle, the use of sub-critical systems driven by an external neutron source provides additional options. In most of these proposed systems, the purpose is to improve waste management of the spent fuel from reactors (or combination of reactors) by using such driven systems primarily for waste transmutation. With sufficient external neutron source strength, it may be possible to use a driven system alone with limited recycle and no enrichment needed.

Accelerator Driven Systems

In a typical ADS, charged particles (e.g., protons) from an accelerator are used to generate a neutron source via spallation in a heavy metal target (e.g., tungsten, lead, tantalum, mercury). The nuclides to be irradiated/transmuted are located in a blanket, and the bulk of the total power level and neutrons available for transmutation are produced via the neutron multiplication process in the fission blanket, the same process that occurs in reactors. The spallation neutron target also produces radioactive nuclides and decay heat which must be addressed.

Fusion-Fission Hybrid Systems

In a typical FFH, a fusion device provides the neutron source. Similarly to the ADS, a blanket containing the material to be irradiated / transmuted is employed and used to produce the bulk of the total power level. The neutrons available for transmutation are produced via the neutron multiplication process in the sub-critical fission blanket, just as in critical reactors. Both inertial confinement and magnetic fusion devices are two fusion approaches that have been considered for providing external neutron sources for coupled nuclear systems.

B-2.4 Neutron Spectrum

The kinetic energy of the neutrons in fission systems is very important in determining a number of system characteristics, including fission product distribution, formation of higher actinides including new fissile material, and creation of activation products. All of these characteristics have an impact on one or more of the high-level nuclear energy system criteria, and as a result, differences in neutron energies between fission systems can be a useful grouping approach. For these reasons, choice of neutron spectrum is the ***third discriminator*** for dividing the range of fuel cycle performance.

While the variation in nuclear energy spectrum between different neutron fission systems is in principle a continuum, a grouping can be made based on defining three typical neutron energy spectra. Figure B8 shows the two main classes, which are termed 'thermal' and 'fast', based on the predominant energy of the neutrons causing fission in the system. Also shown is a system with intermediate spectrum that lies between the two prominent groups, and while quite similar to the thermal neutron spectrum, is missing the peak in the thermal neutron energy range. The difference in spectrum is essential to understanding the performance of nuclear reactors and how the highly-radioactive actinide and fission product elements are created and destroyed during the course of irradiation, as the example in Figure B7 demonstrates.

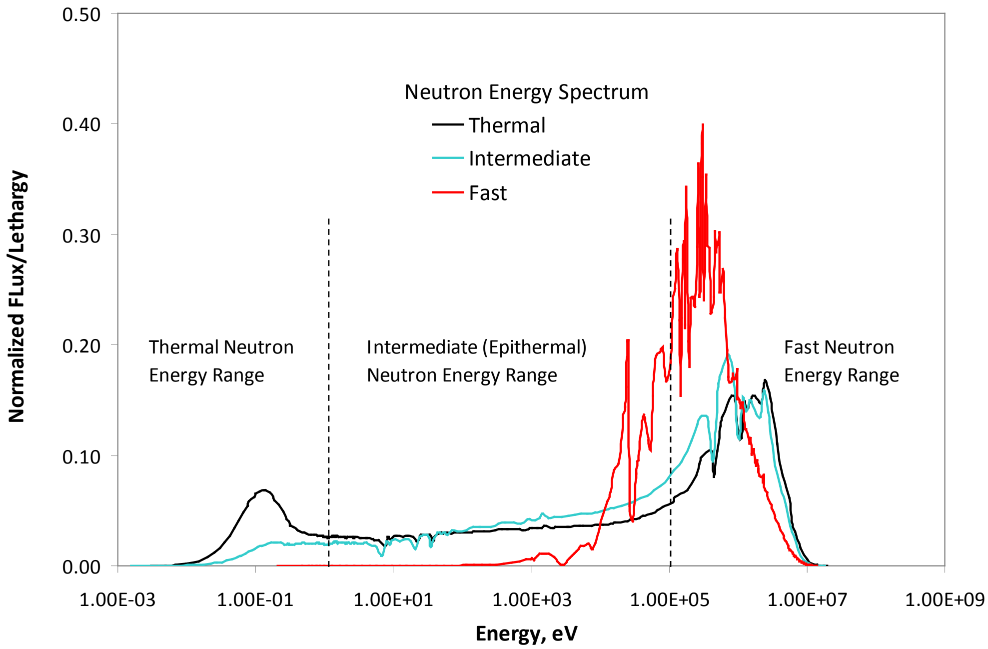

Figure B8. Examples of Neutron Energy Spectra for Thermal, Intermediate, and Fast Neutron Fission Systems.

Actinide transmutation occurs with any neutron energy spectra. A thermal neutron spectrum provides a greater transmutation rate at a given neutron flux due to the generally higher probability of fission or capture for thermal neutrons (higher cross sections). However, a thermal system is more adversely impacted by the neutron capture ("poisoning") effect of fission products, which serve to parasitically capture neutrons that would otherwise be available to transmute the TRU. Therefore, the neutron balance in a thermal spectrum system, which must satisfy criticality requirements, and account for parasitic capture and leakage is such that there are very few excess neutrons available for transmutation of actinides. This is in contrast to the availability of excess neutrons in a fast spectrum system, which allows the inclusion of actinides for transmutation in the fast reactor with less negative impact to the system characteristics. Fast spectrum systems are less affected by fission products, and have a higher flux, which partially compensates for the reduced probability of fission or capture. As discussed above, the relative probabilities of fission and capture are such that the actinides are much more likely to undergo fission rather than capture reactions with fast neutrons as shown in Figure B7.

B-2.4.1 Thermal Neutron Spectrum

Once-through Thermal Systems

Once-through systems require fabrication of nuclear fuel, its use once, and its disposal without recycle. The common attributes include mining of uranium (and/or thorium), fuel fabrication, utilization and disposal as shown in Figure B3. Most once-through systems include uranium enrichment before fuel use and spent fuel storage prior to disposal. The efficiency of uranium (and/or thorium) utilization and the characteristics of the SNF become the primary differentiators in once-through systems. In all once-through systems the SNF contains all the uranium (and/or thorium), plutonium, fission products and minor actinides generated during irradiation, and is typically relied on as the waste form for disposal.

Most current or historic once-through systems use thermal spectrum reactors in which a moderator such as water (as in a PWR), graphite (as in a VHTR) or heavy water (as in a HWR) slow the fission neutrons which are born with an average energy of ~2 MeV to near thermal equilibrium energies of <1 eV. Typical fuel is uranium dioxide enriched to several percent ^{235}U; up to 5% in a PWR and more than 10% in a VHTR. Reactor systems with graphite or D_2O moderators may operate on natural uranium without the need for uranium enrichment due to the more highly moderated neutron spectrum and lower capture in the moderator. The achievable burnup varies directly with the uranium enrichment.

Using thorium in once-through fuel cycles with reactors can only be done along with enriched uranium to provide the self-sustaining nuclear reactions (i.e., fissile material is required) or in externally driven systems that provide additional neutrons. The uranium must be more highly enriched than in a conventional UOX-fuelled system (e.g., 10%-20% instead of <5% in a PWR) to accommodate the higher neutron-absorbing nature of the Th.

Recycle Thermal Systems

Just like in the once-through discussion above, different nuclear systems can be used for recycle. Both limited and continuous recycle can be performed in thermal systems such as LWRs. For example, the LEU-UOX UNF can be reprocessed and the plutonium used to make U/Pu-MOX that is also used to fuel an LWR. This LWR could be the same system in which the plutonium was produced or a different LWR. Options for partial core loading of MOX fuels or full-core loading of MOX fuels have been proposed, but only the former is currently used in commercial reactors. Similarly, innovative concepts using inert matrix fuels have been proposed for deep-burn of actinides in LWRs. Typically, burnup as high as 50-60% has been projected. However, with limited recycle in LWRs, after use the recycle fuel is disposed as SNF.

LWR and other thermal reactor concepts have also been proposed for continuous recycle of plutonium or of all the TRU elements. In this case, the fissile quality of the fuel becomes progressively worse and the fuel radioactivity increases with each recycle, which makes fuel handling (particularly fabrication) difficult and expensive. The use of extended decay storage for LWR UNF (for >30 years) has been proposed to allow radioactivity and decay heat to decrease, facilitating UNF reprocessing and recycle fuel fabrication. The longer decay time reduces the buildup of higher actinide elements with recycle by allowing the curium isotopes to decay. In this case, the ^{241}Pu decays to ^{241}Am in storage, which results in ^{238}Pu through transmutation and decay, instead of using ^{241}Pu in recycle fuel which can transmute into ^{242}Pu and higher Am and Cm isotopes, although the resulting loss of fissile ^{241}Pu and the neutron absorbing nature of ^{241}Am in the recycle fuel also needs to be considered. In order to have a self-sustaining critical system based on multi-recycle of TRU in thermal reactors, it is also necessary to add enriched uranium to the recycle fuel.

Thermal reactor systems using liquid fuels, such as the molten salt reactor, allow the possibility of having the fuel continuously recycled on-line. Coupled systems with a liquid fuel fission blanket and an external neutron source have also been proposed. Thorium based fuels may also be used in limited recycle systems with the creation of fissile ^{233}U.

Continuous recycle systems are designed to achieve the highest possible resource utilization and to produce minimum waste. This could be achieved through nearly complete burnup of fissionable material resulting in just fission products with minimal minor actinides in the HLW stream. Continuous recycle with critical systems can be done with fast reactors to avoid generation of higher actinides, although this constraint may be alleviated with long-term interim storage prior to recycle in thermal reactors. Continuous recycle in thermal systems is typically considered with thorium-based fuels, which have better neutron production characteristics because of the higher ‘η’ for ^{233}U (see Figure B6) and may also result in a reduced generation of higher actinides. These systems require the initial use of a fissile material (typically enriched uranium) as thorium does not contain a fissile nuclide.

B-2.4.2 Intermediate (Epi-thermal) Neutron Spectrum

As shown in Figure B8, the intermediate neutron spectrum, also called “epi-thermal” is different from the thermal neutron spectrum in that it does not have the peak in the thermal neutron energy range, indicating fewer reactions typical of thermal neutrons. The spectrum is quite similar to the thermal spectrum in both the intermediate and fast neutron energy range. As a result, the neutron interactions are a mix of those observed for the thermal and fast neutron spectra. This spectrum is achieved by using less moderation, as in the supercritical water reactor (SCWR) example shown in Figure B8.

B-2.4.3 Fast Neutron Spectrum

Once-through Fast Systems

Fast neutron systems have generally been associated with the recycle fuel cycles due to their capability to breed fissile materials, recovery via reprocessing, and re-use. More recently however, once-through fast reactors have been proposed using naturally-occurring fuel materials (uranium and thorium). In these systems, it is planned to use fuel assemblies containing low enriched uranium fuel and blanket assemblies containing uranium or thorium. The fuel is planned to be irradiated to burnups as high as 30-40%. To achieve high-burnup and the long core residence that are planned, the core power density is derated, thus resulting in larger core sizes than traditional fast reactors. Operated with a conversion ratio near unity, fast reactor systems can achieve burnup limited only by fuel and cladding lifetime.

Recycle Fast Spectrum Systems

Fast reactors can operate on recycled plutonium and/or TRU. Because the fuel cycle operations for the fast reactors have been designed to be done remotely, the additional transmutation of the minor actinides is considered feasible in such systems. Designs for TRU conversion ratio (the ratio of TRU created to that consumed) range from very low (i.e., 0.0 to 0.25), to more traditional values (>0.5). The initial motivation for the low conversion ratio core was to develop designs that could provide nearly the same actinide burning capabilities as the accelerator-driven systems. If effective uranium resource utilization is a primary focus for the fuel cycle, the fast reactors could be run with high fissile conversion ratios (>1.0), ratio of fissile material created to that consumed, for the production of additional fissile material for the overall nuclear system.

B-2.5 Nuclear Fuel

Nuclear fuel is the ***fourth discriminator.*** For fuel cycles operating at steady-state, there are three fuel material choices for nuclear reactors using natural resources: uranium, uranium / thorium, and thorium (assuming in this case that the system breeds sufficient fissile ^{233}U to contribute to fission power). The main differences resulting from the choice of fuel material are in several areas: the ability to utilize resources, the composition of the fission product wastes, and the actinide content after irradiation. A contributing factor is the neutron energy spectrum for fission, since that also affects the fission product and actinide distribution in the irradiated fuel

B-2.5.1 Uranium-Based Fuel Cycles

Uranium-based fuels (natural uranium, which is ^{238}U with about 0.7% ^{235}U, or uranium enriched in ^{235}U) have been utilized or are being considered for most nuclear energy systems under the once-through and recycle strategies. These systems include thermal reactors (e.g., the LWRs), fast reactors, and subcritical systems driven by externally-produced neutron sources, such as in fusion-fission hybrid and accelerator-driven systems. Uranium for fuels can be obtained by a number of methods, including mining and milling of natural uranium ore, in-situ leaching of natural uranium deposits or extracting uranium from seawater. Natural uranium has three isotopes, ^{238}U, the fertile isotope (predominant), and ^{235}U, the fissile isotope and small amounts of ^{234}U. Both natural uranium and enriched uranium fuels have been used for nuclear systems. Besides natural uranium, depleted uranium from the enrichment process and uranium extracted from LWR UNF have been employed or are considered for reactor fuels. Neutron fission of ^{235}U has a characteristic distribution of fission products. At the same time, fuel containing ^{238}U will absorb neutrons creating ^{239}Pu, another fissile isotope, but with a fission product distribution different from that of ^{235}U, and also dependent on neutron energy. The relative amount of ^{235}U and ^{239}Pu fission that has occurred in creating the spent fuel affects the spent fuel content and can potentially affect waste management from the fuel cycle as indicated by the fission product distributions shown in Figures B9-B11.

The ability to create new fissile material is also dependent on neutron energy, as discussed with Figure B6, with a fast neutron spectrum being much more efficient, allowing the development of fast reactors that are either “break-even", i.e., once started, no additional fissile material is needed, or “breeder” reactors, where excess fissile material can be generated to operate other reactors, all based on converting ^{238}U into ^{239}Pu. However, the conversion of ^{238}U to ^{239}Pu is not efficient enough in thermal reactors to allow the development of such systems, although as noted above, the use of ^{238}U in a thermal neutron spectrum does create significant amounts of ^{239}Pu, which is present in the discharged fuel.

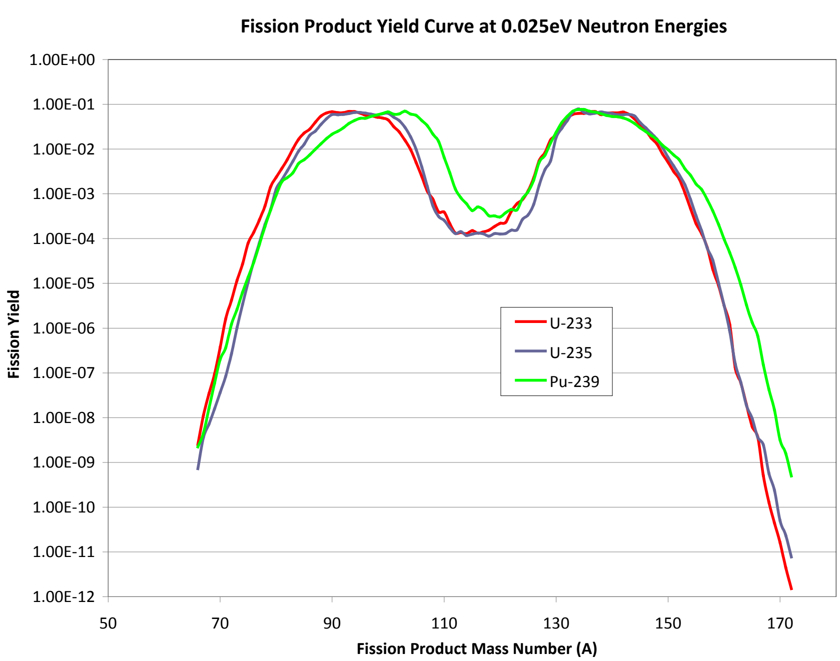

Figure B9. Example Fission Yield for 0.025 eV Neutron Energy.

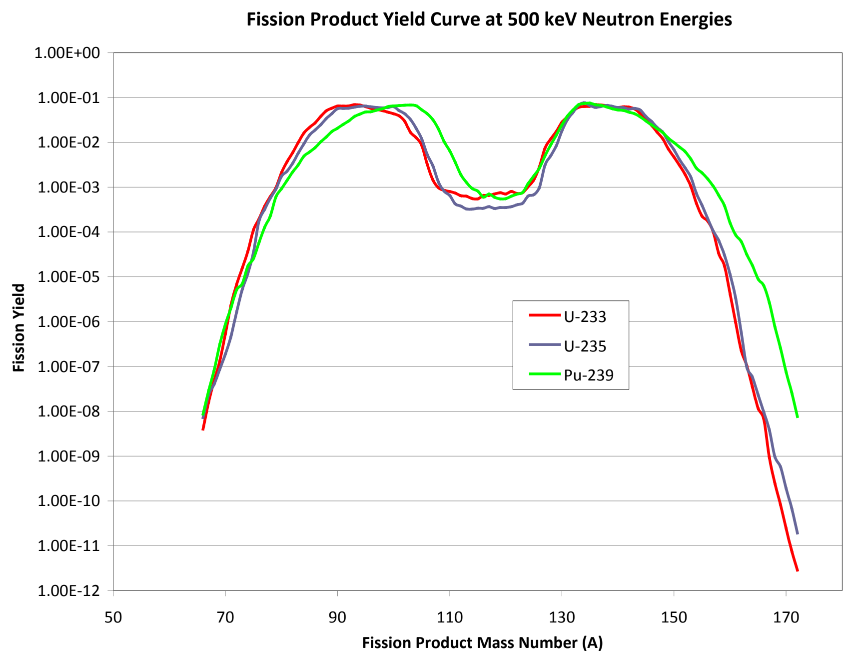

Figure B10. Example Fission Yield for 500 keV Neutron Energy.

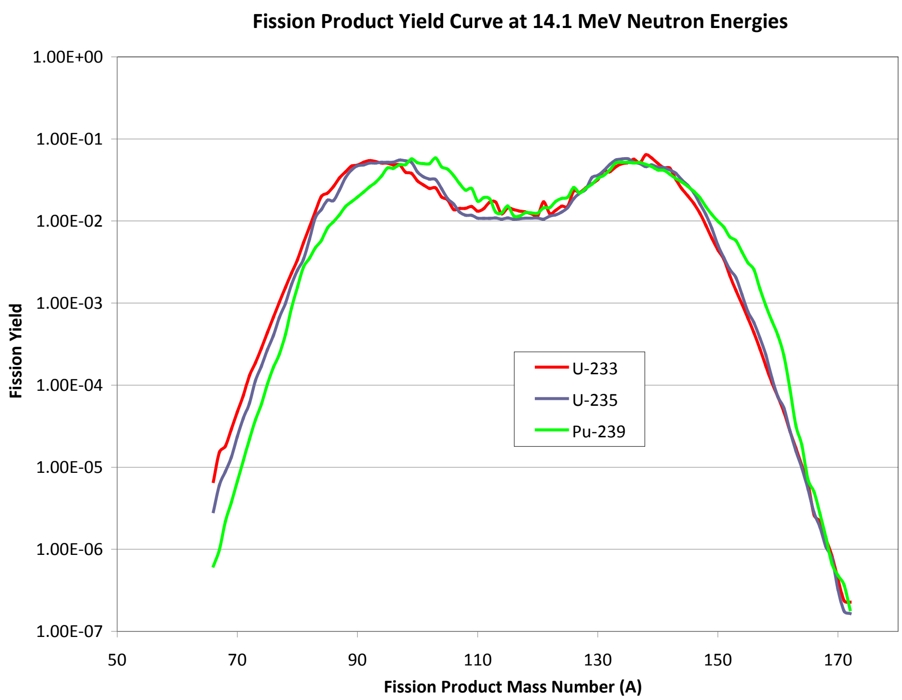

Figure B11. Example Fission Yield for 14 MeV Neutron Energy.

B-2.5.2 Uranium / Thorium-Based Fuel Cycles

Thorium has been considered as an option to uranium-based fuel since the earliest days of the nuclear industry, initially based on considerations of resource utilization (thorium is approximately three to four times more plentiful than uranium), and more recently as a result of concerns about proliferation and waste management (e.g., claims that the high-energy gammas from ^{232}U daughters will make the material less attractive, reduced production of plutonium and higher actinides, improved physical and nuclear properties for potential waste management applications). Since there are no naturally-occurring fissile thorium isotopes, thorium is only useful as a resource for breeding new fissile materials, in this case ^{233}U, which can be done in either thermal or fast systems. Consequently, an isotope such as ^{233}U, ^{235}U, or ^{239}Pu must be present in sufficient quantities for a critical reactor to operate and to allow the excess neutrons to breed more ^{233}U from ^{232}Th.

Thorium can be used in both once-through and recycle options, and in both thermal and fast systems. The thorium-uranium system allows breeding of ^{233}U (breeding ratio greater than unity) in both thermal and fast systems, although the ability to breed in a thermal spectrum generally would require specially designed systems that are different from current commercial LWRs. The production of ^{232}U and its associated decay products accompanying the production of ^{233}U cause radiation hazards in handling. In considering the thorium-based fuel system, it is essential to recognize the need for fissile material such as ^{233}U, enriched uranium, or plutonium to operate the reactor.

As shown in Figures B9-B11, neutron fission of ^{233}U is quite similar to that for ^{235}U for all neutron spectra, but the use of a combination of uranium and thorium means that some ^{239}Pu will still be generated, reducing the differences in fission product content between uranium fueled systems and those fueled with uranium/thorium.

B-2.5.3 Thorium-Based Fuel Cycles

Since thorium does not have any fissile isotopes, use of pure thorium-based fuel cycles requires either ^{233}U from breeding from ^{232}Th or an external source of neutrons. Its main use is for creating fissile ^{233}U from fertile ^{232}Th, and the ^{233}U can be used either in the same system or as a fuel resource for other systems. A major difference is that since no natural uranium is used in such systems, the fission product distribution will be different than for those systems using uranium-based fuel.

With a fissile ^{233}U "breakeven" core design (i.e., producing ^{233}U from ^{232}Th at the same rate as it fissions), a thorium based fuel cycle could be employed for power generation. As discussed above, however, fissile material or an external neutron source would be required initially to sustain the neutron chain reaction prior to the attainment of the breakeven state after sufficient ^{233}U has been created. Such a design is typically considered possible with the use of thorium blankets in a thermal spectrum system, although it may also be used in other systems. This is because of the favorable number of neutrons produced per absorption (η, i.e., eta) with ^{233}U fuel in the thermal spectrum (as shown in Figure B6). Example systems include the thermal breeder experiment in a modified PWR geometry that was demonstrated in the Light Water Breeder Reactor (LWBR) at Shippingport in the late 1970s and early 1980, and the utilization of thorium fuel in a molten salt reactor system.

B-2.6 Enrichment

Whether enrichment is required for the fuel cycle is the ***fifth discriminator***. In a once-through fuel cycle, there is no reprocessing of fuel either during or after irradiation. As a result, the fission product and actinide content of UNF are primarily affected by the fuel material(s) and the discharge burnup, i.e., the extent to which the fuel has been consumed. In order for a nuclear reactor power plant to operate and produce power, the reactor must contain fissionable materials. In the once-through fuel cycle with reactors, there must be a naturally-occurring supply of fissionable (fissile) material for making new nuclear fuel, of which ^{235}U is the only one that occurs in any significant amount in nature. As discussed in the previous section, only uranium or uranium/thorium fuel are usable in the once-through fuel cycle utilizing critical nuclear reactors since thorium by itself is not capable of sustaining a fission chain reaction. In the case where an external source supplies neutrons, in principle one could also start with thorium-only fuel but the plant would not produce power until sufficient ^{233}U has been created in the fuel.

Similarly, natural or depleted uranium-based fuel could be used with an external neutron source but significant power would not be produced until sufficient ^{239}Pu has been created.

It is possible to use natural uranium for new fuel, as in heavy-water- or graphite-moderated reactors, although fuel usage may be inefficient, requiring frequent refueling of the reactor and generating large amounts of irradiated fuel per unit of energy produced. For many reactor technologies, the uranium needs to be enriched in ^{235}U content in order to sustain the nuclear chain reaction. Enrichment allows fuel to be used longer before discharge, thus reducing the quantity of used fuel per unit of energy produced and altering the amounts and proportions of fission products and actinide elements.

A by-product of the uranium enrichment process is the depleted uranium tails that could, if desired, be used again in the enrichment process depending on the ^{235}U content, but in a once-through fuel cycle, depleted uranium would typically be considered a waste stream requiring disposal. Uranium enrichment is generally limited to less than 20% ^{235}U, called low-enriched uranium (LEU), due to proliferation concerns, placing an upper limit on burnup in reactors. Consideration of highly-enriched uranium (HEU) would allow higher burnup. If near-complete burnup of the fuel in reactors for once-through fuel cycles is an objective, then, the system must have very high uranium enrichment (possibly beyond 90%). Such high uranium enrichment may also introduce safety and operational concerns, and the use of HEU is typically not considered for commercial power production. On the other hand, externally-driven subcritical systems, such as the fusion-fission hybrid system, do not require uranium enrichment to achieve high burnup, and are being promoted by the developers for near-complete burnup of the fuel. The system would build in and consume fissile material, but it is not likely that such systems will be able to achieve complete burnup of the fuel in practice due to the long irradiation time that would be required at typical neutron flux levels.

If uranium enrichment is required, gaseous diffusion or gas centrifuge technology is typically used today for this purpose. Laser isotope separation and other advanced enrichment options are being developed. Currently, in the U.S., enriched uranium fuels have also been obtained from the down-blending of weapons-grade highly-enriched uranium to low-enriched uranium for use in commercial reactors.

In considering uranium enrichment, it is important to note that continuous recycle fuel strategies where fissile material is created at the same rate that it is consumed (i.e., fissile breakeven) or at a higher rate, can displace or potentially eliminate the need for enrichment. This is possible in thermal neutron spectra with the ^{232}Th / ^{233}U combination, and in fast reactors with both ^{232}Th / ^{233}U and ^{238}U / ^{239}Pu, with breeding using ^{238}U being much more effective.

In evaluating the importance of fuel resources in a nuclear fuel cycle, it should be recognized that the significant environmental impacts and public health effects from nuclear energy may arise in the front end of the fuel cycle, in particular from the mining and milling of uranium ore to obtain the uranium needed for fuel. It is important to recognize the need for environmental protection of all steps of the nuclear fuel cycle and the potential environmental impacts of alternate fuel cycles, but in particular for uranium mining and milling since the release of uranium daughter products from mines and tailings results in a general dose to workers and the general population that may exceed the impacts from both reactor operations and waste management, for both once-through and recycle approaches.

Although some critical systems (e.g., concepts generically referred to as “breed-and-burn”) can avoid the need for enrichment at equilibrium, enrichment or fissile material with greater fissile content than natural uranium is generally required for initial start-up. Once the reactor is operating, feed material could be natural uranium, depleted uranium, or thorium. The initial start-up requirement for fissile material for successive cores could come from the discharge of earlier cores or other sources of fissile material. In Section B-3, if enrichment is only required for start-up and not at equilibrium, it is denoted with “No*”.

B-2.7 Recycled Elements

While recycle has been discussed in previous sections, the issue of exactly which elements (or their isotopes) are being recycled has not been discussed up to this point. In the past, plutonium recycle has been the major focus of fuel cycle R&D efforts, although significant effort has been expended in the last 15 years on transmutation of all actinides for waste management purposes. It is also possible to divide the TRU group into subgroups, with Pu in one group and the minor actinides in another. For thorium-based fuels, the bred ^{233}U is the major isotope that is recycled. The elements (or their isotopes) that are recycled in the fuel cycle are the ***sixth discriminator***.

A related issue is the potential recycle of fission products. In the thousand- to million-years post-irradiation time period, fission product contribution to the *inhalation and ingestion radiotoxicity level* in spent nuclear fuel is quite small or negligible compared to the contribution of the actinides. However, in fuel cycles in which the actinides are continuously recycled, the contributions can become comparable. When the *radiation dose* at offsite locations to a repository is the measure of acceptability, the relative contributions of the fission products become significant, and fission products can be the leading contributors to the total dose. This is partly because some fission products tend to have a higher mobility than the actinides.

Studies have shown that the *long-term risk* of a geologic repository can be dominated by fission products because of their higher mobility than actinides. Dose contributions arise primarily from ^{129}I, ^{135}Cs, ^{99}Tc, ^{126}Sn and ^{79}Se, their order of importance depending on the repository concept.[B2] The fission product risk peaks in the time range 10,000 to 1,000,000 years after the closure of a repository, whereas the (smaller) actinide risk arises "only" after one million years. Reference B2 identified as the important fission products: ^{99}Tc and ^{237}Np for Yucca Mountain (spent UOX) oxidizing environment; ^{129}I, ^{126}Sn, and ^{229}Th for TILA-99 (spent UOX, reducing environment); ^{79}Se, ^{135}Cs, ^{99}Tc, and ^{231}Pa for Kristallin-I (vitrified HLW in granite); and ^{79}Se, ^{129}I, and ^{229}Th for SAFIR-2 (vitrified HLW in clay).

Consequently, even if a recycle strategy is attractive, the potential of improving on the evaluation and screening metric data by further reducing of the amount of actinides sent as waste to a repository (by reduction in the separation efficiency) might be limited because of the presence of fission products in the waste. This leads to the consideration of fission product transmutation as a potential approach for further reducing the activity and radiotoxicity of the high level waste to improve fuel cycle performance.

Reference B2 indicates that the fission product elements to focus on for potential transmutation should be Cs, Se, I, Zr, Tc, Pd, and Sn. Considerations based on how well the associated isotopes could be transmuted tend to suggest that the only nuclides to consider for transmutation are ^{99}Tc- and ^{129}I. As an example of why some of the other fission products are eliminated for transmutation, consider the case of ^{135}Cs. The element Cs has 3 major isotopes ^{133}Cs (stable), ^{135}Cs (long-lived) and ^{137}Cs (30-yr half life), which makes transmutation of ^{135}Cs difficult because successive neutron capture in ^{133}Cs produces more ^{135}Cs. There is the possibility of isotopic separation to mitigate such effects, but it is quite challenging due to the highly radioactive ^{137}Cs. Neutron balance considerations in the reactor also tend to eliminate the transmutation of Zr and Pd because of the much higher amount of neutrons required to transmute the associated isotopes. The need for additional separations also eliminates ^{107}Pd due to potential expense.

The OECD report [B2] concluded that the transmutation of long-lived fission products could, in principle, be a useful method to mitigate the long-term risk of geologic repositories. However, the practical feasibility of the required processes is less obvious than in the case of the actinides and, so far, has been established only for ^{99}Tc. Reference B2 further concluded that for most potentially troublesome long-lived fission products, including ^{135}Cs, ^{126}Sn, ^{79}Se and possibly also ^{129}I, partitioning followed by special conditioning and confinement in a very stable matrix may remain the only realistic method for reducing their radiological impact. For the purposes of creating the groups of fuel cycles for recycle cases in this study, recycle only considers the actinide elements, but fission product recycle is considered as a generic issue applicable to all recycle fuel cycles and is not used to define the fuel cycle options as discussed in Section B-3.

B-2.8 Further Considerations

In general, there are other fuel cycle characteristics that could distinguish between Fuel Cycle Option Groups as described in the following sections. These characteristics were not used in the Evaluation and Screening study to create additional fuel cycle options since they either did not make differences in the physics-based characteristics of the fuel cycle, they could be treated generically for fuel cycles, or they were outside of the scope of the Nuclear Fuel Cycle Evaluation and Screening.

B-2.8.1 Disposal Environment

Wastes from a nuclear fuel cycle, including highly-radioactive long-lived wastes such as SNF and HLW, require disposal. As discussed in Appendix A, a number of geologic environment options may be possible for the disposal of SNF and HLW that require long-term isolation from the environment. However, in principle, many geologic environments could be used for the development of an acceptable repository that would apply to any once-through or recycle fuel cycle option. Although the SNF and HLW characteristics may influence the design of the repository in each disposal environment, if the repository performs acceptably, by definition the repository contents are adequately managed. As a result, the technology options represented by choices for geologic disposal environments and the corresponding repository designs were not included in this study, consistent with the approach taken to define the other characteristics. The purpose of this study was not to consider specific options for disposal, but does acknowledge that there are multiple options that are applicable to any fuel cycle. This approach allowed disposal to be treated generically for all fuel cycles, and as a result, it was not necessary to consider specific disposal options that would have created additional Fuel Cycle Option Groups.

B-2.8.2 Thermal Efficiency

Thermal efficiency in electricity production is determined by the operating temperatures of the reactor, with higher temperatures resulting in greater efficiency. Higher thermal efficiency results in more efficient fuel utilization, less waste generated per unit of electricity produced, and possibly other effects. With thermal efficiencies typically being about 33% for LWRs, 40% for fast reactors, and almost 50% for Very High Temperature Reactors (VHTRs), there is the potential that such differences may be significant in comparing fuel cycle performance but these are differences arising from specific implementing technologies and are not characteristic of the fuel cycle option itself. For example, both LWRs and VHTRs are thermal reactors, and either could be used in a fuel cycle option that uses thermal spectrum irradiation. For consistency in identifying those differences that are attributable to the fuel cycle option characteristics, a uniform thermal efficiency of 33% was assumed for all power production facilities for this Study as described in Appendix D-1.1.

B-2.8.3 SNF Post-Processing

As discussed above, SNF post-processing could be considered for any fuel cycle that would require disposal of SNF, with the resulting disposal of HLW and LLW replacing disposal of intact SNF, similar to reprocessing. For this study, SNF post-processing was considered as a general issue for all of the fuel cycles disposing of SNF, and any potential for substantial improvement can be determined by considering a single generic specific example rather than creating a large number of fuel cycle options where SNF post-processing is the only difference between fuel cycle options.

B-2.8.4 More than 2 stages in a Fuel Cycle Option

A question arises for identifying fuel cycle options as the entire range of fuel cycle performance is considered, specifically about how many "stages" are necessary for fuel cycle grouping. A "stage" can be considered as a complete nuclear power production system, but many fuel cycle options use more than one irradiation environment, such as thermal and fast. The part of the fuel cycle that uses thermal neutron irradiation is one stage, and the part that uses fast neutron irradiation is the second stage. In principle, there is no limit to the number of stages that one might propose, but the important issue is whether such fuel cycles would have different performance than a comparable fuel cycle with fewer stages. Since the study used only two irradiation environments, thermal and fast spectrum as discussed in Section B-3, many fuel cycles with more than 2 stages have performance that could be represented by a comparable 2 stage system. The following examples that use both thermal and fast reactors illustrate the reasoning for this approach.

Consider the following 3-Stage system: thermal / thermal / fast TRU burner, continuous recycle;

- 1st Stage – thermal critical reactor using LEU-UOX fuel
- 2nd Stage – thermal critical reactor using U/Pu MOX, U/Pu from 1st Stage
- 3rd Stage – fast critical reactor TRU burner, MA from 1st Stage, U/TRU from 2nd and 3rd Stages

Then consider the following 2-Stage system: thermal / fast TRU burner, continuous recycle;

- 1st Stage – thermal critical reactor using both LEU-UOX fuel and U/Pu MOX with U/Pu from LEU-UOX fuel
- 2nd Stage – fast critical reactor TRU burner, U/TRU from 1st and 2nd Stages

The 3-Stage system employs a first thermal critical reactor stage that uses only LEU-UOX fuel, and a 2nd thermal critical reactor stage that only uses U/Pu MOX provided by the first stage. The 2-Stage system has both of these fuels used in the same thermal critical reactor, but with the fuel materials provided in the same manner. The fast critical reactor TRU burner is essentially the same in both cases. Even though these two fuel cycles are structured differently, in terms of fuel cycle performance, they would be considered to be identical, and the 3-Stage system could logically be represented by the appropriate 2-Stage fuel cycle option.

B-3. Identification of a Comprehensive Set of Fuel Cycle Option Groups

For perspective on the relationship of this Study to past similar efforts, Table 1 in the Main Report provides a brief summary of some of the previous studies conducted over the past 40 years. As described in the table, 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 reflects a broad range of issues relevant to the present time, and considers the entire range of potential fuel cycle performance.

In the Evaluation and Screening (E&S), a comprehensive set of fuel cycle options was represented by an associated comprehensive set of *Fuel Cycle Option Groups* (see Figure B2). In order to ensure that a comprehensive set of Fuel Cycle Option Groups was considered in the E&S, the basic physics characteristics related to the fuel material that determine the performance of a Nuclear Energy System (NES) were identified: the fuel materials going in, how they are used, and the waste materials coming out and destined for ultimate disposal. These basic physics characteristics are discussed in Section B-2, and include:

- **Once-through or recycle (limited or continuous)**
  - determines the amount and form of fuel and waste materials that are ultimately disposed
- **Characteristics of the irradiation device**
  - critical reactor and/or externally driven, sub-critical system

- **Neutron spectrum (typically categorized as thermal, intermediate, or fast)**
  - affects neutron balance (e.g., are there sufficient neutrons available to maintain the desired reactions?)
  - affects the amount of fuel material required for criticality (typically the requirement for fissile materials is lower for thermal spectrum systems which can also reduce the level of enrichment needed)
  - ratio of fission-to-capture affects whether a nuclide preferentially fissions (is effectively destroyed, creating fission products) or undergoes successive captures to create heavier isotopes of the same or higher mass number elements
  - affects the distribution of the yield of fission products
  - affects the amount of fertile material converted to fissile (conversion ratio)

- **Choices for the fuel materials used in the irradiation device**
  - fuel materials choices affect the yield of fission and activation products (e.g., the use of thorium will result in a reduced production of higher actinides, but greater production of other isotopes); these include:
    - choice of fissile material(s): principally ^{235}U, ^{239}Pu, ^{241}Pu, ^{233}U
    - choice of fertile material(s): principally ^{238}U, ^{232}Th

- **Whether uranium enrichment is needed**
  - depends on the fuel materials, neutron spectrum, and core design. Breeding of fissile material can be used to displace uranium enrichment
  - affects material feed characteristics and effective utilization

- **Which elements in the fuel are recycled**
  - U (includes ^{233}U bred from Th); Pu; MA; All TRU; Th; FP

- **Treatment of the fuel following discharge from the reactor**
  - use of extended storage prior to disposal or reprocessing
  - any processing of discharged fuel (e.g., limited processing for waste management purposes, reprocessing for recycle of selected elements and segregation from elements destined for disposal, removal of fission products in a Molten Salt Reactor)
  - affects the nature of the material for disposal as well as the material destined for recycle

- **Content and characteristics of final waste forms sent to geologic disposal and the disposal environment**
  - spent fuel contains all discharged radioactive materials in the same form as the irradiated fuel, i.e., the fuel form is unchanged
  - processing can alter the form(s) for storage and disposal
  - with recycle, High-Level Waste (HLW) can be designed to contain a subset of the content of spent fuel, e.g., only those elements requiring geologic isolation
  - separations efficiency determines carryover of recycled elements into wastes
  - many disposal forms, environments and design concepts are possible in principle, with differing abilities for isolating each element–however, the disposal challenge varies more directly with waste streams quantity and characteristics.

Application of these characteristics to the definition of Fuel Cycle Option Groups containing fuel cycle options that would be expected to have similar physics-based performance resulted in the following “hierarchical” structure where each "stage" is an irradiation system with the supporting infrastructure:

Once-Through Hierarchy:

- Reactivity: Critical or Sub-Critical
- Spectrum: Thermal; Intermediate; Fast

- Incoming Feed Fuel Material: U (non-enriched uranium); Th (thorium); U and Th
- Enrichment Required: No; Yes

Single-Stage Recycle Hierarchy:

- Limited or Continuous
- Reactivity: Critical or Sub-Critical
- Spectrum: Thermal; Intermediate; Fast
- Incoming Feed Fuel Material: U; Th; U and Th
- Recycled Elements: U (includes bred ^{233}U); Pu (plutonium); MA (minor actinide); All TRU (trans-uranium or transuranic); Th; FP (fission products)
- Enrichment Required: No; Yes

2-Stage Recycle Hierarchy:

- Limited or Continuous
- Reactivity for Stage 1: Critical or Sub-Critical
- Reactivity for Stage 2: Critical or Sub-Critical
- Spectrum for Stage-1: Thermal; Intermediate; Fast
- Spectrum for Stage-2: Thermal; Intermediate; Fast
- Incoming Feed Fuel Material: U; Th; U and Th
- Recycled Elements: U(includes bred ^{233}U); Pu; MA; All TRU; Th; FP
- Enrichment Required (in at least one stage): No; Yes
- Recycle to Stage-1: No; Yes

Tables B2-B4 show the number of possible groups resulting from all possible permutations of the individual features listed above, i.e., the number in the far right-hand column for each row is obtained by multiplication of the number of individual "elements" in the preceding columns. The resulting groups, which are formed by combinations of elements from each of the columns, encompass the entire range of fuel cycle features that can affect physics-based performance, and is clearly explainable as to the content of the list and the corresponding groups. This structure also makes it easy to place any specific fuel cycle option into the appropriate group based on its fundamental physics characteristics, allowing immediate assessment of the potential performance and identification of any benefits that would be associated with such options.

Table B2. Once-through Fuel Cycle Option Groups Based on Characteristics Affecting Performance.

KEY CHARACTERISTICS							TOTAL GROUPS: Permutation of Columns 1-7
ONCE-THROUGH							
1	2	3	4	5	6	7	
	Reactivity	**Spectrum**	**Incoming Feed Fuel Material**		**Requires Enrichment at Equilibrium**		
	Critical Sub-Critical	Thermal Intermediate Fast	U		No Yes		12
	Critical Sub-Critical	Thermal Intermediate Fast	UTh		No Yes		12
	Critical Sub-Critical	Thermal Intermediate Fast	Th		No		6
			TOTAL - ONCE-THROUGH FUEL CYCLE OPTION GROUPS				**30**

Table B3. Single-Stage Recycle Fuel Cycle Option Groups Based on Characteristics Affecting Performance.

KEY CHARACTERISTICS							TOTAL GROUPS Permutation of Columns 1-7
SINGLE-STAGE RECYCLE							
1	2	3	4	5	6	7	
Limited or Continuous	**Reactivity**	**Spectrum**	**Incoming Feed Fuel Material**	**Recycled Elements**	**Requires Enrichment at Equilibrium**		
Limited Continuous	Critical Sub-Critical	Thermal Intermediate Fast	U	U Pu MA All TRU FP	No Yes		120
Limited Continuous	Critical Sub-Critical	Thermal Intermediate Fast	UTh	U Pu MA All TRU Th FP	No Yes		144
Limited Continuous	Critical Sub-Critical	Thermal Intermediate Fast	Th	U Pu MA All TRU Th FP	No		72
			Total Limited Single-Stage				**168**
			Total Continuous Single-Stage				**168**
			TOTAL - SINGLE-STAGE RECYCLE FUEL CYCLE OPTION GROUPS				**336**

Table B4. Two-Stage Recycle Fuel Cycle Option Groups Based on Characteristics Affecting Performance.

KEY CHARACTERISTICS							TOTAL GROUPS Permutation of Columns 1-7
TWO-STAGE RECYCLE							
1	2	3	4	5	6	7	
Limited or Continuous	**Reactivity by stage**	**Spectrum**	**Incoming Feed Fuel Material**	**Recycled Elements**	**Requires Enrichment at Equilibrium**	**Recycle to Stage 1**	
Limited Continuous	Crit/Crit Crit/SubCrit SubCrit/Crit SubCrit/SubCrit	T – T T – Int. T – F Int. – T Int. – Int. Int. – F F – T F – Int. F – F	U	U Pu MA All TRU FP	No Yes	No Yes	1440
Limited Continuous	Crit/Crit Crit/SubCrit SubCrit/Crit SubCrit/SubCrit	T – T T – Int. T – F Int. – T Int. – Int. Int. – F F – T F – Int. F – F	UTh	U Pu MA All TRU Th FP	No Yes	No Yes	1728
Limited Continuous	Crit/Crit Crit/SubCrit SubCrit/Crit SubCrit/SubCrit	T – T T – Int. T – F Int. – T Int. – Int. Int. – F F – T F – Int. F – F	Th	U Pu MA All TRU Th FP	No	No Yes	864
			Total Limited Two-Stage				2016
			Total Continuous Two-Stage				2016
			TOTAL - TWO-STAGE RECYCLE FUEL CYCLE OPTION GROUPS				**4032**
TOTAL POSSIBLE FUEL CYCLE OPTION GROUPS – 4398 (Includes TOTALS from Tables B2 and B3)							

Note: T = Thermal; Int. = Intermediate; F = Fast; Crit = Critical; SubCrit = Subcritical

Several principles were used in developing Tables B2-B4:

- Some combinations of recycled elements were not used to create fuel cycle options (e.g., U and Pu together) as those combinations would not fundamentally affect the physics-based performance of the nuclear energy systems in the fuel cycle option group. This situation was addressed by recognizing that in general recycled elements are made into either fertile fuel (the matrix material includes U or Th) or non-fertile/inert matrix fuel (the matrix material consists of materials such as zirconium, other non-fertile metals or ceramics) by considering the recycle fuel cycle options as “with-or-without uranium” when appropriate, for example by co-extracting uranium and plutonium.

- As described above, two-stage Fuel Cycle Options Groups were used to represent fuel cycle option groups with two or more stages, since physics characteristics, such as resource utilization, and spent fuel/HLW mass and compositions, of those multi-stage systems can be adequately represented by suitable two-stage systems.
- For multi-stage systems, the recycle of specified elements can be performed in one or several stages to take advantage of spectral characteristics, etc.
- The use of the "equilibrium" assumption is discussed in Appendix A.
- As noted earlier, other irradiation approaches were considered, including the use of non-neutron elementary particles (such as protons, electrons, ions, and photons) to induce nuclear fission and other reactions. These were considered impractical for energy production or material transmutation, as they have low efficiencies and low intensities. Therefore, they were not considered in the present work.

Although the Fuel Cycle Option Groups represented by all combinations of the elements in Tables B2-B4 covered the full range of combinations of characteristics affecting the physics-based performance of fuel cycle options, it was not necessary to include all of these groups for the E&S since some of the groups are physically not possible and were, therefore, not retained as part of the evaluation. For the remaining groups, many of the groups have similar fuel cycle performance, which allowed groups to be combined while retaining the comprehensive nature of the study. It was determined that forty (40) groups were adequate/sufficient to reflect the performance of the 4398 fuel cycle option groups in Tables B2-B4. Section B-4 provides a discussion of how the 4398 groups were combined for the purpose of the E&S.

B-4. Evaluation Groups

Once a comprehensive set of *Fuel Cycle Option Groups* was developed (as shown in Tables B2-B4), a process was used to determine the extent to which the Fuel Cycle Option Groups could be combined based on similarity in physics-based fuel cycle performance relative to the "benefit criteria" (primarily resource utilization, waste management, and environmental impact), including such characteristics as the effects of the irradiation environment, mass flows, compositions, and resource use. As the Fuel Cycle Option Groups were collected into such interim groups, at the end of this stepwise process, successive combination of these interim groups eventually resulted in a final set of groups called *Evaluation Groups*, where each Evaluation Group consists of one or more similar Fuel Cycle Option Groups, as shown on Figure B2. As a result, Evaluation Groups may contain Fuel Cycle Option Groups with a range of overall performance characteristics, and options with lower performance will benefit from being included with better performing options.

Development of the set of Fuel Cycle Option Groups that still retains and reflects the performance of the comprehensive set of fuel cycle options in Tables B2-B4 required several steps, as follows:

Step-1

The first step used a set of physics-based characteristics to develop "rules" that would allow combining Fuel Cycle Option Groups. The results of this assessment included the following considerations:

1. Pu and Pu decay products dominate both resource utilization and waste hazard for all TRU elements. Therefore, minor actinide-only recycle does not significantly alter performance in the absence of recycle of the Pu. However, the performance of MA-only recycle can be obtained by comparing the results for Pu-recycle and TRU-recycle without the need for identifying additional groups. In addition, no distinction was made between situations where the TRU is recycled in a homogeneous fuel (all the TRU elements together) or a heterogeneous fashion (e.g., Pu driver

plus MA targets). Also, options with TRU recycle may involve recycle of Pu and MA in separate irradiation systems, e.g., a reactor and an externally driven system (EDS).

2. Recycle of Pu or TRU in a uranium-based system generally also includes the recycle of uranium in the fabrication of recycle fuel unless non-fertile/inert matrix fuel is used to enhance burnup of the Pu or TRU. Therefore, most of the effects of uranium recycle are reflected in the groups that recycle Pu or TRU without the need for identifying additional groups for uranium–only recycle.

3. Similarly, thorium-only recycle in Fuel Cycle Option Groups using UTh or Th fuel may be possible, but performance is similar to Th-based fuel cycles that recycle U3 (^{233}U predominantly in uranium) in fuel containing recycled Th. Therefore, most of the effects of thorium recycle are reflected in groups that recycle U3 without the need for identifying additional groups for thorium–only recycle.

4. Recycle of Pu/MA/TRU only, in a single-stage Th system, results in essentially similar performance as Th-based systems with no *Pu/MA/TRU only* recycle, since the Pu/MA/TRU content is very low, i.e., there is little effect of such recycle in this case. Consequently, Th Fuel Cycle Option Groups both "with or without" (WOWO) TRU recycle were placed in the same Evaluation Group.

5. The performance of intermediate spectrum systems potentially approaches that of fast spectrum systems, so they were placed in the same Evaluation Group with the corresponding fast spectrum Fuel Cycle Option Groups.

6. Sub-Critical/Sub-Critical two-stage, or indeed any multi-stage Fuel Cycle Option Group based purely on sub-critical components would provide essentially the same performance as the equivalent single-stage sub-critical Fuel Cycle Option Group, and could be in the same Evaluation Group.

7. FP recycle, with disposal of TRU and U (or U3 and Th), and FP losses from separations was handled as a generic issue as described above, applicable to all fuel cycles using recycle of fuel materials and therefore was not explicitly considered in identifying the Fuel Cycle Option Groups.

The items in "red italics" in Tables B5-B7 reflect the application of these "rules." Note that Tables B5-B7 are now aligned using the three fuel cycle types: once-through, limited recycle, and continuous recycle, which is different from the once-through/single-stage/two (multi)-stage organization in Tables B2-B4 that arose from performing permutations on fuel cycle characteristics. The combination of single and multi-stage recycle Fuel Cycle Option Groups into the same Evaluation Group necessitated this change in alignment at this step. The number of groups resulting from this first step of the process allowed a total of 636 Fuel Cycle Option Groups as shown in Tables B5-B7 to represent the performance of the initial 4398 Fuel Cycle Option Groups in Tables B2-B4. Characteristics highlighted in red and italicized were used to combine a Fuel Cycle Option Group having those characteristics with another Fuel Cycle Option Group (with the combination retaining the identity of this Fuel Cycle Option Group).

Table B5. Combined Once-through Groups Resulting from Application of Performance "Rules".

KEY CHARACTERISTICS						**TOTAL GROUPS**
ONCE-THROUGH						
Reactivity	**Spectrum**	**Incoming Feed Fuel Material**		**Requires Enrichment at Equilibrium**		
Critical Sub-Critical	Thermal *Intermediate* Fast	U		No Yes		8
Critical Sub-Critical	Thermal *Intermediate* Fast	UTh		No Yes		8
Critical Sub-Critical	Thermal *Intermediate* Fast	Th		No		4
			TOTAL - COMBINED ONCE-THROUGH FUEL CYCLE OPTION GROUPS			**20**

Table B6. Combined Limited Recycle Groups Resulting from Application of Performance "Rules".

KEY CHARACTERISTICS						**TOTAL GROUPS**
LIMITED RECYCLE						
Reactivity	**Spectrum**	**Incoming Feed Fuel Material**	**Recycled Elements**	**Requires Enrichment at Equilibrium**	**Recycle to Stage 1**	
Critical Sub-Critical	Thermal *Intermediate* Fast	U	*U* Pu *MA* All TRU *FP*	No Yes	NA Single-Stage	16
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	U	*U* Pu *MA* All TRU *FP*	No Yes	No	48
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	U	*U* Pu *MA* All TRU *FP*	No Yes	Yes	48
Critical Sub-Critical	Thermal *Intermediate* Fast	UTh	U Pu *MA* All TRU *Th* *FP*	No Yes	NA Single-Stage	24
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	UTh	U Pu *MA* All TRU *Th* *FP*	No Yes	No	72
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	UTh	U Pu *MA* All TRU *Th* *FP*	No Yes	Yes	72

Critical Sub-Critical	Thermal *Intermediate* Fast	Th	U *Pu* *MA* *All TRU Th* *FP*	No	NA Single-Stage	4
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	Th	U *Pu* *MA* *All TRU* *Th* *FP*	No	No	12
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	Th	U *Pu* *MA* *All TRU* *Th* *FP*	No	Yes	12
			TOTAL - COMBINED LIMITED RECYCLE FUEL CYCLE OPTION GROUPS			**308**

Table B7. Combined Continuous Recycle Groups Resulting from Application of Performance "Rules".

KEY CHARACTERISTICS						**TOTAL GROUPS**
CONTINUOUS RECYCLE						
Reactivity	**Spectrum**	**Incoming Feed Fuel Material**	**Recycled Elements**	**Requires Enrichment at Equilibrium**	**Recycle to Stage 1**	
Critical Sub-Critical	Thermal *Intermediate* Fast	U	*U* Pu *MA* All TRU *FP*	No Yes	NA Single-Stage	16
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	U	*U* Pu *MA* All TRU *FP*	No Yes	No	48
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	U	*U* Pu *MA* All TRU *FP*	No Yes	Yes	48
Critical Sub-Critical	Thermal *Intermediate* Fast	UTh	U Pu *MA* All TRU *Th* *FP*	No Yes	NA Single-Stage	24

Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	UTh	U Pu *MA* All TRU *Th* *FP*	No Yes		72
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	UTh	U Pu *MA* All TRU *Th* *FP*	No Yes	Yes	72
Critical Sub-Critical	Thermal *Intermediate* Fast	Th	U *Pu* *MA* *All TRU* *Th* *FP*	No	NA Single-Stage	4
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	Th	U *Pu* *MA* *All TRU* *Th* *FP*	No	No	12
Crit/Crit Crit/Subcrit Subcrit/Crit *Subcrit/Subcrit*	T – T *T – Int.* T – F *Int. – T* *Int. – Int.* *Int. – F* F – T *F – Int.* F – F	Th	U *Pu* *MA* *All TRU* *Th* *FP*	No	Yes	12
		TOTAL - COMBINED CONTINUOUS RECYCLE FUEL CYCLE OPTION GROUPS				**308**
TOTAL COMBINED FUEL CYCLE GROUPS – 636 (Includes TOTALS from Tables B5 and B6)						

Step-2

In the next step in the process, these combined Fuel Cycle Option Groups were further combined if the fuel cycle performance characteristics of the groups were similar. The three main physics-based Evaluation Criteria are resource utilization, waste management and environmental impact. Subsequent combining of groups to identify Evaluation Groups was based on the following observations or guidelines:

- **Front-End Guidelines:** A fuel resource is needed for a given amount of power generation and fuel cycle option groups can be placed into resource utilization bins reflecting similar performance on this characteristic. Uranium utilization in the current light-water reactor fuel cycle is about 0.6%. When uranium enrichment is used, the depleted uranium is generally considered to be waste. However, in recycle systems or certain once-through breed-and-burn concepts it may be either a waste or a resource depending on how the depleted uranium is used.

Since the E&S is attempting to identify substantial improvements, consideration of the performance potential of the Fuel Cycle Option Groups resulted in thresholds for resource utilization of 3% (beyond what is possible with extensions of current practice) and 30% (requiring substantial internal conversion, or breeding). The following three ranges were used for further combining groups:

- 0-3%
- 3-30%
- 30-100%

No formal calculations were done in developing these ranges and they were applied in the process of combining fuel cycle option groups by the EST based on their judgment. Subsequent reactor physics analyses performed for the Analysis Examples confirmed those judgments.

- **Back-End Guidelines:** All fuel cycles dispose of isotopes that have short half-lives that make handling difficult, and isotopes that have long half-lives that require isolation from the biosphere for very long times. Depending on the characteristics of the fuel cycle (e.g., uranium or thorium, once-through vs. recycle, etc.), only <u>the content of disposed wastes (amount and isotopic distribution) varies</u>. Recycle fuel cycles will always have some losses from processing of elements recovered for recycle as part of the waste. As a result, the nature of disposal issues is still the same, although the amounts may be different. Thorium-based fuel cycles dispose of a different mix of isotopes than uranium-based fuel cycles, but the short-term and long-term hazards from the disposed isotopes are comparable.

  The following general guidelines were used to identify materials that are disposed for various fuel cycle option groups:

  - Once-Through and Limited Recycle – SNF is disposed in both; HLW will also be disposed with limited recycle.
  - Continuous Recycle:
    - Pu or U3 recycle – MA and FP are separated and disposed; losses from Pu or U3 separations are also disposed; separated U and/or Th may be disposed or recycled with the Pu or U3.
    - TRU recycle – FP are separated and disposed; losses from TRU separations are also disposed; separated U and/or Th may be disposed or recycled with the TRU.

– **Amount of Waste Generated**: Fuel Cycle Option Groups were combined based on the reduction in the amount of material that needs to be disposed per unit of energy generation based on one or more orders of magnitude reduction in mass of recycled element from spent fuel as compared to spent fuel discharged from a PWR with a burnup of 50 GWd/MTHM.

Developing a set of Fuel Cycle Option Groups that captured the characteristics and fuel cycle performance of the 636 fuel cycle option groups listed in Tables B5-B7 to serve as *Evaluation Groups* for the E&S required the establishment of such guidelines (discussed above) to allow further combining of the Fuel Cycle Option Groups. The resulting groups have Fuel Cycle Option Groups with different characteristics, such as combining uranium-fueled and uranium-thorium-fueled fuel cycles, or critical and sub-critical systems, in the same group. The Evaluation and Screening Team (EST) applied these concepts to develop this final set of groups, i.e., the Evaluation Groups (EGs) that represented the entire set of fuel cycle options in Tables B2-B4. This resulted in forty (40) Evaluation Groups as follows:

Once-Through Fuel Cycle: 8 Evaluation Groups
Limited Recycle Fuel Cycle: 10 Evaluation Groups
Continuous Recycle Fuel Cycle: 22 Evaluation Groups

These Evaluation Groups were selected to span the range of characteristics that reflect and affect the performance of the fuel cycle options listed in Tables B5-B7. Each EG was also intended to inform on the impact of specific fuel cycle characteristics, e.g., uranium vs. thorium feed, recycle of plutonium vs. TRU, etc.

Step-3

As the final step in the process, recognizing that the E&S would be performed relative to the nine high-level criteria specified in the Charter, an assessment of the forty (40) Evaluation Groups was conducted to ensure that:

- The Evaluations Groups can inform on the high-level Evaluation Criteria for the E&S, especially those related to the "benefit criteria" (nuclear waste management; proliferation risk; nuclear material security risk; safety; environmental impact; resource utilization).
- No Fuel Cycle Option Group was in an Evaluation Group that may cause it to be inadvertently screened out because they were included in an Evaluation Group that may have poorer performance against the physics-based criteria.

Members of the EST as well as other fuel cycle experts associated with the Fuel Cycle Options Campaign examined each Evaluation Group to ensure that these objectives were met.

B-4.1 Table Summary of the Evaluation Groups

In the following, a nomenclature is used to represent/identify individual groups based on the features that reflect physics performance (e.g., reactivity, spectrum, etc.). The resulting "short-hand notation" for the descriptive taxonomy is shown in Table B8, and is summarized below.

Fuel Cycles:
Once-Through = OT
Single-Stage Continuous = SC
Single-Stage Limited = SL
Multi-Stage Continuous = MC
Multi-Stage Limited = ML

Reactivity:
Critical = C
Sub-Critical = S

Spectrum:
Thermal = T
Fast = F

Incoming Feed Fuel Material:
Uranium = U
Uranium and Thorium = UTh
Thorium = Th

Recycled Elements:
Uranium bred from thorium = U3 (primarily ^{233}U)
Plutonium = Pu
Transuranics = TRU

Enrichment Required at Equilibrium:
No = N (if enrichment is only required for startup, N*)
Yes = Y

The forty (40) Evaluation Groups and the combined Fuel Cycle Option Groups from Tables B5-B7 are shown in Tables B9, B10, and B11 for once-through, limited and continuous recycle fuel cycles, respectively. It should be noted that the assignment of individual Fuel Cycle Option Groups to the EGs is not unique and depended to some degree on which criteria/metrics were used in making the assignments. One group in each EG is highlighted in "yellow" and is intended to represent the focus of each EG, i.e., the EG is designed to inform mainly on the highlighted Fuel Cycle Option Group, but is able to inform on the others in the EG since the performance on the physics-based metrics was similar (may not perform as well, but don't perform substantially better). Also shown is a brief summary of the characteristics of the EG (e.g., feed material, spectra, etc.) and the *Analysis Example* (AE) identified for each EG. The AE are generic fuel cycle options that included only the fuel(s) and reactor technology(s), but all other parts of the fuel cycle were still represented at the functional level with no other technologies specified. This specification of technology for the fuels and the irradiation facilities was required to perform the reactor physics analyses (e.g., pressurized water reactor (PWR), sodium fast reactor (SFR), accelerator-driven system (ADS), fusion-fission hybrid (FFH)) to generate quantitative data which were subsequently used to inform on the metric data.

Relative to the Fuel Cycle Option Groups in Tables B5-B7, an additional group was added for Once Through, and only 372 of the 636 combined Fuel Cycle Option Groups need to be individually listed in Tables B9 – B11, as follows:

Once-Through: 21-groups in the second column of Table B9 vs. 20-groups in Table B5. The group in Table B6 identified by (OT-C-T-U-Y) was split into two groups, EG01 and EG02, in what follows with the same descriptive taxonomy. EG01 was identified as a separate, distinct group and contains a single fuel cycle option (the present once-through commercial LWR–represented by a PWR–with disposal of spent nuclear fuel in a geologic repository) and is identified as the **"Basis of Comparison"** for the other EGs in the E&S.

Limited Recycle: 176-groups in the second column of Table B10 vs. 308-groups in Table B6. The 44 single-stage groups are listed, but only 132 of the 264 two-stage groups are listed since the other 132 only differ by whether or not there is recycle to Stage-1 and, therefore, have the same descriptive taxonomy.

Continuous Recycle: 176-groups in the second column of Table B11 vs. 308-groups in Table B7. The 44 single-stage groups are listed, but only 132 of the 264 two-stage groups are listed since they only differ by whether or not there is recycle to Stage-1 and, therefore, have the same descriptive taxonomy.

Overall, because a stand-alone group was created to serve as the Basis of Comparison (thereby increasing the number of once-through groups from 20 to 21), one additional group was added to the 372 groups derived/identified from Tables B5-B7 resulting in a total of 373 listed Fuel Cycle Option Groups in Tables B9-B11.

In the following tables, under the column for Enrichment Required, "No" is sometimes indicated with *. i.e., "No*". This indicates that uranium enrichment is not required at equilibrium, but that uranium enrichment is needed for the initial fuel when starting up the reactor for the first time. Once the reactor has started, the reactor creates sufficient fissile material such that uranium enrichment is not needed for the new fuel.

Also, in describing the reactor for the Analysis Example, the following form is used:
Reactor ([Startup]; Driver; Blanket; Waste), where:

- [Startup] – if fissile fuel material for initial startup is different than at steady-state, it is indicated here
- Waste – indicates only waste requiring geologic disposal; low-level waste (LLW) is also created by all fuel cycles
- Th – natural thorium or recovered Th; RTh may also be used to indicate recovered Th

Table B8. Nomenclature for Descriptive Taxonomy of Fuel Cycle Option Group Identifiers.

	Identifier	A Reactivity	B Spectrum	C Incoming Feed Fuel Material	D Recycled Elements	E Requires Enrichment
Once-Through	OT-A-B-C-E	C=Critical S=Sub-Critical	T=Thermal F=Fast	U UTh Th		N=No (No* if enrichment is only needed for startup) Y=Yes
Single-Stage Continuous	SC-A-B-C-D-E	C=Critical S=Sub-Critical	T=Thermal F=Fast	U UTh Th	U3 Pu TRU	N=No (No* if enrichment is only needed for startup) Y=Yes
Single-Stage Limited	SL-A-B-C-D-E	C=Critical S=Sub-Critical	T=Thermal F=Fast	U UTh Th	U3 Pu TRU	N=No (No* if enrichment is only needed for startup) Y=Yes
Multi-Stage Continuous	MC-A-B-C-D-E	C=Critical S=Sub-Critical C/S=Critical & Sub-Critical S/C=Sub-Critical & Critical	T=Thermal F=Fast T/F=Thermal and Fast F/T=Fast and Thermal	U UTh Th	U3 Pu TRU	N=No (No* if enrichment is only needed for startup) Y=Yes
Multi-Stage Limited	ML-A-B-C-D-E	C=Critical S=Sub-Critical C/S=Critical & Sub-Critical S/C=Sub-Critical & Critical	T=Thermal F=Fast T/F=Thermal and Fast F/T=Fast and Thermal	U UTh Th	U3 Pu TRU	N=No (No* if enrichment is only needed for startup) Y=Yes

Table B9. Grouping and Analysis Examples for Once-Through Fuel Cycles.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Included Fuel Cycle Option Groups From Table B6</th><th colspan="5">Key Characteristics</th><th rowspan="2">Characteristics</th></tr>
<tr><th>Reactivity</th><th>Spectrum</th><th>Feed material</th><th>Recycled element</th><th>Requires Enrich.</th></tr>
<tr><td>Evaluation group EG01</td><td>OT-C-T-U-Y</td><td>Critical</td><td>Thermal</td><td>U</td><td>-</td><td>Yes</td><td>• Natural U feed
• Enriched to <5 w/o U-235
• Critical reactor
• Thermal spectrum
• Resource utilization ~0.6%

Basis for comparison</td></tr>
<tr><td rowspan="2">Analysis Example For EG01</td><td colspan="3">Option description</td><td colspan="4">Once-Through: PWR LEU base case (50 GWd/t burnup)</td></tr>
<tr><td colspan="3">Reactor ([Startup];Driver; Blanket; Waste)</td><td colspan="4">PWR([--]; LEU; --; discharged fuel (DF))</td></tr>
<tr><td rowspan="4">Evaluation group EG02</td><td>OT-C-T-U-Y</td><td>Critical</td><td>Thermal</td><td>U</td><td>-</td><td>Yes</td><td rowspan="4">• Natural U feed
• Enrichments in range 5-20 w/o U-235
• Critical reactors and EDS
• Thermal or fast spectra
• Resource utilization up to 3%</td></tr>
<tr><td>OT-C-F-U-Y</td><td>Critical</td><td>Fast</td><td>U</td><td>-</td><td>Yes</td></tr>
<tr><td>OT-S-T-U-Y</td><td>SubCrit.</td><td>Thermal</td><td>U</td><td>-</td><td>Yes</td></tr>
<tr><td>OT-S-F-U-Y</td><td>SubCrit.</td><td>Fast</td><td>U</td><td>-</td><td>Yes</td></tr>
<tr><td rowspan="2">Analysis Example For EG02</td><td colspan="3">Option description</td><td colspan="4">Once-Through: HTGR (graphite-moderated, He-cooled)</td></tr>
<tr><td colspan="3">Reactor ([Startup];Driver; Blanket; Waste)</td><td colspan="4">HTGR([--]; LEU; --; DF)</td></tr>
<tr><td>Evaluation group EG03</td><td>OT-C-T-U-N</td><td>Critical</td><td>Thermal</td><td>U</td><td></td><td>No</td><td>• Natural U feed
• No Enrichment
• Critical reactors
• Thermal spectra
• Resource utilization up to 3%</td></tr>
<tr><td rowspan="2">Analysis Example For EG03</td><td colspan="3">Option description</td><td colspan="4">Once-Through: HWR with NU</td></tr>
<tr><td colspan="3">Reactor ([Startup];Driver; Blanket; Waste)</td><td colspan="4">HWR([--]; NU; --; DF)</td></tr>
</table>

	Included Fuel Cycle Option Groups From Table B6	Key Characteristics: Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	Characteristics
Evaluation group EG04	OT-C-F-U-N	Critical	Fast	U	-	No*	• Natural U, UTh or Th feed • No Enrichment except for startup • Critical reactors • Fast spectra • Resource utilization between 3 and 30%
	OT-C-F-UTh-N	Critical	Fast	UTh	-	No*	
	OT-C-F-Th-N	Critical	Fast	Th	-	No*	
Analysis Example For EG04	Option description			Once-Through: SFR, with irradiated blanket fuel used as driver fuel			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR ([LEU]; IB; U; DF); IB is intact irradiated blanket used as driver fuel			
Evaluation group EG05	OT-C-T-UTh-Y	Critical	Thermal	UTh	-	Yes	• Natural UTh feed • Enrichment • Critical reactors and EDS • Thermal or fast spectra • Resource utilization up to 3%
	OT-S-T-UTh-Y	SubCrit.	Thermal	UTh	-	Yes	
	OT-C-F-UTh-Y	Critical	Fast	UTh	-	Yes	
	OT-S-F-UTh-Y	SubCrit.	Fast	UTh	-	Yes	
Analysis Example For EG05	Option description			Once-Through: HTGR (graphite-moderated, He-cooled) with LEU and Th fuel			
	Reactor ([Startup];Driver; Blanket; Waste)			HTGR([--]; LEU/Th; --; DF)			
Evaluation group EG06	OT-S-T-Th-N	SubCrit	Thermal	Th	-	No*	• Natural UTh or Th feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Thermal spectra • Resource utilization between 30 and 100% **** analyses of the critical systems have demonstrated that these are not feasible
	OT-S-T-UTh-N	SubCrit.	Thermal	UTh	-	No*	
	OT-C-T-Th-N	Critical.	Thermal	Th	-	No*	
	OT-C-T-UTh-N	Critical	Thermal	UTh	-	No*	
Analysis Example For EG06	Option description			Once-Through: FFH using thorium to create uranium (mainly U-233) in the fuel			
	Reactor ([Startup];Driver; Blanket; Waste)			FFH([LEU]; --; Th; DF)			

	Included Fuel Cycle Option Groups From Table B6	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG07	OT-S-F-U-N	SubCrit.	Fast	U	-	No	• Natural U feed • No Enrichment • EDS • Thermal or Fast spectra • Resource utilization between 30 and 100%
	OT-S-T-U-N	SubCrit.	Thermal	U	-	No	
Analysis Example For EG07	Option description			Once-Through: ADS using uranium to create plutonium (mainly Pu-239) in the fuel			
	Reactor ([Startup];Driver; Blanket; Waste)			ADS([--]; --; NU; DF)			
Evaluation group EG08	OT-S-F-Th-N	SubCrit.	Fast	Th	-	No	• Natural UTh or Th feed • No Enrichment • EDS • Fast spectra • Resource utilization between 30 and 100%
	OT-S-F-UTh-N	SubCrit.	Fast	UTh	-	No	
Analysis Example For EG08	Option description			Once-Through: FFH using thorium to create uranium (mainly U-233) in the fuel			
	Reactor ([Startup];Driver; Blanket; Waste)			FFH([--]; --; Th; DF)			

Table B10. Grouping and Analysis Examples for Limited Recycle Fuel Cycles.

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation group EG09	SL-C-F-U-Pu-N	Critical	Fast	U	Pu	No*	• Natural U, UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and multi-stage • Fast spectra • Limited recycle of Pu or TRU • Resource utilization between 30 and 100%
	SL-C-F-U-TRU-N	Critical	Fast	U	TRU	No*	
	SL-S-F-U-Pu-N	SubCrit.	Fast	U	Pu	No	
	SL-S-F-U-TRU-N	SubCrit.	Fast	U	TRU	No	
	SL-C-F-UTh-Pu-N	Critical	Fast	UTh	Pu	No*	
	SL-C-F-UTh-TRU-N	Critical	Fast	UTh	TRU	No*	
	SL-S-F-UTh-Pu-N	SubCrit.	Fast	UTh	Pu	No	
	SL-S-F-UTh-TRU-N	SubCrit.	Fast	UTh	TRU	No	
	ML-C-F/F-U-Pu-N	Critical	Fast & Fast	U	Pu	No*	
	ML-C/S-F/F-U-Pu-N	Critical & SubCrit.	Fast&Fast	U	Pu	No*	
	ML-S/C-F/F-U-Pu-N	SubCrit. & Critical	Fast&Fast	U	Pu	No*	
	ML-C-F/F-U-TRU-N	Critical	Fast & Fast	U	TRU	No*	
	ML-C/S-F/F-U-TRU-N	Critical & SubCrit.	Fast&Fast	U	TRU	No*	
	ML-S/C-F/F-U-TRU-N	SubCrit. & Critical	Fast&Fast	U	TRU	No*	
	ML-C-F/F-UTh-Pu-N	Critical	Fast & Fast	UTh	Pu	No*	
	ML-C/S-F/F-UTh-Pu-N	Critical & SubCrit.	Fast & Fast	UTh	Pu	No*	
	ML-S/C-F/F-UTh-Pu-N	SubCrit. & Critical	Fast & Fast	UTh	Pu	No*	
	ML-C-F/F-UTh-TRU-N	Critical	Fast & Fast	UTh	TRU	No*	
	ML-C/S-F/F-UTh-TRU-N	Critical & SubCrit.	Fast & Fast	UTh	TRU	No*	
	ML-S/C-F/F-UTh-TRU-N	SubCrit. & Critical	Fast & Fast	UTh	TRU	No*	
Analysis Example For EG09	Option description			Limited Recycle: SFR using uranium with the SFR DF reprocessed to obtain TRU for recycle with uranium			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU]; TRU/RU; NU; DF+HLW)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation group EG10	SL-C-T-UTh-U3-N	Critical	Thermal	UTh	U3 (WOWO TRU)	No*	• Natural UTh, or Th feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and multi-stage • Thermal and/or Fast spectra • Limited recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU. Explicit recycle of Pu or TRU from UTh fueled systems with no enrichment is included with comparable systems fuelled with natural U without enrichment. • Resource utilization between 3 and 30%
	SL-C-F-UTh-U3-N	Critical	Fast	UTh	U3 (WOWO TRU)	No*	
	SL-S-T-UTh-U3-N	SubCrit.	Thermal	UTh	U3 (WOWO TRU)	No	
	SL-S-F-UTh-U3-N	SubCrit.	Fast	UTh	U3 (WOWO TRU)	No	
	SL-C-T-Th-U3-N	Critical	Thermal	Th	U3 (WOWO TRU)	No*	
	SL-C-F-Th-U3-N	Critical	Fast	Th	U3 (WOWO TRU)	No*	
	SL-S-T-Th-U3-N	SubCrit.	Thermal	Th	U3 (WOWO TRU)	No	
	SL-S-F-Th-U3-N	SubCrit.	Fast	Th	U3 (WOWO TRU)	No	
	ML-C-T/T-UTh-U3-N	Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	No*	
	ML-C-T/F-UTh-U3-N	Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	No*	
	ML-C-F/T-UTh-U3-N	Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	No*	
	ML-C-F/F-UTh-U3-N	Critical	Fast & Fast	UTh	U3 (WOWO TRU)	No*	
	ML-C/S-T/T-UTh-U3-N	Critical & SubCrit.	Thermal & Thermal	UTh	U3 (WOWO TRU)	No*	
	ML-C/S-T/F-UTh-U3-N	Critical & SubCrit.	Thermal & Fast	UTh	U3 (WOWO TRU)	No*	
	ML-C/S-F/T-UTh-U3-N	Critical & SubCrit.	Fast & Thermal	UTh	U3 (WOWO TRU)	No*	
	ML-C/S-F/F-UTh-U3-N	Critical & SubCrit.	Fast & Fast	UTh	U3 (WOWO TRU)	No*	
	ML-S/C-T/T-UTh-U3-N	SubCrit. & Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	No*	

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
	ML-S/C-T/F-UTh-U3-N	SubCrit. & Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	No*	
	ML-S/C-F/T-UTh-U3-N	SubCrit. & Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	No*	
	ML-S/C-F/F-UTh-U3-N	SubCrit. & Critical	Fast & Fast	UTh	U3 (WOWO TRU)	No*	
	ML-C-T/T-Th-U3-N	Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	No*	
	ML-C-T/F-Th-U3-N	Critical	Thermal& Fast	Th	U3 (WOWO TRU)	No*	
	ML-C-F/T-Th-U3-N	Critical	Fast & Thermal	Th	U3 (WOWO TRU)	No*	
	ML-C-F/F-Th-U3-N	Critical	Fast & Fast	Th	U3 (WOWO TRU)	No*	
	ML-C/S-T/T-Th-U3-N	Critical & SubCrit.	Thermal & Thermal	Th	U3 (WOWO TRU)	No*	
	ML-C/S-T/F-Th-U3-N	Critical & SubCrit.	Thermal & Fast	Th	U3 (WOWO TRU)	No*	
	ML-C/S-F/T-Th-U3-N	Critical & SubCrit.	Fast & Thermal	Th	U3 (WOWO TRU)	No*	
	ML-C/S-F/F-Th-U3-N	Critical & SubCrit.	Fast & Fast	Th	U3 (WOWO TRU)	No*	
	ML-S/C-T/T-Th-U3-N	SubCrit. & Critical	Thermal & Thermal	Th	U3 (WOWO TRU)	No*	
	ML-S/C-T/F-Th-U3-N	SubCrit. & Critical	Thermal & Fast	Th	U3 (WOWO TRU)	No*	
	ML-S/C-F/T-Th-U3-N	SubCrit. & Critical	Fast & Thermal	Th	U3 (WOWO TRU)	No*	
	ML-S/C-F/F-Th-U3-N	SubCrit. & Critical	Fast & Fast	Th	U3 (WOWO TRU)	No*	
Analysis Example For EG10	Option description			Limited Recycle: MSR using thorium with the MSR DF reprocessed to obtain uranium (mainly U-233) for recycle			
	Reactor ([Startup];Driver; Blanket; Waste)			MSR([LEU]; U3/Th; --; DF+HLW)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation group EG11	SL-C-F-U-Pu-Y	Critical	Fast	U	Pu	Yes	• Natural U, UTh feed • Enrichment • Critical reactors and EDS • Single and multi-stage • Thermal or Fast spectra • Limited recycle of U3 (primarily U-233) bred from Th, and Pu or TRU from U. • Resource utilization up to 3%
	SL-C-F-U-TRU-Y	Critical	Fast	U	TRU	Yes	
	SL-S-F-U-Pu-Y	SubCrit.	Fast	U	Pu	Yes	
	SL-S-F-U-TRU-Y	SubCrit.	Fast	U	TRU	Yes	
	SL-C-F-UTh-U3-Y	Critical	Fast	UTh	U3 (WOWO TRU)	Yes	
	SL-C-F-UTh-Pu-Y	Critical	Fast	UTh	Pu	Yes	
	SL-C-F-UTh-TRU-Y	Critical	Fast	UTh	TRU	Yes	
	SL-S-T-UTh-U3-Y	SubCrit.	Thermal	UTh	U3 (WOWO TRU)	Yes	
	SL-S-T-UTh-Pu-Y	SubCrit.	Thermal	UTh	Pu	Yes	
	SL-S-T-UTh-TRU-Y	SubCrit.	Thermal	UTh	TRU	Yes	
	SL-S-F-UTh-U3-Y	SubCrit.	Fast	UTh	U3 (WOWO TRU)	Yes	
	SL-S-F-UTh-Pu-Y	SubCrit.	Fast	UTh	Pu	Yes	
	SL-S-F-UTh-TRU-Y	SubCrit.	Fast	UTh	TRU	Yes	
	ML-C-F/F-U-Pu-Y	Critical	Fast & Fast	U	Pu	Yes	
	ML-C-F/F-U-TRU-Y	Critical	Fast & Fast	U	TRU	Yes	
	ML-C-F/F-UTh-U3-Y	Critical	Fast & Fast	UTh	U3 (WOWO TRU)	Yes	
Analysis Example For EG11	Option description			Limited Recycle: SFR using LEU fuel, and thorium with the SFR DF reprocessed to obtain uranium (mainly U-233) for recycle			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([--]; LEU/U3/Th; Th; DF+HLW)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation group EG12	SL-C-T-U-Pu-N	Critical	Thermal	U	Pu	No*	• Natural U, UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and multi-stage • Thermal or Thermal and Fast spectra • Limited recycle of Pu or TRU from U • Resource utilization up to 3%
	SL-C-T-U-TRU-N	Critical	Thermal	U	TRU	No*	
	SL-C-T-UTh-Pu-N	Critical	Thermal	UTh	Pu	No*	
	SL-C-T-UTh-TRU-N	Critical	Thermal	UTh	TRU	No*	
	SL-S-T-UTh-Pu-N	SubCrit.	Thermal	UTh	Pu	No	
	SL-S-T-UTh-TRU-N	SubCrit.	Thermal	UTh	TRU	No	
	ML-C-T/T-U-Pu-N	Critical	Thermal & Thermal	U	Pu	No*	
	ML-C-T/T-U-TRU-N	Critical	Thermal & Thermal	U	TRU	No*	
	ML-C/S-T/T-U-Pu-N	Critical & SubCrit.	Thermal & Thermal	U	Pu	No*	
	ML-C/S-T/T-U-TRU-N	Critical & SubCrit.	Thermal & Thermal	U	TRU	No*	
	ML-S/C-T/T-U-Pu-N	SubCrit. & Critical	Thermal & Thermal	U	Pu	No*	
	ML-S/C-T/T-U-TRU-N	SubCrit. & Critical	Thermal & Thermal	U	TRU	No*	
	ML-C-T/T-UTh-Pu-N	Critical	Thermal & Thermal	UTh	Pu	No*	
	ML-C-T/T-UTh-TRU-N	Critical	Thermal & Thermal	UTh	TRU	No*	
	ML-C/S-T/T-UTh-Pu-N	Critical & SubCrit.	Thermal & Thermal	UTh	Pu	No*	
	ML-C/S-T/T-UTh-TRU-N	Critical & SubCrit.	Thermal & Thermal	UTh	TRU	No*	
	ML-S/C-T/T-UTh-Pu-N	SubCrit. & Critical	Thermal & Thermal	UTh	Pu	No*	
	ML-S/C-T/T-UTh-TRU-N	SubCrit. & Critical	Thermal & Thermal	UTh	TRU	No*	
	SL-S-T-U-Pu-N	SubCrit.	Thermal	U	Pu	No	
	SL-S-T-U-TRU-N	SubCrit.	Thermal	U	TRU	No	
	ML-C/S-T/F-U-Pu-N	Critical & SubCrit.	Thermal & Fast	U	Pu	No*	

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
	ML-C/S-F/T-U-Pu-N	Critical & SubCrit.	Fast & Thermal	U	Pu	No*	
	ML-C/S-T/F-U-TRU-N	Critical & SubCrit.	Thermal & Fast	U	TRU	No*	
	ML-C/S-F/T-U-TRU-N	Critical & SubCrit.	Fast & Thermal	U	TRU	No*	
	ML-S/C-T/F-U-Pu-N	SubCrit. & Critical	Thermal & Fast	U	Pu	No	
	ML-S/C-F/T-U-Pu-N	SubCrit. & Critical	Fast & Thermal	U	Pu	No	
	ML-S/C-T/F-U-TRU-N	SubCrit. & Critical	Thermal & Fast	U	TRU	No	
	ML-S/C-F/T-U-TRU-N	SubCrit. & Critical	Fast & Thermal	U	TRU	No	
Analysis Example For EG12	Option description			Limited Recycle: HWRs using uranium with the HWR DF reprocessed to obtain plutonium (mainly Pu-239) for recycle with U into PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			HWR([--]; NU; --; -HLW)→PWR([--]; Pu/RU; --; DF)			

Evaluation group EG13	SL-C-T-U-Pu-Y	Critical	Thermal	U	Pu	Yes	• Natural U feed • Enrichment • Critical reactors and EDS • Single and multi-stage • Thermal spectra • Limited recycle of Pu or TRU • Resource utilization up to 3%
	SL-C-T-U-TRU-Y	Critical	Thermal	U	TRU	Yes	
	ML-C-T/T-U-Pu-Y	Critical	Thermal & Thermal	U	Pu	Yes	
	ML-C-T/T-U-TRU-Y	Critical	Thermal & Thermal	U	TRU	Yes	
	SL-S-T-U-Pu-Y	SubCrit.	Thermal	U	Pu	Yes	
	SL-S-T-U-TRU-Y	SubCrit.	Thermal	U	TRU	Yes	
Analysis Example For EG13	Option description			Limited Recycle: PWRs using LEU fuel with the PWR DF reprocessed to obtain plutonium (mainly Pu-239) for recycle with U into other PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --; HLW)→PWR([--]; Pu/RU; --; DF)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation group EG14	ML-C-T/F-U-Pu-N	Critical	Thermal & Fast	U	Pu	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Multi-stage • Thermal and Fast spectra • Limited recycle of Pu or TRU from U • Resource utilization between 3 and 30%
	ML-C-F/T-U-Pu-N	Critical	Fast & Thermal	U	Pu	No*	
	ML-C-T/F-U-TRU-N	Critical	Thermal & Fast	U	TRU	No*	
	ML-C-F/T-U-TRU-N	Critical	Fast & Thermal	U	TRU	No*	
	ML-C-T/F-UTh-Pu-N	Critical	Thermal & Fast	UTh	Pu	No*	
	ML-C-F/T-UTh-Pu-N	Critical	Fast & Thermal	UTh	Pu	No*	
	ML-C-T/F-UTh-TRU-N	Critical	Thermal & Fast	UTh	TRU	No*	
	ML-C-F/T-UTh-TRU-N	Critical	Fast & Thermal	UTh	TRU	No*	
	ML-C/S-T/F-UTh-Pu-N	Critical & SubCrit.	Thermal & Fast	UTh	Pu	No*	
	ML-C/S-F/T-UTh-Pu-N	Critical & SubCrit.	Fast & Thermal	UTh	Pu	No*	
	ML-C/S-T/F-UTh-TRU-N	Critical & SubCrit.	Thermal & Fast	UTh	TRU	No*	
	ML-C/S-F/T-UTh-TRU-N	Critical & SubCrit.	Fast & Thermal	UTh	TRU	No*	
	ML-S/C-T/F-UTh-Pu-N	SubCrit. & Critical	Thermal & Fast	UTh	Pu	No*	
	ML-S/C-F/T-UTh-Pu-N	SubCrit. & Critical	Fast & Thermal	UTh	Pu	No*	
	ML-S/C-T/F-UTh-TRU-N	SubCrit. & Critical	Thermal & Fast	UTh	TRU	No*	
	ML-S/C-F/T-UTh-TRU-N	SubCrit. & Critical	Fast & Thermal	UTh	TRU	No*	
Analysis Example For EG14	Option description			Limited Recycle: SFRs using uranium fuel with the SFR DF reprocessed to obtain plutonium (mainly Pu-239) for recycle with U in the SFRs and into the PWRs.			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU]; Pu/RU; NU; -HLW) →PWR([--]; Pu /RU; --; DF)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation group EG15	ML-C-T/F-U-Pu-Y	Critical	Thermal & Fast	U	Pu	Yes	• Natural U feed • Enrichment • Critical reactors • Multi-stage • Thermal and Fast spectra • Limited recycle of Pu or TRU • Resource utilization up to 3%
	ML-C-F/T-U-Pu-Y	Critical	Fast & Thermal	U	Pu	Yes	
	ML-C-T/F-U-TRU-Y	Critical	Thermal & Fast	U	TRU	Yes	
	ML-C-F/T-U-TRU-Y	Critical	Fast & Thermal	U	TRU	Yes	
Analysis Example For EG15	Option description			Limited Recycle: PWRs using LEU fuel, with the PWR DF reprocessed to obtain plutonium (mainly Pu-239) for recycle with U into SFRs			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --; HLW)→SFR([--]; Pu/RU; RU; DF)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation Group EG16	ML-C/S-T/T-U-Pu-Y	Critical & SubCrit.	Thermal & Thermal	U	Pu	Yes	• Natural U feed • Enrichment • Critical reactors and EDS • Multi-stage • Thermal and/or Fast spectra • Limited recycle of Pu or TRU • Resource utilization up to 3%
	ML-C/S-T/T-U-TRU-Y	Critical & SubCrit.	Thermal & Thermal	U	TRU	Yes	
	ML-S/C-T/T-U-Pu-Y	SubCrit. & Critical	Thermal & Thermal	U	Pu	Yes	
	ML-S/C-T/T-U-TRU-Y	SubCrit. & Critical	Thermal & Thermal	U	TRU	Yes	
	ML-C/S-F/F-U-Pu-Y	Critical & SubCrit.	Fast & Fast	U	Pu	Yes	
	ML-C/S-F/F-U-TRU-Y	Critical & SubCrit.	Fast & Fast	U	TRU	Yes	
	ML-S/C-F/F-U-Pu-Y	SubCrit. & Critical	Fast & Fast	U	Pu	Yes	
	ML-S/C-F/F-U-TRU-Y	SubCrit. & Critical	Fast & Fast	U	TRU	Yes	
	ML-C/S-T/F-U-Pu-Y	Critical & SubCrit.	Thermal & Fast	U	Pu	Yes	
	ML-C/S-F/T-U-Pu-Y	Critical & SubCrit.	Fast & Thermal	U	Pu	Yes	
	ML-C/S-T/F-U-TRU-Y	Critical & SubCrit.	Thermal & Fast	U	TRU	Yes	
	ML-C/S-F/T-U-TRU-Y	Critical & SubCrit.	Fast & Thermal	U	TRU	Yes	
	ML-S/C-T/F-U-Pu-Y	SubCrit. & Critical	Thermal & Fast	U	Pu	Yes	
	ML-S/C-F/T-U-Pu-Y	SubCrit. & Critical	Fast & Thermal	U	Pu	Yes	
	ML-S/C-T/F-U-TRU-Y	SubCrit. & Critical	Thermal & Fast	U	TRU	Yes	
	ML-S/C-F/T-U-TRU-Y	SubCrit. & Critical	Fast & Thermal	U	TRU	Yes	
Analysis Example For EG16	Option description			Limited Recycle: PWRs using LEU fuel, with the PWR DF reprocessed to obtain plutonium (mainly Pu-239) for recycle into ADSs			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --; HLW) → ADS([--]; Pu/IMF; --; DF)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	**Spectrum**	**Feed Material**	**Recycled Element**	**Requires Enrichment**	
Evaluation Group EG17	SL-C-T-UTh-Pu-Y	Critical	Thermal	UTh	Pu	Yes	• Natural UTh feed • Enrichment • Critical reactors and EDS • Single and Multi-stage • Thermal and/or Fast spectra • Limited recycle of Pu or TRU from U • Resource utilization up to 3%
	SL-C-T-UTh-TRU-Y	Critical	Thermal	UTh	TRU	Yes	
	ML-C-T/T-UTh-Pu-Y	Critical	Thermal & Thermal	UTh	Pu	Yes	
	ML-C-T/F-UTh-Pu-Y	Critical	Thermal & Fast	UTh	Pu	Yes	
	ML-C-F/T-UTh-Pu-Y	Critical	Fast & Thermal	UTh	Pu	Yes	
	ML-C-F/F-UTh-Pu-Y	Critical	Fast & Fast	UTh	Pu	Yes	
	ML-C-T/T-UTh-TRU-Y	Critical	Thermal & Thermal	UTh	TRU	Yes	
	ML-C-T/F-UTh-TRU-Y	Critical	Thermal & Fast	UTh	TRU	Yes	
	ML-C-F/T-UTh-TRU-Y	Critical	Fast & Thermal	UTh	TRU	Yes	
	ML-C-F/F-UTh-TRU-Y	Critical	Fast &Fast	UTh	TRU	Yes	
	ML-C/S-T/T-UTh-Pu-Y	Critical & SubCrit.	Thermal & Thermal	UTh	Pu	Yes	
	ML-C/S-T/F-UTh-Pu-Y	Critical & SubCrit.	Thermal & Fast	UTh	Pu	Yes	
	ML-C/S-F/T-UTh-Pu-Y	Critical & SubCrit.	Fast & Thermal	UTh	Pu	Yes	
	ML-C/S-F/F-UTh-Pu-Y	Critical & SubCrit.	Fast & Fast	UTh	Pu	Yes	
	ML-C/S-T/T-UTh-TRU-Y	Critical & SubCrit.	Thermal & Thermal	UTh	TRU	Yes	
	ML-C/S-T/F-UTh-TRU-Y	Critical & SubCrit.	Thermal & Fast	UTh	TRU	Yes	
	ML-C/S-F/T-UTh-TRU-Y	Critical & SubCrit.	Fast & Thermal	UTh	TRU	Yes	

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
	ML-C/S-F/F-UTh-TRU-Y	Critical & SubCrit.	Fast & Fast	UTh	TRU	Yes	
	ML-S/C-T/T-UTh-Pu-Y	SubCrit. & Critical	Thermal & Thermal	UTh	Pu	Yes	
	ML-S/C-T/F-UTh-Pu-Y	SubCrit. & Critical	Thermal & Fast	UTh	Pu	Yes	
	ML-S/C-F/T-UTh-Pu-Y	SubCrit. & Critical	Fast & Thermal	UTh	Pu	Yes	
	ML-S/C-F/F-UTh-Pu-Y	SubCrit. & Critical	Fast & Fast	UTh	Pu	Yes	
	ML-S/C-T/T-UTh-TRU-Y	SubCrit. & Critical	Thermal & Thermal	UTh	TRU	Yes	
	ML-S/C-T/F-UTh-TRU-Y	SubCrit. & Critical	Thermal & Fast	UTh	TRU	Yes	
	ML-S/C-F/T-UTh-TRU-Y	SubCrit. & Critical	Fast & Thermal	UTh	TRU	Yes	
	ML-S/C-F/F-UTh-TRU-Y	SubCrit. & Critical	Fast & Fast	UTh	TRU	Yes	
Analysis Example For EG17	Option description			Limited Recycle: PWRs using LEU fuel, with the PWR DF reprocessed to obtain Pu (mainly Pu-239) for recycle into PWRs using thorium fuel			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --;HLW) → PWR([--]; Pu/Th; --; DF)			

	Included Fuel Cycle Option Groups From Table B7	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed Material	Recycled Element	Requires Enrichment	
Evaluation group EG18	SL-C-T-UTh-U3-Y	Critical	Thermal	UTh	U3 (WOWO TRU)	Yes	• Natural UTh feed • Enrichment • Critical reactors and EDS • Single and Multi-stage • Thermal and/or Fast spectra • Limited recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU. Explicit recycle of Pu or TRU from UTh with enrichment is included with the comparable systems fuelled with enriched U (i.e., EG17). • Resource utilization up to 3%
	ML-C-T/T-UTh-U3-Y	Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	Yes	
	ML-C-T/F-UTh-U3-Y	Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	Yes	
	ML-C-F/T-UTh-U3-Y	Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	Yes	
	ML-C/S-T/T-UTh-U3-Y	Critical & SubCrit.	Thermal & Thermal	UTh	U3 (WOWO TRU)	Yes	
	ML-C/S-T/F-UTh-U3-Y	Critical & SubCrit.	Thermal & Fast	UTh	U3 (WOWO TRU)	Yes	
	ML-C/S-F/T-UTh-U3-Y	Critical & SubCrit.	Fast & Thermal	UTh	U3 (WOWO TRU)	Yes	
	ML-S/C-T/T-UTh-U3-Y	SubCrit. & Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	Yes	
	ML-S/C-T/F-UTh-U3-Y	SubCrit. & Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	Yes	
	ML-S/C-F/T-UTh-U3-Y	SubCrit. & Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	Yes	
	ML-C/S-F/F-UTh-U3-Y	Critical & SubCrit.	Fast & Fast	UTh	U3 (WOWO TRU)	Yes	
	ML-S/C-F/F-UTh-U3-Y	SubCrit. & Critical	Fast & Fast	UTh	U3 (WOWO TRU)	Yes	
Analysis Example For EG18	Option description		PWRs using LEU and thorium fuel, with the PWR DF reprocessed to obtain uranium (mainly U-233) for recycle into PWRs using thorium fuel				
	Reactor ([Startup];Driver; Blanket; Waste)		PWR([--]; LEU/Th;--; HLW) → PWR([--]; U3/Th/RU; --; DF)				

Table B11. Grouping and Analysis Examples for Continuous Recycle Fuel Cycles.

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG19	SC-C-T-U-Pu-N	Critical	Thermal	U	Pu	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and Multi-stage • Thermal spectra • Continuous recycle of Pu from U. • Resource utilization up to 3%
	SC-S-T-U-Pu-N	SubCrit.	Thermal	U	Pu	No	
	MC-C-T/T-U-Pu-N	Critical	Thermal & Thermal	U	Pu	No*	
	SC-C-T-UTh-Pu-N	Critical	Thermal	UTh	Pu	No*	
	SC-S-T-UTh-Pu-N	SubCrit.	Thermal	UTh	Pu	No	
	MC-C-T/T-UTh-Pu-N	Critical	Thermal & Thermal	UTh	Pu	No*	
Analysis Example For EG19	Option description		Continuous Recycle: HWRs using uranium fuel with recycle of Pu and U				
	Reactor ([Startup];Driver; Blanket; Waste)		HWR([NU]; Pu/NU/RU; --; HLW)				
Evaluation group EG20	SC-C-T-U-TRU-N	Critical	Thermal	U	TRU	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and Multi-stage • Thermal spectra • Continuous recycle of TRU from U. • Resource utilization up to 3%
	SC-S-T-U-TRU-N	SubCrit.	Thermal	U	TRU	No	
	MC-C-T/T-U-TRU-N	Critical	Thermal & Thermal	U	TRU	No*	
	SC-C-T-UTh-TRU-N	Critical	Thermal	UTh	TRU	No*	
	SC-S-T-UTh-TRU-N	SubCrit.	Thermal	UTh	TRU	No	
	MC-C-T/T-UTh-TRU-N	Critical	Thermal & Thermal	UTh	TRU	No*	
Analysis Example For EG20	Option description		Continuous Recycle: HWRs using uranium fuel with recycle of TRU and U				
	Reactor ([Startup];Driver; Blanket; Waste)		HWR([NU]; TRU/NU/RU; --; HLW)				

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG21	SC-C-T-U-Pu-Y	Critical	Thermal	U	Pu	Yes	• Natural U feed • Enrichment • Critical reactors and EDS • Single and Multi-stage • Thermal spectra • Continuous recycle of Pu. • Resource utilization up to 3%
	SC-S-T-U-Pu-Y	SubCrit.	Thermal	U	Pu	Yes	
	MC-C-T/T-U-Pu-Y	Critical	Thermal & Thermal	U	Pu	Yes	
Analysis Example For EG21	Option description			Continuous Recycle: PWR using LEU with recycle of Pu and U			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU/Pu/RU; --;HLW)			
Evaluation group EG22	SC-C-T-U-TRU-Y	Critical	Thermal	U	TRU	Yes	• Natural U feed • Enrichment • Critical reactors and EDS • Single and Multi-stage • Thermal spectra • Continuous recycle of TRU. • Resource utilization up to 3%
	SC-S-T-U-TRU-Y	SubCrit.	Thermal	U	TRU	Yes	
	MC-C-T/T-U-TRU-Y	Critical	Thermal & Thermal	U	TRU	Yes	
Analysis Example For EG22	Option description			Continuous Recycle: PWR using LEU with recycle of TRU and U			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU/TRU/RU; --;HLW)			
Evaluation group EG23	SC-C-F-U-Pu-N	Critical	Fast	U	Pu	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and Multi-stage • Fast spectra • Continuous recycle of Pu from U. • Resource utilization between 30% and 100%
	SC-S-F-U-Pu-N	SubCrit.	Fast	U	Pu	No	
	MC-C-F/F-U-Pu-N	Critical	Fast & Fast	U	Pu	No*	
	SC-C-F-UTh-Pu-N	Critical	Fast	UTh	Pu	No*	
	SC-S-F-UTh-Pu-N	SubCrit.	Fast	UTh	Pu	No	
	MC-C-F/F-UTh-Pu-N	Critical	Fast & Fast	UTh	Pu	No*	
Analysis Example For EG23	Option description			Continuous Recycle: SFR using uranium fuel with recycle of Pu and U			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU]; Pu/RU; NU/RU; HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG24	SC-C-F-U-TRU-N	Critical	Fast	U	TRU	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and Multi-stage • Fast spectra • Continuous recycle of TRU from U. • Resource utilization between 30% and 100%
	SC-S-F-U-TRU-N	SubCrit.	Fast	U	TRU	No	
	MC-C-F/F-U-TRU-N	Critical	Fast & Fast	U	TRU	No*	
	SC-C-F-UTh-TRU-N	Critical	Fast	UTh	TRU	No*	
	SC-S-F-UTh-TRU-N	SubCrit.	Fast	UTh	TRU	No	
	MC-C-F/F-UTh-TRU-N	Critical	Fast & Fast	UTh	TRU	No*	
Analysis Example For EG24	Option description			Continuous Recycle: SFR using uranium fuel with recycle of TRU and U			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU]; TRU/RU;-- -; HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG25	SC-C-T-UTh-U3-Y	Critical	Thermal	UTh	U3 (WOWO TRU)	Yes	• Natural UTh feed • Enrichment • Critical reactors and EDS • Single and Multi-stage • Thermal spectra • Continuous recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU, and continuous recycle of Pu or TRU from U. • Resource utilization up to 3%
	SC-C-T-UTh-Pu-Y	Critical	Thermal	UTh	Pu	Yes	
	SC-C-T-UTh-TRU-Y	Critical	Thermal	UTh	TRU	Yes	
	SC-S-T-UTh-U3-Y	SubCrit.	Thermal	UTh	U3 (WOWO TRU)	Yes	
	SC-S-T-UTh-Pu-Y	SubCrit.	Thermal	UTh	Pu	Yes	
	SC-S-T-UTh-TRU-Y	SubCrit.	Thermal	UTh	TRU	Yes	
	MC-C-T/T-UTh-U3-Y	Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	Yes	
	MC-C-T/T-UTh-Pu-Y	Critical	Thermal & Thermal	UTh	Pu	Yes	
	MC-C-T/T-UTh-TRU-Y	Critical	Thermal & Thermal	UTh	TRU	Yes	
Analysis Example For EG25	Option description			Continuous Recycle: PWR using LEU and Th with recycle of uranium (recovered from LEU and mainly U-233 from Th), Th, and TRU			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU/TRU/RU; U3/Th;HLW)			

<table>
<tr><th rowspan="2"></th><th rowspan="2">Included Fuel Cycle Option Groups From Table B8</th><th colspan="5">Key Characteristics</th><th rowspan="2">Characteristics</th></tr>
<tr><th>Reactivity</th><th>Spectrum</th><th>Feed material</th><th>Recycled element</th><th>Requires Enrich.</th></tr>
<tr><td rowspan="6">Evaluation group EG26</td><td>SC-C-T-UTh-U3-N</td><td>Critical</td><td>Thermal</td><td>UTh</td><td>U3 (WOWO TRU)</td><td>No*</td><td rowspan="6">Natural UTh or Th feed
No Enrichment (enrichment may be required for startup of critical; may be used for subcrit)
Critical reactors and EDS
Single and Multi-stage
Thermal spectra
Continuous recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU.
Resource utilization between 30% and 100%</td></tr>
<tr><td>SC-S-T-UTh-U3-N</td><td>SubCrit.</td><td>Thermal</td><td>UTh</td><td>U3 (WOWO TRU)</td><td>No</td></tr>
<tr><td>SC-C-T-Th-U3-N</td><td>Critical</td><td>Thermal</td><td>Th</td><td>U3 (WOWO TRU)</td><td>No*</td></tr>
<tr><td>SC-S-T-Th-U3-N</td><td>SubCrit.</td><td>Thermal</td><td>Th</td><td>U3 (WOWO TRU)</td><td>No</td></tr>
<tr><td>MC-C-T/T-UTh-U3-N</td><td>Critical</td><td>Thermal & Thermal</td><td>UTh</td><td>U3 (WOWO TRU)</td><td>No*</td></tr>
<tr><td>MC-C-T/T-Th-U3-N</td><td>Critical</td><td>Thermal & Thermal</td><td>Th</td><td>U3 (WOWO TRU)</td><td>No*</td></tr>
<tr><td rowspan="2">Analysis Example For EG26</td><td colspan="3">Option description</td><td colspan="4">Continuous Recycle: MSR using uranium (mainly U-233), thorium, and TRU with recycle</td></tr>
<tr><td colspan="3">Reactor ([Startup];Driver; Blanket; Waste)</td><td colspan="4">MSR([LEU]; U3/Th/TRU; --; HLW)</td></tr>
</table>

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG27	SC-C-F-UTh-U3-Y	Critical	Fast	UTh	U3 (WOWO TRU)	Yes	• Natural U or UTh feed • Enrichment • Critical reactors and EDS • Single and Multi-stage • Fast spectra • Continuous recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU, and continuous recycle of Pu or TRU from U. • Resource utilization up to 3%
	SC-C-F-UTh-Pu-Y	Critical	Fast	UTh	Pu	Yes	
	SC-C-F-UTh-TRU-Y	Critical	Fast	UTh	TRU	Yes	
	SC-S-F-UTh-U3-Y	SubCrit.	Fast	UTh	U3 (WOWO TRU)	Yes	
	SC-S-F-UTh-Pu-Y	SubCrit.	Fast	UTh	Pu	Yes	
	SC-S-F-UTh-TRU-Y	SubCrit.	Fast	UTh	TRU	Yes	
	MC-C-F/F-UTh-U3-Y	Critical	Fast & Fast	UTh	U3 (WOWO TRU)	Yes	
	MC-C-F/F-UTh-Pu-Y	Critical	Fast & Fast	UTh	Pu	Yes	
	MC-C-F/F-UTh-TRU-Y	Critical	Fast & Fast	UTh	TRU	Yes	
	SC-S-F-U-Pu-Y	SubCrit.	Fast	U	Pu	Yes	
	SC-S-F-U-TRU-Y	SubCrit.	Fast	U	TRU	Yes	
	SC-C-F-U-Pu-Y	Critical	Fast	U	Pu	Yes	
	MC-C-F/F-U-Pu-Y	Critical	Fast & Fast	U	Pu	Yes	
	SC-C-F-U-TRU-Y	Critical	Fast	U	TRU	Yes	
	MC-C-F/F-U-TRU-Y	Critical	Fast & Fast	U	TRU	Yes	
Analysis Example For EG27	Option description			Continuous Recycle: SFR using LEU fuel with recycle uranium (recovered from LEU and mainly U-233 from Th) and thorium			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([--]; LEU/U3/RU;Th; HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG28	SC-C-F-UTh-U3-N	Critical	Fast	UTh	U3 (WOWO TRU)	No*	• Natural UTh or Th feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Single and Multi-stage • Fast spectra • Continuous recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU • Resource utilization between 30% and 100%
	SC-S-F-UTh-U3-N	SubCrit.	Fast	UTh	U3 (WOWO TRU)	No	
	SC-C-F-Th-U3-N	Critical	Fast	Th	U3 (WOWO TRU)	No*	
	SC-S-F-Th-U3-N	SubCrit.	Fast	Th	U3 (WOWO TRU)	No	
	MC-C-F/F-UTh-U3-N	Critical	Fast & Fast	UTh	U3 (WOWO TRU)	No*	
	MC-C-F/F-Th-U3-N	Critical	Fast & Fast	Th	U3 (WOWO TRU)	No*	
Analysis Example For EG28	Option description			Continuous Recycle: SFR using uranium (mainly U-233) and thorium with recycle			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU]; U3/Th;Th; HLW)			
Evaluation group EG29	MC-C-T/F-U-Pu-N	Critical	Thermal & Fast	U	Pu	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup) • Critical reactors • Multi-stage • Thermal and Fast spectra • Continuous recycle of Pu from U. • Resource utilization between 30% and 100%
	MC-C-F/T-U-Pu-N	Critical	Fast & Thermal	U	Pu	No*	
	MC-C-T/F-UTh-Pu-N	Critical	Thermal & Fast	UTh	Pu	No*	
	MC-C-F/T-UTh-Pu-N	Critical	Fast & Thermal	UTh	Pu	No*	
Analysis Example For EG29	Option description			Continuous Recycle: SFRs using uranium and plutonium (mainly Pu-239) with recycle, with uranium and plutonium (mainly Pu-239) also used in PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU]; Pu/RU; NU;HLW)→PWR([--]; Pu/RU; --;HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG30	MC-C-T/F-U-TRU-N	Critical	Thermal & Fast	U	TRU	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup) • Critical reactors • Multi-stage • Thermal and Fast spectra • Continuous recycle of TRU from U. • Resource utilization between 30% and 100%
	MC-C-F/T-U-TRU-N	Critical	Fast & Thermal	U	TRU	No*	
	MC-C-T/F-UTh-TRU-N	Critical	Thermal & Fast	UTh	TRU	No*	
	MC-C-F/T-UTh-TRU-N	Critical	Fast & Thermal	UTh	TRU	No*	
Analysis Example For EG30	Option description			Continuous Recycle: SFRs using recycle of TRU and uranium from the SFRs and MA from the PWRs, with recycle uranium and plutonium (mainly Pu-239) used in PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU]; TRU/RU; NU; HLW)→PWR([--]; TRU/Pu/RU; --; HLW)			
Evaluation group EG31	MC-C-T/F-U-Pu-Y	Critical	Thermal & Fast	U	Pu	Yes	• Natural U feed • Enrichment • Critical reactors • Multi-stage • Thermal and Fast spectra • Continuous recycle of Pu from U. • Resource utilization up to 3%
	MC-C-F/T-U-Pu-Y	Critical	Fast & Thermal	U	Pu	Yes	
Analysis Example For EG31	Option description			Continuous Recycle: PWRs using LEU, with PWR DF reprocessed to obtain Pu and U for recycle in SFRs			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --;HLW)→SFR([--]; Pu/RU; --; HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG32	MC-C-T/F-U-TRU-Y	Critical	Thermal & Fast	U	TRU	Yes	• Natural U feed • Enrichment • Critical reactors • Multi-stage • Thermal and Fast spectra • Continuous recycle of TRU from U. • Resource utilization up to 3%
	MC-C-F/T-U-TRU-Y	Critical	Fast & Thermal	U	TRU	Yes	
Analysis Example For EG32	Option description			Continuous Recycle: PWRs using LEU, with PWR DF reprocessed to obtain TRU and U for recycle in SFRs			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --; HLW)→SFR([--]; TRU/RU; --; HLW)			
Evaluation group EG33	MC-C/S-T/F-U-Pu-N	Critical & SubCrit.	Thermal & Fast	U	Pu	No*	• Natural U or UTh feed • No Enrichment (enrichment may be

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
	MC-C/S-F/T-U-Pu-N	Critical & SubCrit.	Fast & Thermal	U	Pu	No*	
	MC-S/C-T/T-U-Pu-N	SubCrit. & Critical	Thermal & Thermal	U	Pu	No*	
	MC-S/C-T/F-U-Pu-N	SubCrit. & Critical	Thermal & Fast	U	Pu	No*	
	MC-S/C-F/T-U-Pu-N	SubCrit. & Critical	Fast & Thermal	U	Pu	No*	
	MC-C/S-T/T-U-Pu-N	Critical & SubCrit.	Thermal & Thermal	U	Pu	No*	
	MC-C/S-F/F-U-Pu-N	Critical & SubCrit.	Fast & Fast	U	Pu	No*	
	MC-S/C-F/F-U-Pu-N	SubCrit. & Critical	Fast & Fast	U	Pu	No*	
	MC-C/S-T/T-UTh-Pu-N	Critical & SubCrit.	Thermal & Thermal	UTh	Pu	No*	
	MC-C/S-T/F-UTh-Pu-N	Critical & SubCrit.	Thermal & Fast	UTh	Pu	No*	
	MC-C/S-F/T-UTh-Pu-N	Critical & SubCrit.	Fast & Thermal	UTh	Pu	No*	
	MC-C/S-F/F-UTh-Pu-N	Critical & SubCrit.	Fast & Fast	UTh	Pu	No*	
	MC-S/C-T/T-UTh-Pu-N	SubCrit. & Critical	Thermal & Thermal	UTh	Pu	No*	
	MC-S/C-T/F-UTh-Pu-N	SubCrit. & Critical	Thermal & Fast	UTh	Pu	No*	

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
	MC-S/C-F/T-UTh-Pu-N	SubCrit. & Critical	Fast & Thermal	UTh	Pu	No*	
	MC-S/C-F/F-UTh-Pu-N	SubCrit. & Critical	Fast & Fast	UTh	Pu	No*	
Analysis Example For EG33	Option description			Continuous Recycle: ADSs using uranium and plutonium (mainly Pu-239) with recycle, and recycle of uranium and plutonium (mainly Pu-239) in PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			ADS([--]; Pu/RU; NU/RU; HLW)→PWR([--]; Pu/RU/NU; --;HLW)			
Evaluation group EG34	MC-C/S-T/F-U-TRU-N	Critical & SubCrit.	Thermal & Fast	U	TRU	No*	• Natural U or UTh feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Multi-stage • Thermal and/or Fast spectra • Continuous recycle of TRU from U. • Resource utilization between 30% and 100%
	MC-C/S-F/T-U-TRU-N	Critical & SubCrit.	Fast & Thermal	U	TRU	No*	
	MC-S/C-T/F-U-TRU-N	SubCrit. & Critical	Thermal & Fast	U	TRU	No*	
	MC-S/C-F/T-U-TRU-N	SubCrit. & Critical	Fast & Thermal	U	TRU	No*	
	MC-C/S-T/T-U-TRU-N	Critical & SubCrit.	Thermal & Thermal	U	TRU	No*	
	MC-S/C-T/T-U-TRU-N	SubCrit. & Critical	Thermal & Thermal	U	TRU	No*	
	MC-C/S-F/F-U-TRU-N	Critical & SubCrit.	Fast & Fast	U	TRU	No*	
	MC-S/C-F/F-U-TRU-N	SubCrit. & Critical	Fast & Fast	U	TRU	No*	
	MC-C/S-T/T-UTh-TRU-N	Critical & SubCrit.	Thermal & Thermal	UTh	TRU	No*	
	MC-C/S-T/F-UTh-TRU-N	Critical & SubCrit.	Thermal & Fast	UTh	TRU	No*	

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
	MC-C/S-F/T-UTh-TRU-N	Critical & SubCrit.	Fast & Thermal	UTh	TRU	No*	
	MC-C/S-F/F-UTh-TRU-N	Critical & SubCrit.	Fast & Fast	UTh	TRU	No*	
	MC-S/C-T/T-UTh-TRU-N	SubCrit. & Critical	Thermal & Thermal	UTh	TRU	No*	
	MC-S/C-T/F-UTh-TRU-N	SubCrit. & Critical	Thermal & Fast	UTh	TRU	No*	
	MC-S/C-F/T-UTh-TRU-N	SubCrit. & Critical	Fast & Thermal	UTh	TRU	No*	
	MC-S/C-F/F-UTh-TRU-N	SubCrit. & Critical	Fast & Fast	UTh	TRU	No*	
Analysis Example For EG34	Option description			Continuous Recycle: ADSs using uranium and TRU with recycle, and recycled of TRU and U in PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			ADS([--]; TRU/RU; NU/RU; HLW)→PWR([--]; TRU/RU; --; HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG35	MC-C/S-T/F-U-Pu-Y	Critical & SubCrit.	Thermal & Fast	U	Pu	Yes	• Natural U feed • Enrichment • Critical reactors and EDS • Multi-stage • Thermal and/or Fast spectra • Continuous recycle of Pu from U. • Resource utilization up to 3%
	MC-C/S-F/T-U-Pu-Y	Critical & SubCrit.	Fast & Thermal	U	Pu	Yes	
	MC-S/C-T/F-U-Pu-Y	SubCrit. & Critical	Thermal & Fast	U	Pu	Yes	
	MC-S/C-F/T-U-Pu-Y	SubCrit. & Critical	Fast & Thermal	U	Pu	Yes	
	MC-C/S-T/T-U-Pu-Y	Critical & SubCrit.	Thermal & Thermal	U	Pu	Yes	
	MC-S/C-T/T-U-Pu-Y	SubCrit. & Critical	Thermal & Thermal	U	Pu	Yes	
	MC-C/S-F/F-U-Pu-Y	Critical & SubCrit.	Fast & Fast	U	Pu	Yes	
	MC-S/C-F/F-U-Pu-Y	SubCrit. & Critical	Fast & Fast	U	Pu	Yes	
Analysis Example For EG35	Option description			Continuous Recycle: PWRs using LEU with recycle of the Pu in ADSs			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --; HLW)→ADS([--]; Pu/IMF; --; HLW)			

<table>
<tr><th rowspan="2"></th><th rowspan="2">Included Fuel Cycle Option Groups From Table B8</th><th colspan="6">Key Characteristics</th><th rowspan="2">Characteristics</th></tr>
<tr><th>Reactivity</th><th>Spectrum</th><th>Feed material</th><th>Recycled element</th><th>Requires Enrich.</th></tr>
<tr><td rowspan="8">Evaluation group EG36</td><td>MC-C/S-T/F-U-TRU-Y</td><td>Critical & SubCrit.</td><td>Thermal & Fast</td><td>U</td><td>TRU</td><td>Yes</td><td rowspan="8">• Natural U feed
• Enrichment
• Critical reactors and EDS
• Multi-stage
• Thermal and/or Fast spectra
• Continuous recycle of TRU from U.
• Resource utilization up to 3%</td></tr>
<tr><td>MC-C/S-F/T-U-TRU-Y</td><td>Critical & SubCrit.</td><td>Fast & Thermal</td><td>U</td><td>TRU</td><td>Yes</td></tr>
<tr><td>MC-S/C-T/F-U-TRU-Y</td><td>SubCrit. & Critical</td><td>Thermal & Fast</td><td>U</td><td>TRU</td><td>Yes</td></tr>
<tr><td>MC-S/C-F/T-U-TRU-Y</td><td>SubCrit. & Critical</td><td>Fast & Thermal</td><td>U</td><td>TRU</td><td>Yes</td></tr>
<tr><td>MC-C/S-T/T-U-TRU-Y</td><td>Critical & SubCrit.</td><td>Thermal & Thermal</td><td>U</td><td>TRU</td><td>Yes</td></tr>
<tr><td>MC-S/C-T/T-U-TRU-Y</td><td>SubCrit. & Critical</td><td>Thermal & Thermal</td><td>U</td><td>TRU</td><td>Yes</td></tr>
<tr><td>MC-C/S-F/F-U-TRU-Y</td><td>Critical & SubCrit.</td><td>Fast & Fast</td><td>U</td><td>TRU</td><td>Yes</td></tr>
<tr><td>MC-S/C-F/F-U-TRU-Y</td><td>SubCrit. & Critical</td><td>Fast & Fast</td><td>U</td><td>TRU</td><td>Yes</td></tr>
<tr><td rowspan="2">Analysis Example For EG36</td><td colspan="3">Option description</td><td colspan="5">Continuous Recycle: PWRs using LEU with recycled Pu and recycled U, with recycle of MA in ADSs</td></tr>
<tr><td colspan="3">Reactor ([Startup];Driver; Blanket; Waste)</td><td colspan="5">PWR([--]; LEU/Pu/RU; --; HLW) →ADS([--]; MA/IMF; --; HLW)</td></tr>
</table>

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG37	MC-C-T/F-UTh-U3-Y	Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	Yes	• Natural UTh feed • Enrichment • Critical reactors • Multi-stage • Thermal and Fast spectra • Continuous recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU, and continuous recycle of Pu or TRU from U. • Resource utilization between 3% and 30%
	MC-C-F/T-UTh-U3-Y	Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	Yes	
	MC-C-T/F-UTh-Pu-Y	Critical	Thermal & Fast	UTh	Pu	Yes	
	MC-C-F/T-UTh-Pu-Y	Critical	Fast & Thermal	UTh	Pu	Yes	
	MC-C-T/F-UTh-TRU-Y	Critical	Thermal & Fast	UTh	TRU	Yes	
	MC-C-F/T-UTh-TRU-Y	Critical	Fast & Thermal	UTh	TRU	Yes	
Analysis Example For EG37	Option description			Continuous Recycle: PWRs using LEU, with recycle of TRU and U in SFRs using thorium blankets, followed by recycle of uranium (recovered from LEU and mainly U-233 from Th) in PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; --;HLW) → SFR([--]; TRU/RU; Th; HLW) → PWR([--]; U3/RU; --; HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG38	MC-C-T/F-UTh-U3-N	Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	No*	• Natural UTh or Th feed • No Enrichment (enrichment may be required for startup) • Critical reactors • Multi-stage • Thermal and Fast spectra • Continuous recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU. • Resource utilization between 30% and 100%
	MC-C-F/T-UTh-U3-N	Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	No*	
	MC-C-T/F-Th-U3-N	Critical	Thermal & Fast	Th	U3 (WOWO TRU)	No*	
	MC-C-F/T-Th-U3-N	Critical	Fast & Thermal	Th	U3 (WOWO TRU)	No*	
Analysis Example For EG38	Option description			Continuous Recycle: SFRs using uranium (mainly U-233) and thorium with recycle, and recycle of uranium (mainly U-233) and thorium in PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			SFR([LEU];U3/Th; Th; HLW) →PWR([--]; U3/Th; --; HLW)			
Evaluation group EG39	MC-C/S-T/F-UTh-U3-Y	Critical & SubCrit.	Thermal & Fast	UTh	U3 (WOWO TRU)	Yes	• Natural UTh feed • Enrichment

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
	MC-C/S-F/T-UTh-U3-Y	Critical & SubCrit.	Fast & Thermal	UTh	U3 (WOWO TRU)	Yes	
	MC-C/S-T/T-UTh-Pu-Y	Critical & SubCrit.	Thermal &Thermal	UTh	Pu	Yes	
	MC-C/S-T/F-UTh-Pu-Y	Critical & SubCrit.	Thermal & Fast	UTh	Pu	Yes	
	MC-C/S-F/T-UTh-Pu-Y	Critical & SubCrit.	Fast & Thermal	UTh	Pu	Yes	
	MC-C/S-F/F-UTh-Pu-Y	Critical & SubCrit.	Fast & Fast	UTh	Pu	Yes	
	MC-C/S-T/T-UTh-TRU-Y	Critical & SubCrit.	Thermal & Thermal	UTh	TRU	Yes	
	MC-C/S-T/F-UTh-TRU-Y	Critical & SubCrit.	Thermal & Fast	UTh	TRU	Yes	
	MC-C/S-F/T-UTh-TRU-Y	Critical & SubCrit.	Fast & Thermal	UTh	TRU	Yes	
	MC-C/S-F/F-UTh-TRU-Y	Critical & SubCrit.	Fast & Fast	UTh	TRU	Yes	
	MC-S/C-T/T-UTh-U3-Y	SubCrit. & Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	Yes	
	MC-S/C-T/F-UTh-U3-Y	SubCrit. & Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	Yes	
	MC-S/C-F/T-UTh-U3-Y	SubCrit. & Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	Yes	
	MC-S/C-F/F-UTh-U3-Y	SubCrit. & Critical	Fast & Fast	UTh	U3 (WOWO TRU)	Yes	
	MC-S/C-T/T-UTh-Pu-Y	SubCrit. & Critical	Thermal & Thermal	UTh	Pu	Yes	

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
	MC-S/C-T/F-UTh-Pu-Y	SubCrit. & Critical	Thermal & Fast	UTh	Pu	Yes	
	MC-S/C-F/T-UTh-Pu-Y	SubCrit. & Critical	Fast & Thermal	UTh	Pu	Yes	
	MC-S/C-F/F-UTh-Pu-Y	SubCrit. & Critical	Fast & Fast	UTh	Pu	Yes	
	MC-S/C-T/T-UTh-TRU-Y	SubCrit. & Critical	Thermal & Thermal	UTh	TRU	Yes	
	MC-S/C-T/F-UTh-TRU-Y	SubCrit. & Critical	Thermal & Fast	UTh	TRU	Yes	
	MC-S/C-F/T-UTh-TRU-Y	SubCrit. & Critical	Fast & Thermal	UTh	TRU	Yes	
	MC-S/C-F/F-UTh-TRU-Y	SubCrit. & Critical	Fast & Fast	UTh	TRU	Yes	
	MC-C/S-T/T-UTh-U3-Y	Critical & SubCrit.	Thermal & Thermal	UTh	U3 (WOWO TRU)	Yes	
	MC-C/S-F/F-UTh-U3-Y	Critical & SubCrit.	Fast & Fast	UTh	U3 (WOWO TRU)	Yes	
Analysis Example For EG39	Option description			Continuous Recycle: PWRs using LEU driver and thorium blankets, with other PWRs using recycle uranium (mainly U-233) and thorium, followed by ADSs using recycle TRU in an inert matrix.			
	Reactor ([Startup];Driver; Blanket; Waste)			PWR([--]; LEU; Th; HLW) →PWR([--]; U3/Th; --; HLW) →ADS([--]; TRU/IMF; --;HLW)			

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
Evaluation group EG40	MC-C/S-T/T-UTh-U3-N	Critical & SubCrit.	Thermal & Thermal	UTh	U3 (WOWO TRU)	No*	• Natural UTh or Th feed • No Enrichment (enrichment may be required for startup of critical; may be used for subcrit) • Critical reactors and EDS • Multi-stage • Thermal and/or Fast spectra • Continuous recycle of U3 (primarily U-233) bred from Th, plus any build-up of TRU. • Resource utilization between 30% and 100%
	MC-C/S-T/F-UTh-U3-N	Critical & SubCrit.	Thermal & Fast	UTh	U3 (WOWO TRU)	No*	
	MC-C/S-F/T-UTh-U3-N	Critical & SubCrit.	Fast & Thermal	UTh	U3 (WOWO TRU)	No*	
	MC-C/S-F/F-UTh-U3-N	Critical & SubCrit.	Fast & Fast	UTh	U3 (WOWO TRU)	No*	
	MC-S/C-T/T-UTh-U3-N	SubCrit. & Critical	Thermal & Thermal	UTh	U3 (WOWO TRU)	No*	
	MC-S/C-T/F-UTh-U3-N	SubCrit. & Critical	Thermal & Fast	UTh	U3 (WOWO TRU)	No*	
	MC-S/C-F/T-UTh-U3-N	SubCrit. & Critical	Fast & Thermal	UTh	U3 (WOWO TRU)	No*	
	MC-S/C-F/F-UTh-U3-N	SubCrit. & Critical	Fast & Fast	UTh	U3 (WOWO TRU)	No*	
	MC-C/S-T/T-Th-U3-N	Critical & SubCrit.	Thermal & Thermal	Th	U3 (WOWO TRU)	No*	
	MC-C/S-T/F-Th-U3-N	Critical & SubCrit.	Thermal & Fast	Th	U3 (WOWO TRU)	No*	
	MC-C/S-F/T-Th-U3-N	Critical & SubCrit.	Fast & Thermal	Th	U3 (WOWO TRU)	No*	
	MC-C/S-F/F-Th-U3-N	Critical & SubCrit.	Fast & Fast	Th	U3 (WOWO TRU)	No*	
	MC-S/C-T/T-Th-U3-N	SubCrit. & Critical	Thermal & Thermal	Th	U3 (WOWO TRU)	No*	

	Included Fuel Cycle Option Groups From Table B8	Key Characteristics					Characteristics
		Reactivity	Spectrum	Feed material	Recycled element	Requires Enrich.	
	MC-S/C-T/F-Th-U3-N	SubCrit. & Critical	Thermal & Fast	Th	U3 (WOWO TRU)	No*	
	MC-S/C-F/T-Th-U3-N	SubCrit. & Critical	Fast & Thermal	Th	U3 (WOWO TRU)	No*	
	MC-S/C-F/F-Th-U3-N	SubCrit. & Critical	Fast & Fast	Th	U3 (WOWO TRU)	No*	
Analysis Example For EG40	Option description			Continuous Recycle: ADSs using thorium with reprocessing of the ADS DF to obtain uranium (mainly U-233) for recycle in PWRs using thorium and recycled uranium (mainly U-233) from the PWRs			
	Reactor ([Startup];Driver; Blanket; Waste)			ADS([--];--; Th; HLW) → PWR([--]; U3/Th; --; HLW)			

B-4.2 Placing Future Potential Fuel Cycle Options into Evaluation Groups

This section discusses in a general sense how the Evaluation Groups developed as part of this Evaluation and Screening (E&S) and presented above can be used to inform on the performance of future potential fuel cycle options. It is noted that the 40 Evaluation Groups have been constructed to meet the E&S Charter direction that "*The set of fuel cycle options that will be evaluated must be as comprehensive as possible with respect to the potential performance of fuel cycle options.*" These Evaluation Groups contain numerous potential fuel cycle options, both in the details of how they are configured and the approach an option takes to meet a certain fuel cycle objective. As described above, the approach in this Study is based on the fundamental physics controlling the performance of a fuel cycle, and in principle, with the entire range of fuel cycle performance represented, any future fuel cycle would be able to be placed in the appropriate Evaluation Group.

This Study identified and characterized fuel cycles at the physics-based functional level, not at the technology level, and it was not necessary to analyze all possible specific fuel cycle options or variants since their performance is already represented by the Evaluation Groups. For example, the Study did not need to specifically consider fuel cycles involving isotopic separation within the fuel cycle since such options can be placed in one of the 40 Evaluation Groups (see example below). It was not necessary to perform analyses of different technologies for a given reactor spectrum type, such as multiple analyses for a fast spectrum reactor in an Evaluation Group that could have included separate cases with sodium-cooled, lead-cooled, and gas-cooled fast reactors or molten salt-cooled fast-spectrum reactor, etc, since their physics-based performance is very similar. However, consideration was given to advanced concepts proposed within the program and by external developers, as discussed above, in selecting Analysis Examples for each Evaluation Group (Section B-5).

The E&S approach was developed to ensure that any future fuel cycle options that might be proposed could be placed into one of the 40 Evaluation Groups and its performance can be determined in relation to those of other fuel cycles, and in particular to the Basis of Comparison which is used to represent the current option in the United States. This is possible because an Evaluation Group is a collection of options with similar fuel cycle performance, and the set of 40 Evaluation Groups comprehensively represents the performance of all potential fuel cycles. Additionally, the Metric Data for each Evaluation Metric is assigned to a bin covering a range of performance, with a bin selected to identify the best potential of an Evaluation Group for that metric, not the performance of all specific fuel cycles within the group. Not all fuel cycles in an Evaluation Group would necessarily have this level of performance, but the principle in the Study was to identify all potentially promising Evaluation Groups, even if lesser performing fuel cycle options were not eliminated because they were placed in an Evaluation Group with better performing options. The combination of the grouping approach and the use of metric bins however allow any new options to be placed in the appropriate Evaluation Group with the corresponding performance.

To illustrate how the above considerations can be reflected in the EGs, one potential future fuel cycle is discussed in this section to demonstrate the comprehensiveness of the Evaluation Groups and the effectiveness of the approach used in this Study. The Independent Review Team provided an example future fuel cycle option that was used for this test.[B3] The option proposes the separation of Pu (specifically ^{240}Pu) within a fuel cycle involving the continuous recycle of plutonium (in mixed-oxide fuel) in an LWR, with the intention of reducing the creation of higher actinides. Such isotopic separation is intended to ease fuel handling issues in the fuel cycle and potentially reduce cost, and also reduce the amount of higher actinides (above plutonium) that would need to be disposed as nuclear waste. The proposed fuel cycle uses enriched uranium fuel along with the Pu, as in the current fuel cycles in Europe using MOX-Pu recycled fuel. The approach described above for placement of fuel cycle options into Evaluation Groups was used to characterize this option for proper placement by considering the six "discriminators" discussed in Section B-2 of this Appendix. The results are summarized in Table B12.

Table B12. Application of Fuel Cycle Discriminators to Place a Fuel Cycle Option Involving Isotopic Separation of Pu into an Evaluation Group.

Physics Principle or Discriminator	**Results for specified Fuel Cycle Option**
Fuel Cycle Strategy: Once-through or recycle	Recycle system with isotopic separation of ^{240}Pu (and perhaps Pu isotopes above 240)
Type of irradiation device used: Critical reactor or/and externally driven sub-critical system	Critical reactor using LWRs (any thermal system could have been used)
Neutron spectrum: thermal, fast or intermediate	Thermal reactor
Type of nuclear fuel resource	• Natural uranium feed to make LWR-LEU fuel • Recovered Pu will also be used as fissile feed
Enrichment needed	Enriched uranium fuel support is required
Major recycle elements	Pu without ^{240}Pu, or perhaps ^{239}Pu only

The features of the proposed option, provided in Table B12 would place it naturally into "*EG21 – Continuous recycle of enriched-U/Pu in thermal critical reactors*". In this regard, if only ^{240}Pu is removed by the isotopic separation from plutonium and not recycled, the performance of this option under the E&S would be that of EG21 at the functional fuel cycle level since most of the plutonium is recycled and all of the higher actinides are considered wastes. Further examining this option, when fuel cycle options within EG21 are compared using the metrics of this Study, this new option would not be the best performing one within the Evaluation Group. This is because in recycle involving LWRs, higher actinides are always produced due to the 4.5 to 6 year residence time of the fuel in the core. Additionally, ^{240}Pu would be sent to waste instead of being recycled. The Metric Data of the challenge metrics for this option would be worse when compared to the best performing option in the Evaluation Group because both isotopic separation of irradiated materials and other processing or reprocessing technologies are required within the fuel cycle.

Alternatively, if the isotopic separation is used to remove completely (or minimize significantly) all the plutonium isotopes above ^{239}Pu that would otherwise be recycled, the fuel cycle performance will still place this option in EG21. Another possibility is that the higher actinide elements could be recycled as well, still without the ^{240}Pu, which would place the fuel cycle in EG22. Interestingly, as discussed in the Main Report, neither EG21 nor EG22 is ever identified in this Study as a potentially promising option for future development. This assessment highlights that in addition to specifying the future fuel cycle option, all of the fuel cycle parameters must be clearly specified to ensure proper placement in an Evaluation Group in order to inform on its potential performance relative to the Basis of Comparison.

This exercise demonstrates the robustness of the use of the forty (40) Evaluation Groups and metric bins within this E&S study, and the ability to consider future fuel cycle options within this context.

B-5. Analysis Examples

In order to obtain numerical data to support some of the Evaluation Metrics, Analysis Examples (AE) were identified and analyzed for each Evaluation Group. The analyses of the AEs required assumptions since most of the fuel cycle options being considered in the E&S have not been developed or built. In the following section, the descriptions and characteristics of the forty (40) Analysis Examples are provided.

As explained in Appendix A, it is important to note that the principles used to create the Fuel Cycle Option Groups and the resulting Evaluation Groups make the results of an Analysis Example only an initial indication of the performance of the Evaluation Group. Earlier in the study, an attempt was made to identify a Representative Option for each Evaluation Group, where the Representative Option would be among the better performing options for all of the Evaluation Criteria. As the Study proceeded, it became apparent that it was not possible to guarantee a priori that any fuel cycle would be representative of the best performance of all options in the Evaluation Group prior to the analyses being performed.

B-5.1 Characteristics of Analysis Examples for 40 Evaluation Groups

Descriptions of Analysis Examples

Table B13 contains the descriptions of the Analysis Examples as defined for this Evaluation and Screening (E&S). Detailed data on the examples are provided in Tables B14 to B93 and Figures B12 to B51. The information includes calculated reactor performance data, material and mass flows through the fuel cycle starting with natural resource requirements and ending with spent nuclear fuel and waste generated and disposed. The reactor technology and fuel form (e.g., oxide or metal) is specified for each AE since that information was needed to perform the reactor physics calculations, but other parts of the fuel cycle such as any chemical separations are treated generically by only specifying the materials being separated and the efficiency of the separation, not the technology.

With some common high-level assumptions, calculations were performed for these Analysis Examples. The high-level assumptions/guidelines for those calculations are provided in Table B94. Because in some cases there were pre-existing analyses, the information from those analyses was initially utilized. Where it was expected that using existing data might introduce biases to the Evaluation and Screening, the data was re-normalized or additional calculations were performed to ensure consistency of information. An example of such an item is the thermal efficiency that was re-normalized to 33%, as discussed in Section B-2.8.2, for all Analysis Examples prior to the development of the metric data (see also Appendix D-1.1). Other examples can be found in Appendices C and D, in which the approaches for determining the metric data are discussed along with the presentation of the metric data.

Two sets of reviews were conducted of the laboratory calculation files containing the material and mass flow information developed for the Analysis Examples: (1) An internal independent review performed by another staff member in the same national laboratory that conducted the analysis and (2) external independent reviews by staff members of two other national laboratories that are part of the options development team. There was an additional step in which revisions were also reviewed and concurred by the reviewers and subsequently reviewed and concurred by the development team leader (and data keeper). This analysis effort took place over a period of about 2 years and involved periodic team telephone calls and several face-to-face meetings, and the effort was tracked using a project management approach. Although the analysis tools were not the same at each lab involved in the analyses, consistency of analysis was ensured by reviews of comparable analysis results obtained from all of the analysis techniques used by the participating laboratories. The results of these analyses are included in the publicly-available online Fuel Cycle Catalog:
https://connect.sandia.gov/sites/NuclearFuelCycleOptionCatalog .

Definitions for Table B13 and Figures B12-B51:

Reactors: PWR = Pressurized Water Reactor, HTGR = High Temperature, Gas-cooled, Graphite Moderated Reactor; HWR = Heavy Water Reactor; CANDU = Canadian Deuterium Uranium; SFR = Sodium-cooled Fast reactor; MSR = Molten Salt Reactor; FFH = Fusion-Fission Hybrid; FT = Fuel Type; ICF = Inertial Confinement Fusion; ADS = Accelerator-Driven System(s).

Fuel Materials: NU = Natural uranium; DU = Depleted Uranium; RU = Recovered uranium; RTh = Recovered Thorium; LEU = Low Enriched Uranium; U3 = Uranium, which is mainly U-233; TRU = Transuranic Element(s); MA = Minor Actinides; FP = Fission Product(s); U = Uranium; Pu = Plutonium; Th = Thorium (natural or recovered; sometimes RTh is used for recovered Th); U-233 = Uranium-233; U-235 = Uranium-235; UNF = Used Nuclear Fuel(s); SNF = Spent Nuclear Fuel(s); MOX = mixed oxide; UCO = uranium oxy-carbide.

Other materials: Pb-Bi = Lead-Bismuth; Zr = Zirconium.

Table B13. Descriptions of 40 Analysis Examples.

Evaluation Group	Description of Analysis Example
	Once-through Fuel Cycles
EG01	*PWR with LEU fuel:* In this Analysis Example, natural uranium (NU) is enriched and used in making low enriched uranium (LEU) oxide fuel that is irradiated in a Pressurized Water Reactors (PWR) to a burnup of 50 GWd/t. Following irradiation, the discharged spent nuclear fuel (SNF) is sent to disposal. The depleted uranium (DU) from the enrichment process is waste that is sent to disposal. Any low level waste is also sent to disposal.
EG02	*HTGR with LEU fuel:* In this Analysis Example, NU is enriched and used in making LEU UCO fuel that is irradiated in prismatic fuel blocks that comprise the fuel assemblies of a high temperature, helium-cooled, graphite-moderated thermal reactor (HTGR) to a burnup of 120 GWd/t. Following irradiation, the SNF is sent to disposal. The DU from the enrichment process is waste that is sent to disposal. Any low level waste is also sent to disposal.
EG03	*HWR with NU fuel:* In this Analysis Example, natural uranium oxide fuel is irradiated in a Heavy Water Reactor (HWR) such as a CANDU to a discharge burnup of 7.5 GWd/t. Following irradiation, the SNF is sent to disposal. Any low level waste is also sent to disposal.
EG04	*Breed and Burn TRU/U in SFR without Separation:* At the equilibrium state of this Analysis Example, NU (or DU) metallic fuel is irradiated in a Sodium-cooled Fast Reactor (SFR) to a high burnup of 277 GWd/t. The SFR, with a breeding ratio greater than 1, breeds and burns fissile material. Following irradiation, the SNF is sent to disposal. Any low level waste is also sent to disposal. There are many possible concepts, but the one used in this case is a multi-batch fuel management scheme, involving fuel shuffling, in which a fraction of the core is discharged at the end of an operating cycle. The replacement fuel is the NU (or DU) fuel.
EG05	*High-Conversion HTGR with LEU and Th fuel:* In this Analysis Example, both low enriched uranium (LEU) and thorium (Th) fuels are located in the same fuel compacts and loaded into prismatic fuel blocks that comprise the fuel assemblies and are irradiated in an HTGR to a fuel burnup of 100 GWd/t. Following irradiation, the SNF is sent to disposal. The DU from the enrichment process is waste that is sent to disposal. Any low level waste is also sent to disposal.
EG06	*Breed and Burn U-233/Th in Thermal-spectrum FFH:* In this Analysis Example, an inertial confinement fusion (ICF) system is used to produce thermal power and D-T neutrons used for driving a subcritical blanket containing Th molten salt fuel, and breeding and fissioning U-233 at equilibrium, moderated by graphite to produce a thermal neutron spectrum. This is a Fusion-Fission Hybrid (FFH) system with fuel burnup of 118 GWd/t. Pure thorium fuel (no fissile material) is used for startup, which results in a blanket fission power that starts near zero and ramps up to full blanket power over the first few years of operation. The ICF system is self-sufficient in breeding its own replacement tritium, as well as producing power for its laser driver and for plant output. Fission products (FP) that do not stay in solution are removed in continuous online salt treatment process. A small fraction of the fuel salt is continuously discarded during operation. The combination of this FP waste stream and the continuously discharged salt form the waste streams and are sent to disposal. Any low level waste is also sent to disposal.
EG07	*ADS- for Breed and Burn with NU fuel:* NU metallic fuel is irradiated to a fuel burnup of 55 GWd/t in a breed and burn blanket zone of an accelerator-driven system (ADS) in this Analysis Example. Following irradiation, the SNF is sent to

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	disposal. Any low level waste is also sent to disposal. A significant fraction of the fission power generated in the blanket is required to operate the accelerator. Any low level waste is also sent to disposal.
EG08	*Breed and Burn U-233/Th in Fast-spectrum Fusion-Fission Hybrid (FFH):* In this Analysis Example, an ICF system is used to produce thermal power and D-T neutrons to drive a surrounding subcritical blanket that breeds and burns U-233 produced in situ from thorium. The ICF system is self-sufficient in breeding its own replacement tritium, as well as producing power for its laser driver and for plant output. This is an FFH with fuel burnup of 729 GWd/t, which requires a high-burnup fuel to be developed. The high burnup fuel limit (76%) is based on maintaining zero net lifetime tritium supplied to the facility. Following irradiation, the SNF is sent to disposal. Any low level waste is also sent to disposal.
	Limited Recycle Fuel Cycles
EG09	*Breed and Burn TRU/U in SFR:* In the equilibrium state of this Analysis Example a breed and burn mode SFR is fed with NU or DU and refueled with its own reprocessed fuel. It operates with a multi-batch fuel management scheme with fissile conversion ratio (CR) greater than 1. At the end of an operating cycle, one fuel batch is discharged when the accumulated average burnup is 492 GWd/t and this discharged SNF is sent to disposal. The discharged fuel is replaced with DU fuel. Additionally, a fraction of the fuel assemblies is reprocessed in order to overcome the cladding radiation damage limit. Recovered fuel contains Transuranics (TRU), uranium (RU) and partial FP. Non-recovered actinides and FP and material losses from reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG10	*Limited recycle of U-233/Th in MSR:* In the equilibrium state of this Analysis Example, fuel salt containing Th is irradiated in a molten salt reactor (MSR). Natural Th is the only external feed. The fuel salt undergoes continuous online treatment to remove various FP that would otherwise not stay in solution and also undergoes continuous chemical separations processing to further remove FP. Unlike full-recycle cases, some of the fuel salt is directly discharged before undergoing any separations work; this creates a discharged fuel stream with a full range of materials in it, including primary fissile material (U-233) and Th. A discard fraction was chosen that corresponds to 10% of the fuel salt inventory being discarded every year. During separations, all TRU is discarded; separated TRU and FP are sent to disposal. Recovered Th and recovered uranium (mostly, U-233) are returned to the system along with remaining FP. Any low level waste is also sent to disposal.
EG11	*Breed and Burn U-233/Th with LEU Support in SFR with Partial Separation:* In this Analysis Example, SFRs are fed with Th metallic fuel and some LEU metallic fuel. Since the breed and burn mode operation is impractical with Th fuel only, LEU support was needed for this Analysis Example. The core is made of eight batches (seven are thorium fuel, one is LEU fuel) and operates with a fissile breeding ratio slightly below 1. The Th fuel stays in the core for seven cycles, while the LEU fuel resides in the core for a single cycle. During the seven cycles, Th fuel is discharged when the cladding radiation damage limit is reached, and is reprocessed, and charged again into the reactor. In this Analysis Example, the Th fuel was reprocessed three times. At the end of a cycle, a fraction of Th fuel, which consist of trans-thorium (U3), Th and partial FP, is discarded with an average burnup of 377 GWd/t and replaced with pure Th fuel. The LEU fuel is made of 19.9% U-235 in the form of U-10Zr (90 w/o U and 10 w/o Zr) and is burned to 130 GWd/t. Non-recovered actinides and FP and losses during reprocessing are sent to disposal. The discarded fuel, which is SNF, is sent to disposal. Any low level waste is also sent to disposal.
EG12	*Limited recycle of Pu/U from HWR in PWR* This is a two-stage Analysis Example utilizing HWRs and PWRs. In Stage 1, NU oxide fuel is irradiated in an HWR to a discharge burnup of 7.5 GWd/t. The discharged used nuclear fuel (UNF)

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	in Stage 1 is reprocessed and Pu and RU are recovered for use in Stage 2. The excess RU not used for Stage 2, and all of the minor actinides (MA) and FP and material losses from reprocessing are waste that is sent to disposal. The Pu and RU from reprocessed Stage 1 fuel is used in making the Pu/U mixed-oxide (MOX) driver fuel for use in Stage 2. Through reactivity balance analysis, it was determined that the Pu content of the heavy metal in the Stage 2 PWR driver fuel needs to be ~8% to obtain a fuel burnup of 50 GWd/t. The Pu content in the MOX fuel is below the upper limit that could result in a positive void reactivity coefficient. Following irradiation in the PWR, the discharged SNF is sent to disposal. Any low level waste is also sent to disposal.
EG13	*Limited recycle of Pu/U from PWR in PWR burner:* This two-stage Analysis Example involves the limited recycle of Pu in PWRs for the purpose of extending fuel resource. NU is enriched and used in making LEU oxide fuel that is irradiated in the Stage 1 PWR to a burnup of 50 GWd/t. Following discharge from the Stage 1 PWR, the used nuclear fuel (UNF) is reprocessed and the recovered Pu and RU are co-extracted and are used in making Pu/U MOX fuel for the Stage 2 PWR burner. The PWRs in Stage 2 irradiate the MOX fuel to the same burnup as for Stage 1 fuel. The DU from the enrichment process, excess RU, MA, FP and material losses from reprocessing are waste that is sent to disposal. The discharged SNF from the Stage 2 PWR is sent to disposal. Any low level waste is also sent to disposal.
EG14	*Limited recycle of U and Pu Bred in SFR in a PWR:* This is a two-stage Analysis Example using SFR in Stage 1 that is used to breed fissile material used in Stage 2 PWR. Two fuels are used in the Stage 1 SFR breeder. The first is Pu/U metallic driver fuel that is made from NU, and recovered Pu and RU from Stage 1 reprocessed fuel. The second is metallic blanket fuel made from NU and excess RU from Stage 1 recycled fuel, in which the bred Pu for Stage 2 is produced. The metallic driver fuel is irradiated to a burnup of 100 GWd/t and then reprocessed to recover the Pu/U that is recycled back into the Stage 1 SFR. The Stage 1 blanket fuel is reprocessed and the recovered Pu/U is used in making MOX fuel that is recycled in the Stage 2 PWR. FP and MA and material losses from the reprocessing of the driver and blanket fuels are waste that is sent to disposal. In the Stage 2 PWR, the Pu/U MOX fuel is irradiated to a burnup of 50 GWd/t and then discharged as SNF and sent to disposal. Any low level waste is also sent to disposal. Note that by minimizing the Pu content in the Stage 2 PWR MOX fuel, the use of Pu from the blanket of Stage 1 allows maximizing the number of Stage 2 PWRs that can be sustained by the SFR breeders compared to a case where a blend of Pu from the driver and blanket is used.
EG15	*Limited recycle of Pu/U from PWR in SFR burner:* This two-stage Analysis Example involves the use of PWRs and SFRs. NU is enriched and used in making LEU oxide fuel that is irradiated in the PWR to a burnup of 50 GWd/t. The discharged UNF in Stage 1 is reprocessed to recover Pu/RU that is recycled for burning in the Stage 2 SFR. FP, MA, excess RU and material losses from reprocessing and depleted uranium from fuel enrichment are waste that is sent to disposal. Recovered Pu/U from Stage 1 is used in making Pu/U metallic fuel for the Stage 2 SFR burner with the Pu conversion ratio much below 1. The metallic fuel is irradiated to a burnup of 127 GWd/t. The burnup is limited by the maximum allowable fluence on cladding and structure materials that is assumed to be 4×10^{23} n/cm^2 for this Analysis Example. The discharged SNF from the Stage 2 SFR is sent to disposal. Any low level waste is also sent to disposal.
EG16	*Limited recycle of Pu from PWR in ADS burner:* This two-stage Analysis Example involves the burning of Pu created in a Stage 1 PWR in a Stage 2 ADS. NU is enriched and used in making LEU oxide fuel that is irradiated in the PWR to a burnup of 50 GWd/t. The discharged UNF in Stage 1 is reprocessed to recover Pu that is recycled for burning in the Stage 2 ADS. The FP, MA, RU and material losses from reprocessing of the Stage 1 fuel and DU from fuel enrichment are waste that is sent to disposal. Recovered Pu from Stage 1 is used in making Pu non-fertile dispersion metal (zirconium) matrix fuel (Pu Inert Matrix Fuel—IMF) for use in the Stage 2 fast-spectrum Pb-Bi cooled ADS burner. The fuel is irradiated in the ADS burner driven with a proton accelerator spallation neutron source to a burnup of 390 GWd/t. The discharged

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	SNF from the Stage 2 ADS is sent to disposal. Any low level waste is also sent to disposal.
EG17	*Limited recycle of Pu from PWR in an PWR burner fueled with Thorium:* This is a two-stage Analysis Example involving the use of PWRs in both stages, with the Stage 2 PWR being used for burning the Pu produced in the Stage 1 PWR. NU is enriched and used in making low LEU oxide fuel that is irradiated in the Stage 1 PWR to a burnup of 50 GWd/t. The discharged fuel in Stage 1 is reprocessed to recover Pu that is recycled for burning in the Stage 2 PWR burner that uses Th based-fuel. The FP, MA, RU and material losses from reprocessing of the Stage 1 fuel and the DU from fuel enrichment are waste that is sent to disposal. Recovered Pu from Stage 1 is used to make Pu/Th MOX oxide fuel that is irradiated in the Stage 2 PWR burner to a burnup of 50 GWd/t. The discharged SNF from the Stage 2 PWR is sent to disposal. Any low level waste is also sent to disposal.
EG18	*Limited recycle of U-233/Th from PWR in a PWR burner:* This is a two-stage Analysis Example involving the use of PWRs in both stages, with the Stage 2 PWR being used for burning the U-233 produced in the Stage 1 PWR. The PWRs in Stage 1 are fed with LEU/Th homogeneous mixture fuel; the LEU is produced from the enrichment of the source NU fuel material. Initial enrichment of the LEU part of the fuel is <20 % ^{235}U. The Stage 1 fuel is irradiated to 60 GWd/t and the DF is reprocessed to recover U-233/Th that is recycled for burning in the Stage 2 PWR burner. The excess recovered Th is recycled for making fuel for the Stage 1 PWR with supplement of natural Th as necessary. The TRU, FP and material losses from reprocessing of the Stage 1 fuel are waste that is sent to disposal. The fuel for the Stage 2 PWR is made using the U-233/Th from Stage 1 fuel reprocessing and natural thorium and is irradiated to 58 GWd/t burnup. The discharged SNF from the Stage 2 PWR is sent to disposal. Any low level waste is also sent to disposal.
	Continuous Recycle Fuel Cycles
EG19	*Continuous recycle of Pu/U in HWR:* This Analysis Example involves the continuous recycle of Pu in HWR (CANDU). The oxide fuel for the HWR is made from NU and the recovered Pu/U from the reprocessing of the discharged fuel of the same reactor. This oxide fuel is irradiated to a burnup around 8.0 GWd/t. The FP, MA, excess RU and material losses from reprocessing of the fuel are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG20	*Continuous recycle of TRU/U in HWR:* This Analysis Example involves the continuous recycle of TRU in HWR (CANDU). The oxide fuel for the HWR is made from NU and the recovered TRU/U from the reprocessing of the discharged fuel of the same reactor. This oxide fuel is irradiated to a burnup of 7.6 GWd/t. The FP, excess RU and material losses from reprocessing of the used fuel are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG21	*Continuous recycle of Pu/U in PWR:* In this Analysis Example, LEU oxide and Pu/ MOX fuels both contained in the same heterogeneous assemblies are irradiated in PWRs to burnup of 45 GWd/t. The LEU fuel which is produced using source material from the enrichment of NU is utilized to support the continuous recycle of the Pu. The discharged UNF is reprocessed and the Pu and uranium are co-extracted and recycled back into making the MOX fuel for the PWR assemblies; some of the DU from fuel enrichment is used in making the MOX fuel. The FP, excess RU, MA and material losses from reprocessing, and excess DU from fuel enrichment are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG22	*Continuous recycle of TRU/U in PWR :* This Analysis Example is very similar to that for EG21 with the exception that recycle of TRU is the

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	target here. In this Analysis Example, LEU oxide and TRU/U MOX fuels both contained in the same heterogeneous assemblies are irradiated in PWRs to burnup of 45 GWd/t. The LEU fuel which is produced using source material from the enrichment of NU is utilized to support the continuous recycle of the TRU. The discharged UNF is reprocessed and the TRU/U is recycled back into making the MOX fuel for the PWR assemblies; some of the DU from fuel enrichment is used in making the MOX fuel. The FP, excess RU, and material losses from fuel reprocessing, and excess DU from fuel enrichment are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG23	*Continuous recycle of Pu/U in SFR:* In this Analysis Example, an SFR core consists of driver and radial blanket fuels to achieve a break-even conversion ratio (i.e., slightly higher than 1.0 to account for losses in the fuel separation and fabrication) in the equilibrium state. The U-Pu-Zr ternary metallic fuel is irradiated to burnup of 81.5 GWd/t in the driver fuel zone, while the U-Zr binary metallic fuel is irradiated to burnup of 23.5 GWd/t in the radial blanket zone. The average fuel burnup is 72.6 GWd/t. The discharged UNF is reprocessed to recover both Pu and RU that are recycled back into the SFR. The MA, FP, and material losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal. NU is the only *external* makeup feed during fuel production, used for replacing the heavy metal destroyed by fission. Note that this is the traditional SFR breeder. In a growth scenario, the SFR would be configured to breed excess fissile material at a level commensurate with the demand for startup of new reactors.
EG24	*Continuous recycle of TRU/U in SFR:* This is a companion Analysis Example to the one for EG23. In this case, TRU in metallic fuel instead of Pu-only is recycled in the SFR. In this Analysis Example, the SFR uses U-TRU-Zr driver fuel only (no blanket) to achieve a break-even TRU conversion ratio (i.e., slightly higher than 1.0 to account for losses in the fuel separation and fabrication) in the equilibrium state. The U-TRU-Zr metallic fuel is irradiated to burnup of 73 GWd/t and discharged from the reactor. The discharged UNF is reprocessed to recover both TRU and RU that are recycled back into the same SFR. The FP, excess RU, and material losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal. The recovered RU is the primary source of uranium with an external supply of uranium required as makeup for the roughly 7% of heavy metal fissioned each recycle pass.
EG25	*Continuous recycle of U-233/Th in PWR with LEU Support:* This Analysis Example uses PWRs to recycle U-233 derived from Th. The PWRs are based on the seed and blanket concept. Initially, the seed (driver) region contains LEU and the blanket region contains pure Th. The mass fraction of the blanket in the core is 0.64 and the seed is 0.36. The seed fuel is irradiated to 49 GWd/t and then reprocessed. The recovered TRU/U mixed with LEU make-up is used to fabricate a new seed fuel. The enrichment of LEU make-up is 4.9%. The excess RU, FP and material losses from fuel reprocessing and the DU from fuel enrichment are waste that is sent to disposal. The blanket fuel accumulates burnup of 26 GWd/t and on discharge is reprocessed. The U3 and Th fuel materials are then used to make a new blanket fuel. The TRU, FP and material losses from the reprocessing of the used blanket fuel are waste that is sent to disposal. Any low level waste is also sent to disposal. The typical core power density of PWRs was reduced from 104 to 52 W/cc in order to match the linear power density of the standard PWR at beginning of cycle for the seed fuel. It should be noted that the thermal output of the reactor was reduced to 1,700 MWt which will require a bigger reactor fleet to generate 100 GWe compared to standard PWRs.
EG26	*Continuous recycle of U-233/Th in MSR*: In this Analysis Example, fuel salt containing Th is irradiated in an MSR, using enriched uranium for initial startup. At the *equilibrium state*, no enriched uranium fuel is required and natural Th is the only external feed used. The fuel salt undergoes continuous online treatment to remove various FP that would otherwise not stay in solution and also undergoes continuous chemical separations

Evaluation Group	Description of Analysis Example
	processing to further remove FP. Protactinium (Pa) is allowed to decay outside of the reactor to optimize U-233 production. Recovered Th, uranium (mostly, U-233), and transuranics (TRU) are returned to the reactor along with remnants of FP. Separated FP and other material losses are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG27	*Continuous recycle of U-233/Th in SFR with LEU Support:* In this Analysis Example involving U-233 (U3) recycle in SFRs with LEU support, three fuel types are used in the SFR: RU/LEU driver, U3/RU/LEU driver, and Th blanket. All three fuels are irradiated in the SFR and then the discharged UNFs are reprocessed. The uranium isotopic composition (vector) is recovered from the used RU/LEU driver and is recycled back (re-enriched) into RU/LEU fuel with fresh LEU added as makeup to create 19% U-235/U fuel. The uranium vectors (isotopic compositions) from the U3/RU/LEU driver and Th blankets are recovered and mixed to denature the U3, and are also recycled continuously within the U3/RU/LEU driver fuel. Again, LEU is added as makeup. Reprocessing and fabrication of all fuel types occur at a single facility. For the U3/RU/LEU fuel, the separated U3 and RU are mixed with LEU into a single stream and the equivalent U-235 enrichment is about 12.6%. All FP and TRU are considered waste. This Analysis Example is able to achieve breakeven U3 breeding while taking into account losses through reprocessing. The discharged fuel burnup for driver fuels is ~37 GWd/t. Th from the blankets is recovered and used for fabricating new blankets; natural thorium is used as an external feed for the blanket makeup. Natural uranium is used as the only external feed for the LEU component of the driver fuels. In this Analysis Example, FP, TRU and material losses from reprocessing are waste that is sent to disposal. DU waste from fuel enrichment and low level waste are also sent to disposal.
EG28	*Continuous recycle of U-233/Th in SFR:* This Analysis Example uses metallic thorium fuel driver and blanket fuels that are irradiated in SFRs operating at a breakeven trans-thorium (U3, mostly U-233) conversion ratio of ~1.0. The reactor design is based on the typical SFR breeder but with thorium metallic fuel instead of uranium metallic fuel. The discharged fuel burnups for the driver and blanket fuels are 63 and 4 GWd/t, respectively. The discharged fuels are reprocessed for the purpose of recovering U3/Th for recycling in the SFR. The U3/Th and external (make-up) natural thorium are used for making new driver fuel for the SFR. Some of the recovered Th is also used with natural thorium for making the blanket fuel. The FP and losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG29	*Pu/U produced in SFR used to operate PWR in continuous recycle strategy:* This is a two-stage Analysis Example involving SFRs and PWRs in which Pu is produced in the Stage 1 SFR breeder for use in running the Stage 2 PWR. The SFR in Stage 1 uses driver and blanket fuels. In the equilibrium state, Pu/U recovered from the reprocessing of the discharged driver fuels from the Stage 1 SFRs are mixed with NU (used as external feed) to make new Pu/U metallic driver fuel for Stage 1. The blanket is made from natural uranium and recovered uranium from the reprocessing of the Stage 1 blanket fuel. These driver and blanket fuels are irradiated to discharged burnups of 97 and 21 GWd/t, respectively. The excess Pu/U from the reprocessing of the discharged blanket fuel is recycled to Stage 2. The FP, MA and material losses during fuel reprocessing of the Stage 1 fuels are waste that is sent to disposal. Recovered Pu/U from Stage 2 PWR and excess recovered Pu /U from the blanket fuels of Stage 1 SFR are used to make Pu/U MOX fuel for the Stage 2 PWR. No NU is necessary since the Pu/U from Stage 1 brings enough RU. The Pu/U MOX fuel is irradiated to a burnup of 50 GWd/t in the Stage 2 PWR and the discharged UNF is reprocessed. The recovered Pu /U is recycled back to Stage 2. The MA, FP and material losses during fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal. Note that for this Analysis Example to be viable, it is necessary to feed the PWR (MOX) with the high fissile content Pu from the SFR blanket of Stage 1. If a less fissile Pu mixture is used (e.g., a blend of Pu coming from the SFR driver fuel and blanket) the necessary Pu content in the PWR (MOX) becomes higher than the upper limit required by the reactor safety (i.e., ~12% Pu) after a few recycles.

Evaluation Group	Description of Analysis Example
EG30	*TRU/U produced in SFR used to operate PWR in continuous recycle strategy:* This is a counterpart Analysis Example to the example for EG29, with the exception that TRU recycle is the target in this two-stage example. The Stage 1 SFR breeder is used to produce TRU for use in running the Stage 2 PWR. The SFR in Stage 1 uses driver and blanket fuels. In the equilibrium state, recovered TRU/U from Stage 1 and recovered MA from Stage 2 are mixed with NU (used as external feed) to make driver TRU/U metallic fuel. The blanket is made from natural uranium and recovered uranium from the reprocessing of the Stage 1 blanket fuel. The metallic driver fuel in the SFR breeder is irradiated to burnup of 107 GWd/t. The blanket fuel is irradiated to burnup of 23 GWd/t. The discharged UNF from driver fuel is reprocessed to recover TRU/U that is recycled back into Stage 1 for making new driver fuel. The excess recovered TRU/U from the reprocessing of the discharged blanket fuel are recycled for making fuel for the Stage 2 PWR. The FP and material losses during the reprocessing of the Stage 1 fuels are waste that is sent to disposal. Recovered Pu/U from Stage 2 PWR and recovered TRU/U from the blanket fuels of Stage 1 are used to make TRU/U MOX fuel for the Stage 2 PWR. The TRU/U MOX fuel is irradiated to a burnup of 50 GWd/t in the Stage 2 PWR and following discharge is reprocessed. Recovered Pu/U is recycled back to Stage 2. *Recovered MA is sent to Stage 1* to reduce MA content in Stage 2 PWR fuels. FP and material losses during the reprocessing of the Stage 2 fuel are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG31	*Continuous recycle of Pu/U from PWR in SFR burner:* This is a two-stage Analysis Example involving PWRs and SFRs. Low enriched uranium is used to make oxide fuel for the Stage 1 PWR. The fuel is irradiated to a burnup of ~50 GWd/t and following discharge is reprocessed to recover Pu/U that is recycled for making fuel for the Stage 2 SFR. The FP, MA and excess RU and material losses from fuel reprocessing are waste that is sent to disposal. The DU from fuel enrichment is also waste that is sent to disposal. Recovered Pu/U from the reprocessing of Stage 2 fuel and those recovered from Stage 1 are used to make Pu/U MOX fuel for the Stage 2 SFR burner. The Pu/U MOX fuel is irradiated to a burnup of 169 GWd/t in the Stage 2 SFR burner and the discharged UNF is reprocessed and the recovered Pu/U is recycled back to Stage 2. The MA, FP and material losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG32	*Continuous recycle of TRU/U from PWR in SFR burner:* This is a two-stage Analysis Example involving PWRs and SFRs that is similar to the example for EG31, with the exception that TRU is recycled in this example. LEU is used to make oxide fuel for the Stage 1 PWR. The fuel is irradiated to a burnup of ~50 GWd/t and following discharge is reprocessed to recover TRU and RU that are recycled for making fuel for the Stage 2 SFR. The FP, excess RU and material losses from fuel reprocessing are waste that is sent to disposal. The DU from fuel enrichment is also waste that is sent to disposal. Recovered TRU/U from the reprocessing of Stage 2 fuel and those recovered from Stage 1 are used in making metallic fuel for the Stage 2 SFR burner. The TRU/U metallic fuel is irradiated to a burnup of 132 GWd/t in the Stage 2 SFR burner and the discharged UNF is reprocessed and the recovered TRU/U is recycled back to Stage 2. The FP and material losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG33	*Pu/U produced in ADS used to operate PWR in continuous recycle strategy:* In this two-stage Analysis Example, in Stage 1, ternary metallic driver fuel (U-Pu-10Zr) and uranium blanket metallic fuel (U-10Zr) are irradiated in sodium-cooled, fast-spectrum ADS with a fissile conversion ratio greater than 1.0. The average discharge burnup is 77.3 GWd/t for the driver and 11.3 GWd/t for the blanket. The discharged UNF is reprocessed. Recovered Pu/U from the driver fuel and some from the blanket fuel, are recycled and used in making new driver fuel for Stage 1. The RU from the blanket fuel is used with external natural uranium make-up in making new blanket fuel for

Evaluation Group	Description of Analysis Example
	Stage 1. Excess Pu/U recovered from reprocessing of the Stage 1 blanket fuel is sent to Stage 2. MA, FP and material losses from fuel reprocessing are waste that is sent to disposal. Recovered Pu/U from Stage 1 (blanket) and recovered Pu/U from Stage 2 fuel reprocessing are used along with NU make-up in making MOX fuel for the Stage 2 PWR. This fuel is irradiated in Stage 2 PWRs to a burnup of 50 GWd/t and following discharge is reprocessed. The recovered Pu/U is recycled in Stage 2. The MA and FP, and material losses during reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG34	*TRU/U produced in ADS used to operate PWR in continuous recycle strategy:* This is a companion two-stage Analysis Example to the example used for EG33, except TRU recycle is the target in this case. Ternary metal driver fuel (U-TRU-10Zr) and uranium blanket metal fuel (U-10Zr) are irradiated in the Stage 1 sodium-cooled, fast-spectrum ADS with a fissile conversion ratio greater than 1.0. The average discharge burnup is 77.6 GWd/t for the driver and 11.0 GWd/t for the blanket. The discharged UNF is reprocessed. Recovered TRU/U from the driver fuel and some from the blanket fuel, are recycled and used, along with MA from Stage 2, in making new driver fuel for Stage 1. The RU from the reprocessing of the blanket is used with some NU in making new blanket fuel for Stage 1. Excess TRU/U recovered from reprocessing of the blanket is recycled in Stage 2. FP and material losses from fuel reprocessing are waste that is sent to disposal. Recovered TRU/U from Stage 1 (blanket) and recovered Pu/U from Stage 2 are used along with NU make-up in making MOX fuel for stage 2. This fuel is irradiated in Stage 2 PWRs to a burnup of 50 GWd/t and following discharge the UNF is reprocessed to recovered Pu/U that is recycled back into Stage 2. The recovered MA of Stage 2 is used in making the driver fuel of Stage 1. FP and material losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG35	*Continuous recycle of Pu/U from PWR in ADS burner using IMF:* In this two-stage Analysis Example, LEU oxide fuel is irradiated in Stage 1 PWRs to burnup of 50 GWd/t and the discharged UNF is reprocessed. The recovered Pu is recycled in the Stage 2 fast-spectrum ADS. The RU, MA, FP and material losses from fuel reprocessing are waste that is sent to disposal. Recovered Pu from Stage 1 is used is making Pu-Zr dispersion metallic fuel in a zirconium matrix (IMF) for Stage 2. No uranium ensures that no TRU is produced from it and hence enhances the burning of the plutonium. The plutonium-based IMF is irradiated to a burnup of 303 GWd/Mt in the Stage 2 ADS with a conversion ratio of 0.48 and following discharge, the fuel is reprocessed and the recovered Pu is recycled back into Stage 2. The MA, FP and material losses during fuel reprocessing are waste that is sent to disposal. The depleted uranium waste from fuel enrichment and low level waste are also sent to disposal.
EG36	*Continuous recycle of Pu/U in PWR and burning of Minor Actinides in ADS burner using IMF:* In this two-stage Analysis Example, LEU oxide fuel and Pu/U mixed oxide fuel are irradiated in the Stage 1 PWR (heterogenous assemblies with LEU and Pu-MOX) to a burnup of 45 GWd/t and following discharge the UNF is reprocessed. The recovered Pu/U is mixed with some DU from fuel enrichment to fabricate the Pu/U mixed oxide fuel recycled in Stage 1. The FP, material losses, and excess RU from fuel reprocessing, and excess DU are waste that is sent to disposal. The recovered MA from the reprocessing of the discharged UNF from Stage 1 is used in making MA-Zr dispersion metallic fuel in Zr matrix (also called inert matrix fuel) for the Stage 2 sodium-cooled, fast-spectrum ADS. The MA-Zr dispersion fuel is irradiated in the ADS to a burnup of 172 GWd/t and the discharged UNF is reprocessed. The recovered heavy metal (HM) is recycled back into Stage 2. The FP and material losses from reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.

Evaluation Group	Description of Analysis Example
EG37	*Continuous Recycle of TRU/U from PWR in SFR and produce U-233/Th for recycle in Advanced PWR:* This three-stage continuous recycle Analysis Example involves the use of PWRs in Stages 1 and 3 and SFRs in Stage 2. NU is enriched for making LEU oxide fuel for the Stage 1 PWR. This fuel is irradiated to fuel burnup of 50 GWd/t. Following discharge from the Stage 1 PWR, the discharged UNF is reprocessed. The TRU/U is recovered and used in making TRU/U MOX fuel for the Stage 2 SFR. A portion of the DU from the enrichment process is used in Stage 3. The excess DU from the enrichment process, and the excess RU and the FP and material losses from UNF reprocessing in Stage 1 are waste that is sent to disposal. The SFRs in stage 2 are primarily for burning TRU from all stages of the Analysis Example and for creating excess fissile U3 (mostly U-233) for use in Stage 3. The SFR uses driver and blanket fuel assemblies. For the Stage 2 SFR, MOX driver fuel is made from TRU/U from the reprocessing of fuels in Stages 1, 2, and 3. This TRU/U is for making new driver fuel only in Stage 2. Natural Th is used in fabricating initial internal, radial and axial blanket fuels. The driver fuel and the blanket fuel are irradiated to fuel burnups of 103 GWd/t and 14 GWd/t, respectively. Following discharge the UNFs from the SFR are reprocessed. Uranium recovered from blankets, mostly U-233, is used in Stage 3 with denaturing in the separation process (using some DU from the enrichment process for Stage 1). Recovered Th from Stage 2 is used in fabricating blanket fuel for Stage 2 with an additional amount of natural Th as a makeup. The FP and losses from fuel reprocessing are sent to a disposal facility. For the Stage 3 PWRs, uranium (primarily U-233) from blanket fuel of Stage 2 and the DU from Stage 1 are used along with U3/RU from the UNF of Stage 3 (primarily U-233 is fissile material) in making uranium oxide (UOX) fuel for Stage 3. Following irradiation to fuel burnup of 55 GWd/t, the discharged UNF is reprocessed. The recovered TRU/U material is used in making fuel for the Stage 2 SFRs. The U3/RU is recycled within the stage, and the FP and material losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG38	*Continuous Recycle of U-233/Th produced in SFR in PWR:* This two-stage Analysis Example involves U3 recycle using SFR and PWR. The Stage 1 SFR uses driver and blanket zones that are irradiated to fuel burnups of 49 GWd/t and 1.3 GWd/t respectively. The driver fuels in the Stage 1 SFR are loaded with U3/Th that is recovered from the reprocessing of UNF from Stage 1 and external makeup natural Th. The blanket is made from natural Th and recovered Th from the reprocessing of UNF from Stage 1. Excess U3/Th recovered from the reprocessing of the Th blankets is recycled in Stage 2 for making the U3/Th fuel for that stage. Natural Th is used to compensate for the HM mass consumed. FP and material losses from reprocessing are waste that is sent to disposal. The excess recovered U3/Th from Stage 1 and recovered U3/Th from Stage 2 are used in making U3/Th MOX fuel for the Stage 2 PWR. The U3/Th MOX fuel is irradiated to a burnup of 50 GWd/t in the PWR. Discharge UNF is reprocessed and the recovered. U3/Th is recycled back into Stage 2. FP and material losses from fuel reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG39	*Continuous Recycle of U-233 in PWRs and burn TRU in ADS:* This is a three-stage Analysis Example that uses PWRs in Stages 1 and 2 for the recycle of U-233 and a fast-spectrum ADS in Stage 3 for burning TRU. Stage 1 consists of PWRs driven by LEU uranium UOX seed fuel and pure thorium oxide (ThOX) blanket. The core power is derated and the fuel configuration is heterogeneous. The driver and blanket fuels are irradiated to the same burnup of 61.7 GWd/t. The discharged LEU driver fuel is reprocessed and recovered uranium are recycled back into Stage 1 and TRU are recycled into Stage 3. FP, material losses from fuel reprocessing and excess RU are waste that is sent to disposal. Discharged ThOX blanket fuel is reprocessed and the thorium is recycled back into Stage 1, Th/U3 (primarily U-233) is recycled into Stage 2, TRU is recycled to

Evaluation Group	Description of Analysis Example
	Stage 3. FP and material reprocessing losses are waste that is sent to disposal. It was assumed that a fraction of the U-feed for the driver fuel of this stage is NU and RU from Stage 1. The second stage (Stage 2) consists of a PWR using U (primarily U-233) and Th (homogeneous mixture of UOX and ThOX). This fuel is irradiated to fuel burnup of 56 GWd/t within Stage 2. The ThOX is the fertile material; some fraction of the thorium is natural makeup feed and some fraction is Th recycled within Stage 2. A ThOX reprocessing step separates the thorium/uranium, TRU, and FP. The RU/Th is recycled within stage 2, the TRU is used as feed for Stage 3, and the FP and reprocessing losses are waste that is sent to disposal. Stage 3 consists of ADS with an inert matrix fuel (IMF) blanket. The ADS uses TRU makeup feed from the reprocessing steps of Stages 1, 2 and 3. The multiplication factor for the TRU blanket is configured to be sufficiently high that the self-multiplication is substantial. This fuel is irradiated to fuel burnup of 195 GWd/t. The ADS blanket fuel is reprocessed and recycled within stage 3. The FP separated from the blanket and reprocessing losses are waste that is sent to disposal. Any low level waste is also sent to disposal.
EG40	*Produce U-233/Th in ADS and continuously recycle in PWR:* In Stage 1 of this two-stage Analysis Example, lead-cooled fast-spectrum ADS are used to breed uranium (U3, mostly U-233) in a Th blanket fuel that will be used to feed PWRs. The fuel is irradiated to 138 GWd/t. The irradiated ADS fuel is reprocessed, and the recovered U3/Th is used in the making of fuel for Stage 2 and the recovered Th is mixed with natural Th (external feed) and recycled in Stage 1. The FP separated from the blanket and reprocessing losses are waste that is sent to disposal. The PWRs in Stage 2 recycle the U3/Th recovered from the reprocessing of fuel in Stage 2 and the U3/Th from the reprocessing step of Stage 1. The fuel is irradiated to 62.5 GWd/t. A reprocessing step follows that separates the U3/Th which is fed back into the Stage 2 reactor; supplemented by natural thorium as necessary. The TRU and the FP and material losses from reprocessing are waste that is sent to disposal. Any low level waste is also sent to disposal.

For each of the 40 Analysis Examples described above, the following presents the figures for the material flow diagrams and the tables containing the data on reactor and fuel as well as for mass flow.

Evaluation Group EG01

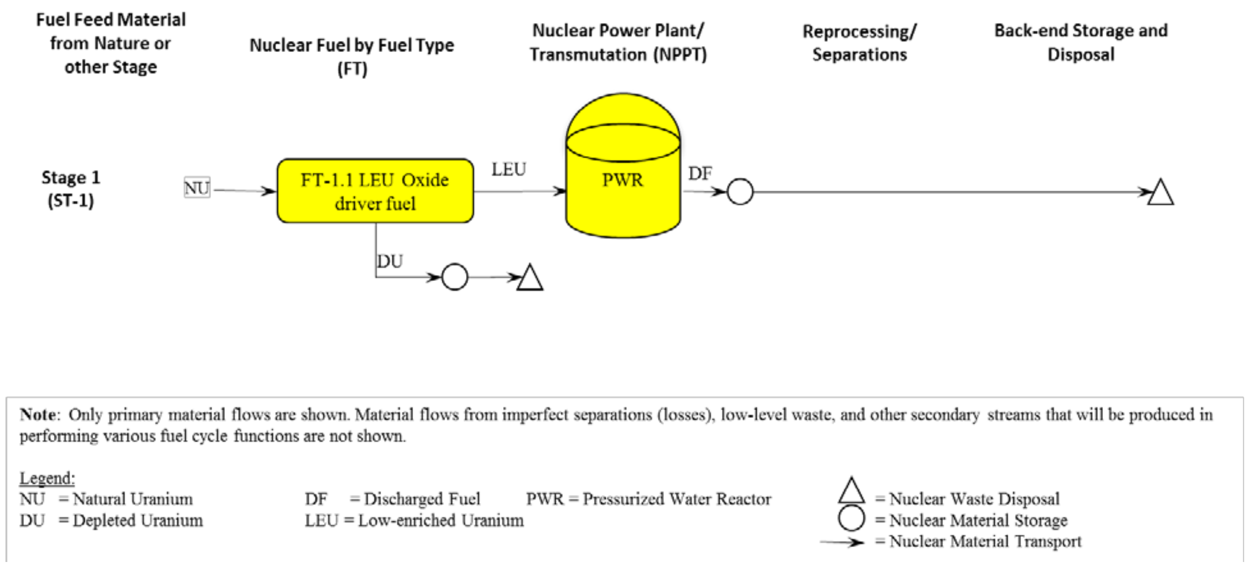


Figure B12. Material Flow Data of Analysis Example for EG01.

Table B14. Reactor and Fuel Information of Analysis Example for EG01.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		PWR
	Core Configuration		PWR with UOX
	Core Thermal Power, MWth		3000
	Net Thermal Efficiency, %		33
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		PWR-UOX
	Purpose		Driver
	Average Discharge Burnup, GWd/t		50
	Fuel Composition	Initial Nuclear Material(s)	LEU
		(U-235+ U-233)/Total U, %	4.21
		Th/Total HM, %	0
		TRU/Total HM, %	0
	Fuel Residence Time in Reactor, EFPY		4.1

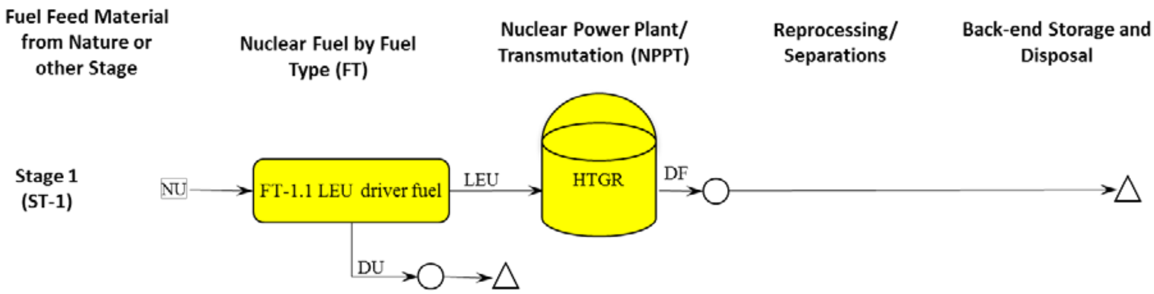
Table B15. Mass Flow Data of Analysis Example for EG01.

Stage		**1**			**Sum** b)
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) a)					
Natural resource	NU	-18,862.8			-18,862.8
	Th				-
Products from fuel or NPPT technology	DU	+16,666.9			+16,666.9
	U	+2,191.5	-2,191.5		0.0
	Pu				
	MA				
	DF		+2,191.5		+2,191.5
Products from Rep/Sep technology	RU				
	Pu				
	MA				
	FP				
Loss		+ 4.4			+ 4.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG02



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
HTGR = High Temperature Gas-Cooled Reactor
DF = Discharged Fuel
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport

U* = primarily U-238 used as fertile material (may include, DU, RU, NU, or blend of these).

Figure B13. Material Flow Data of Analysis Example for EG02.

Table B16. Reactor and Fuel Information of Analysis Example for EG02.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		HTGR
	Core Configuration		Prismatic HTGR with LEU TRISO
	Core Thermal Power, MWth		350
	Net Thermal Efficiency, %		50
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		TRISO-LEU
	Purpose		Driver
	Average Discharge Burnup, GWd/t		120
	Fuel Composition	Initial Nuclear Material(s)	LEU
		(U-235+ U-233)/Total U, %	15.5
		Th/Total HM, %	n.a.
		TRU/Total HM, %	n.a
	Fuel Residence Time in Reactor, EFPY		4.9

Table B17. Mass Flow Data for Analysis Example of EG02.

Stage		**1**			**Sum** [b]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a]					
Natural resource	NU	-20,178.0			-20,178.0
	Th				
Products from fuel or NPPT technology	DU	+19,568.0			+19,568.0
	U	+608.8	-608.8		
	Th				
	Pu				
	MA				
	DF		+608.8 [c]		+608.8
Products from Rep/Sep technology	RU				
	Pu				
	MA				
	FP				
Loss		+1.2			+1.2

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) The 609 tons of spent fuel contain about 2.2% of Pu, 0.2% of MA, 85.1% of U and 12.7% of FP. The U still contains about 5.7% U-235 (together with about 2.3% U-236).

Evaluation Group EG03

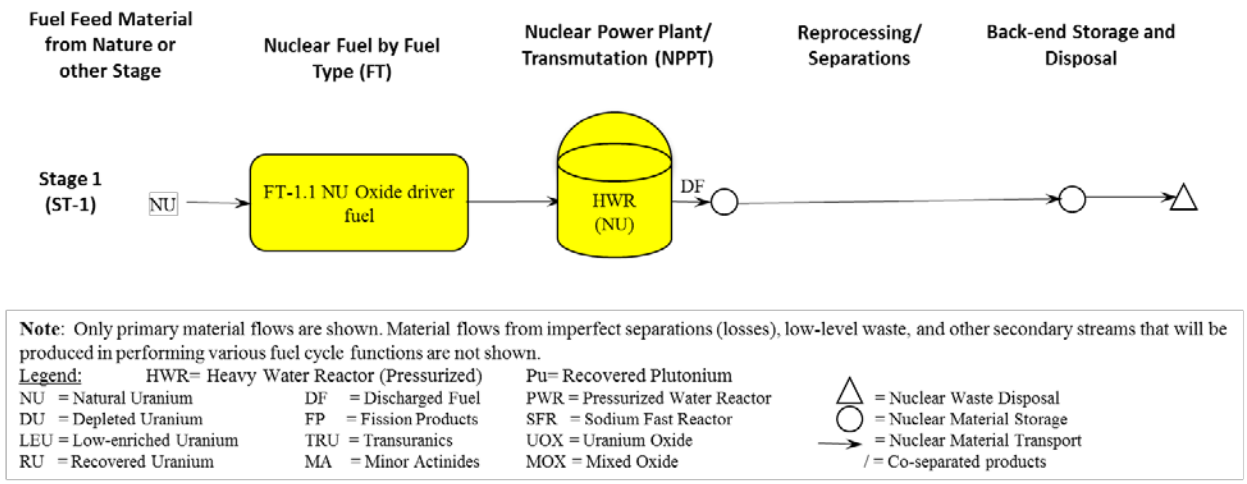


Figure B14. Material Flow Data of Analysis Example for EG03.

Table B18. Reactor and Fuel Information of Analysis Example for EG03.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		HWR (NU)
	Core Configuration		EC6 with 37-element fuel assemblies with UO_2 (380 fuel channels, each with 12 fuel assemblies; on-power fueling)
	Core Thermal Power, MWth		2084
	Net Thermal Efficiency, %		33
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		HWR NU
	Purpose		Driver
	Average Discharge Burnup, GWd/t		7.5
	Fuel Composition	Initial Nuclear Material(s)	NU
		(U-235 + U-233)/Total U, %	0.711
		Th/Total HM, %	0
		TRU/Total HM, %	0
	Fuel Residence Time in Reactor, EFPY		0.63

Table B19. Mass Flow Data of Analysis Example for EG03.

Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	-14,786.7			-14,786.7
	Th				
Products from fuel or NPPT technology	DU				
	U	+14,757.1	-14,757.1		0
	Pu				
	MA				
	DF		+14,757.1		+14,757.1
Products from Rep/Sep technology	RU				
	Pu				
	MA				
	FP				
Loss		+29.6	0		+29.6

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG04

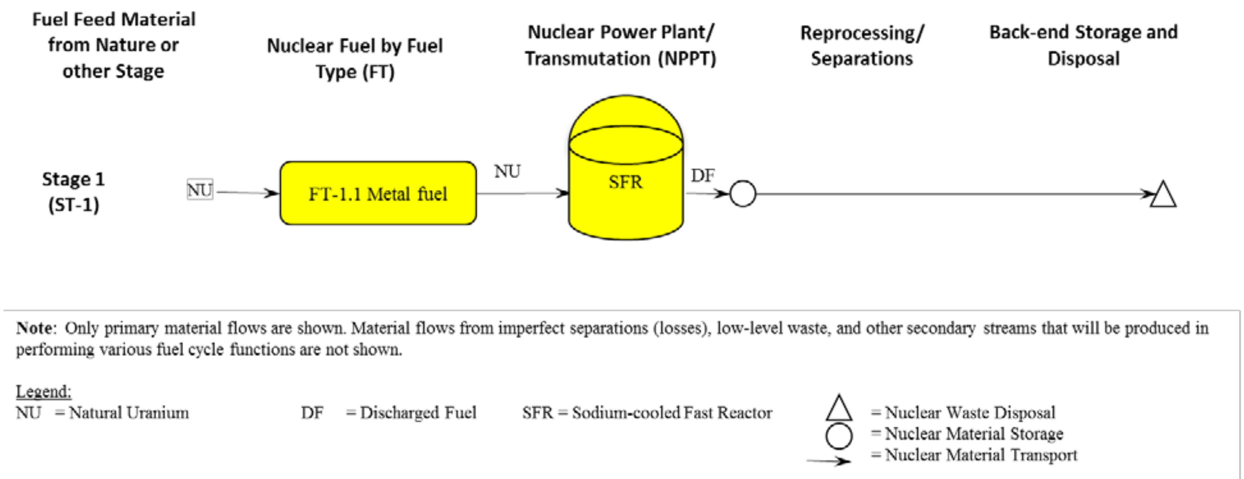


Figure B15. Material Flow Data of Analysis Example for EG04.

Table B20. Reactor and Fuel Information of Analysis Example for EG04.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		SFR
	Core Configuration		SFR-B&B
	Core Thermal Power, MWth		3000
	Net Thermal Efficiency, %		40
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		SFR-metal high burnup
	Purpose		Breed and Burn
	Average Discharge Burnup, GWd/t		276.6
	Fuel Composition	Initial Nuclear Material(s)	NU
		(U-235+ U-233)/Total U, %	0.711
		Th/Total HM, %	0
		TRU/Total HM, %	0
	Fuel Residence Time in Reactor, EFPY		45.9

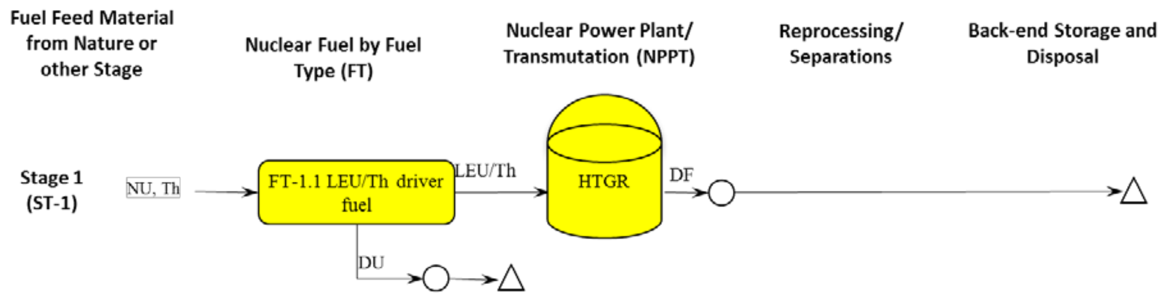
Table B21. Mass Flow Data of Analysis Example for EG04.

Stage		**1**			**Sum** b)
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) a)					
Natural resource	NU	-330.1			-330.1
	Th				-
Products from fuel or NPPT technology	DU				
	U	+329.4	-329.4		0.0
	Pu				
	MA				
	DF		+329.4		+329.4
Products from Rep/Sep technology	RU				
	Pu				
	MA				
	FP				
Loss		+ 0.7			+ 0.7

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG05



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
Th = Thorium
DF = Discharged Fuel
HTGR = High Temperature Gas-Cooled Reactor
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport

U* = primarily U-238 used as fertile material (may include, DU, RU, NU, or blend of these).

Figure B16. Material Flow Data of Analysis Example for EG05.

Table B22. Reactor and Fuel Information of Analysis Example for EG05.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		MHTGR
	Core Configuration		MHTGR with LEU/Th TRISO
	Core Thermal Power, MWth		350
	Net Thermal Efficiency, %		50
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		HTR-TRISO
	Purpose		Driver
	Average Discharge Burnup, GWd/t		97
	Fuel Composition	Initial Nuclear Material(s)	LEU + Th
		(U-235+ U-233)/Total U, %	19.9
		Th/Total HM, %	40.6
		TRU/Total HM, %	0
	Fuel Residence Time in Reactor, EFPY		2.64

Table B23. Mass Flow Data of Analysis Example for EG05.

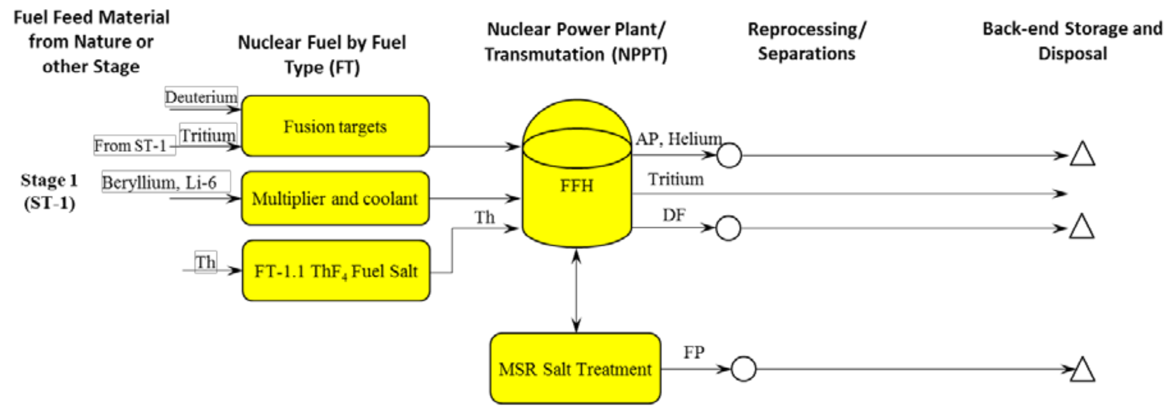
Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	-19,087			-19,087
	Th	-307			-307
Products from fuel or NPPT technology	DU	+18,639			+18,639
	U	+447	-447		
	Th	+306	-306		
	Pu				
	MA				
	DF		+753 [c)]		+753
Products from Rep/Sep technology	RU				
	Pu				
	MA				
	FP				
Loss		+2			+2

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) The 753 tons of spent fuel contain about 1% of Pu and 0.1% of MA, i.e. this HTGR(LEU/Th) once-through fuel cycle option produces almost 3 times less Pu and MA than the standard PWR(LEU) once-through fuel cycle option. The 753 tons of spent fuel also contain 50% of U, 39% of Th and 10% of FP. The U is made up of 1.8% of U-233, 0.2% of U-234, 5.9% of U-235, 3.0% of U-236 and 89.1% of U-238. If this U, which contains 7.7% of fissile isotopes, can be separated and then diluted with DU to obtain the adequate enrichment, it could be used to produce approximately an additional 30 GWe-yr in a PWR(LEU) where the LEU is obtained by blending the RU with some DU.

Evaluation Group EG06



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
ThF_4 = Thorium Tetrafluoride
FFH = Fusion-Fission Hybrid
DF = Discharged Fuel
FP = Fission Products
TRU = Transuranics
MA = Minor Actinides
MSR = Molten Salt Reactor
PWR = Pressurized Water Reactor
SFR = Sodium Fast Reactor
UOX = Uranium Oxide
MOX = Mixed Oxide
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport
/ = Co-separated products
AP = Activation Products from fusion targets, coolant, and beryllium multiplier; storage and disposal requirements are to be determined

Figure B17. Material Flow Data of Analysis Example for EG06.

Table B24. Reactor and Fuel Information of Analysis Example for EG06.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		Fusion-Fission Hybrid
	Core Configuration		ICF with Th molten salt blanket
	Core Thermal Power, MWth		2441
	Net Thermal Efficiency, %		36.41 a)
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		ThF_4 Fuel Salt
	Purpose		Driver
	Average Discharge Burnup, GWd/t		117.71
	Fuel Composition	Initial Nuclear Material(s)	Th
		(U-235+ U-233)/Total U, %	n.a.
		Th/Total HM, %	100
		TRU/Total HM, %	0
	Fuel Residence Time in Reactor, EFPY		3.3

a) Gross electrical power is 1083.8 MW_e, based upon a total thermal power of 2441 MW_{th} and a molten salt thermal conversion efficiency of 44.4%. Net electrical power is 888.8 MW_e after reducing the gross electrical power from fusion by 20 MW_e for the balance of plant and 175 MW_e for the laser systems. The overall system net electrical efficiency is (1083.8 - 20 - 175)/2441=888.8/2441=36.41%.

Table B25. Mass Flow Data of Analysis Example for EG06.

Stage		**1** [c]			**Sum** [b,g]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a]					
Natural resource	NU				
	Th	-678.5			-678.5
	D	-1.21			-1.21
	Li-6 [d] [e]		-3.6		TBD
	Be [f]		TBD		TBD
Products from fuel or NPPT technology	DU				
	Th	+677.2	-677.2		0.0
	D	+1.21	-1.21		0.0
	T [h]	(+1.81)	(-1.81)		0.0
	He		+4.81		+4.81
	FP [i]		+41.6		+41.6 [i]
	DF		+635.5		+635.5
Products from Rep/Sep technology					
Loss		+1.4	0.0		+1.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) Mass flow rates in this table are calculated based upon a total net electrical output of 1083.8 MW_e from a single FFH(Th) molten salt system. The fission blanket produces 861.8 MWe. The fusion system produces 27 MW_e net after powering the lasers and balance of plant.

d) Mass flow data for Li-6 is TBD because it depends on specific reaction rates in the first wall coolant and molten salt fuel that have not yet been determined; the Li-6 mass flow rate would be designed to meet the tritium production requirements of the system.

e) Not enough data is currently available to estimate the natural lithium mass required to meet the Li-6 mass flow rate requirement.

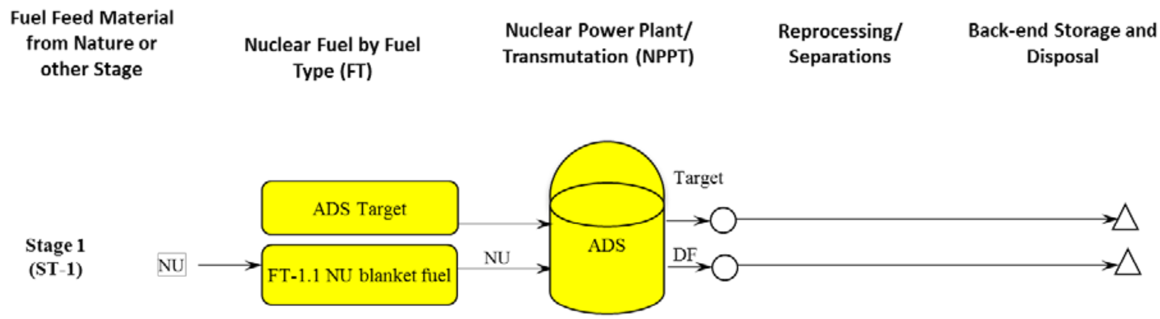
f) Mass flow data for Be is TBD because the mass flow rate to maintain the neutron multiplier region is yet to be determined.

g) Neutron masses are not included in this table. About 0.056 t of neutrons are produced by fusion, and the same mass of neutron is necessary to breed T; therefore, the two flows balance out and do not affect the mass balance in this table.

h) The FFH is required to be tritium self-sufficient, so tritium consumed by fusion and produced by (n,T) reactions on Li-6 balance out. Mass data for T are shown in parentheses for completeness, but are not to be included in the mass balance as loss and production cancel out.

i) This FP waste stream results from treatment processes in operation of reactor. Additional FP masses exist within the DF waste stream.

Evaluation Group EG07



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
RU = Recovered Uranium/U233 (U233 of the thorium/U-stream)

DF = Discharged Fuel
FP = Fission Products
TRU = Transuranics
ThOX = Thorium Oxide

PWR = Pressurized Water Reactor
ADS = Accelerator Driven System
UOX = Uranium Oxide
MOX = Mixed Oxide

△ = Nuclear Waste Disposal
= Nuclear Material Storage
○ = Nuclear Material Transport
→/ = Co-separated products

Figure B18. Material Flow Data of Analysis Example for EG07.

Table B26. Reactor and Fuel Information of Analysis Example for EG07.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		ADS-Burner
	Core Configuration		ADS with U-Zr Blanket Fuel
	Core Thermal Power, MWth		1000
	Net Thermal Efficiency, %		40 (27.7)[a)]
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		SFR-Metallic
	Purpose		Driver
	Average Discharge Burnup, GWd/t		55.2
	Fuel Composition	Initial Nuclear Material(s)	NU
		(U-235+ U-233)/Total U, %	0.711
		Th/Total HM, %	0
		TRU/Total HM, %	0
	Fuel Residence Time in Reactor, EFPY		6

a) The thermal efficiency assumed was 40 %. The electric power required for the accelerator is 123 MWe. Thus, accounting for the accelerator electric power requirements, the net thermal efficiency is 27.7 %.

Table B27. Mass Flow Data of Analysis Example for EG07.

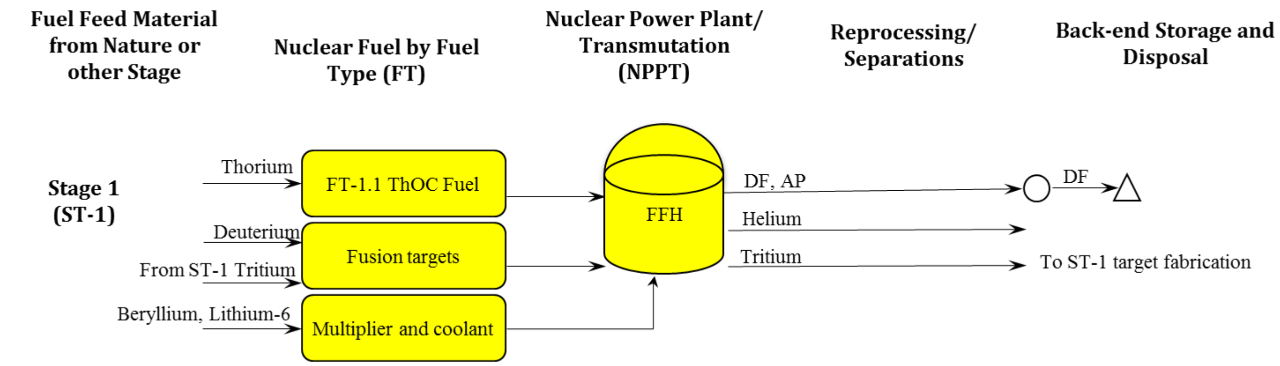
Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	-2,393.8			-2,393.8
	Target(Pb)	-386.0			-386.0
Products from fuel or NPPT technology	DU	+0.0			+0.0
	Target(Pb)	+385.3	-385.3		0.0
	U	+2,389	-2,389		0.0
	Target Discharge		+385.3		+385.3
	DF		+2,389		+2,389
Products from Rep/Sep technology	RU				
	Th				
	U233				
	TRU				
	FP				
Loss		+5.5 [c)]	0.0		+5.5

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) Loss includes 0.7 metric tons (assumed to be 0.2%) from target fabrication.

Evaluation Group EG08



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium	DF = Discharged Fuel	FFH = Fusion-Fission Hybrid	△ = Nuclear Waste Disposal
DU = Depleted Uranium	FP = Fission Products	SFR = Sodium Fast Reactor	○ = Nuclear Material Storage
LEU = Low-enriched Uranium	TRU = Transuranics	UOX = Uranium Oxide	→ = Nuclear Material Transport
RU = Recovered Uranium	MA = Minor Actinides	MOX = Mixed Oxide	Pu/RU = Co-separated products

PWR = Pressurized Water Reactor
AP = Activation Products from fusion targets, coolant, and beryllium multiplier; storage and disposal requirements are to be determined
U* = primarily U-238 used as fertile material (may include, DU, RU, NU, or blend of these).

Figure B19. Material Flow Data of Analysis Example for EG08.

Table B28. Reactor and Fuel Information of Analysis Example for EG08.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**
	NPPT Technology Identifier		TDF: Fusion-Fission Hybrid
	Core Configuration		ICF FLiBe cooled pebbles with Th
	Core Thermal Power, MWth		1500 from fission, 500 from fusion[a)]
	Net Thermal Efficiency, %		33.25 [b)]
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		TDF: FFH-ThOC
	Purpose		Sub-critical thorium breed and burn
	Average Discharge Burnup, GWd/t		729 [c)]
	Fuel Composition	Initial Nuclear Material(s)	Th
		(U-235+ U-233)/Total U, %	n.a.
		Th/Total HM, %	100
		TRU/Total HM, %	0
	Fuel Residence Time in Reactor, (EFPY)		53.2

a) Fusion power is that generated directly by fusion targets. Fission power includes all nuclear reactions in the tritium-breeding and fission blankets. Fission power is zero at start up and requires about 2 years to reach the nominal value.

b) Gross electrical power is 43% (Brayton Cycle) x 2000 MWe. Net electrical power is reduced by 20 MWe for the balance of plant and 175 MWe for the laser. The net electrical efficiency is (860-20-175)/2000 = 665/2000 = 33.25%.
c) Burnup is energy from fission reactions (from the neutronics calculations) divided by 40 MT of initial thorium.

Table B29. Mass Flow Data of Analysis Example for EG08.

Stage		**1** [c)]			**Sum** [b) e)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	Th	-113.17			-113.17
	D	-1.21			-1.21
	Li-6 [f)]		-3.60		-3.60
	Be		TBD		TBD
Products from fuel or NPPT technology	Th	+112.94	-112.94		0.0
	D [d)]	+1.21	-1.21		0.0
	T [d)]	[g)] (+1.81)	(-1.81)		0.0
	DF		+112.94		+112.94
	He [d)]		+4.81		+4.81
Products from Rep/Sep technology					
Loss		+0.23	0.0		+0.23

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr per year.
c) This table assumes that 97% of the electricity is produced by fission and 3% by fusion. The remaining electricity generated by fusion is used to power lasers and balance of plant.
d) Mass flow data for D, T, and He correspond to the minimum required and do not include losses due to fuel fabrication, recovery, and tritium decay.
e) Neutron masses are not included in this table. About 0.056 t of neutrons are produced by fusion, and the same mass of neutron is necessary to breed T; therefore, the two flows balance out and do not affect the mass balance in this table.
f) Not enough data are currently available to estimate natural lithium mass.
g) Under the tritium self-sufficiency assumption, tritium is consumed by fusion and produced by (n,T) reactions on Li-6 in equal amounts. Mass data for T are shown in parentheses for completeness, but are not to be included in the mass balance as loss and production cancel out.

Evaluation Group EG09

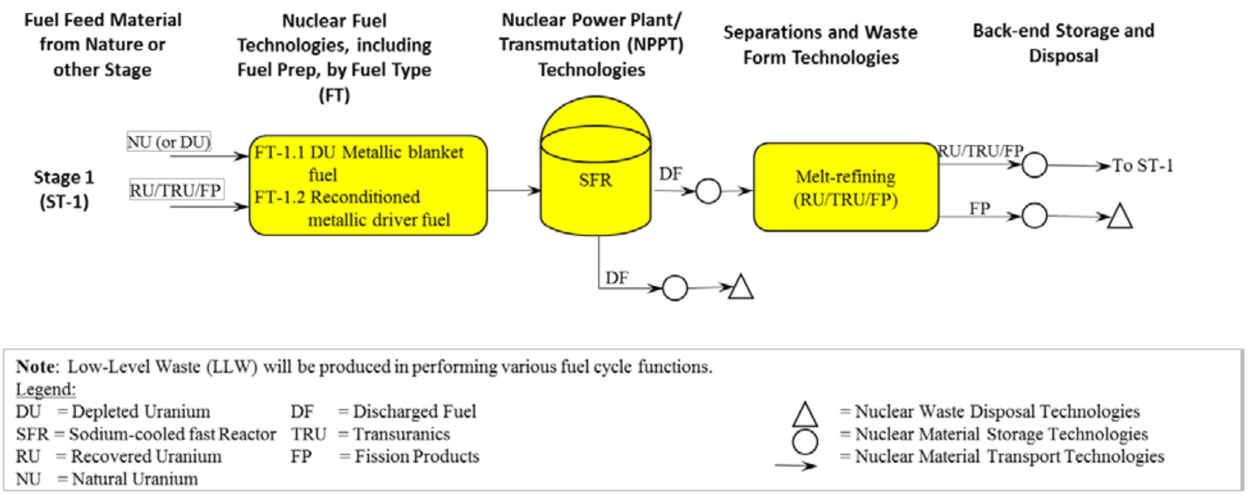


Figure B20. Material Flow Data of Analysis Example for EG09.

Table B30. Reactor and Fuel Information of Analysis Example for EG09.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		SFR	
	Core Configuration		SFR-B&B	
	Core Thermal Power, MWth		3000	
	Net Thermal Efficiency, %		40	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		SFR metallic fuel	Recycled SFR metallic fuel
	Purpose		Blanket	Driver
	Average Discharge Burnup, GWd/t		69	[a] 492
	Fuel Composition	Initial Nuclear Material(s)	NU (or DU)	U/TRU/FP
		(U-235+ U-233)/Total U, %	0.711 (0.25)	~0.1
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	8.5-11.2
	Fuel Residence Time in Reactor, EFPY		23.8	15.9/15.9/7.9 [b]

a) Average burnup when the fuel is discarded, relative to the initial mass of heavy metal.
b) The two first values correspond to the residence time between reprocessings and the third value corresponds to the residence time before discharge

Table B31. Mass Flow Data of Analysis Example for EG09.

Stage		**1**			**Sum** [b]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) [a]					
Natural resource	NU	-185.8			-185.8
	Th				-
Products from fuel or NPPT technology	DU				
	U	541.3	-541.3		0.0
	Pu	48.8	-48.8		0.0
	MA	0.7	-0.7		0.0
	FP	54.4	-54.4		0.0
	DF		645.1	-514.5	[c] 130.7
Products from Rep/Sep technology	RU	-356.5		356.5	0.0
	Pu	-48.9		48.9	0.0
	MA	-0.7		0.7	0.0
	FP-recycled	-54.5		54.5	0.0
	FP-removed			48.7	48.7
Loss		1.3		5.1	6.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) Discharged fuel contains 43.4 t of FP, 72.6 t of uranium and 14.7 t of TRU. During the reprocessings, 49.2 t of FP have been removed/lost from the fuel.

Evaluation Group EG10

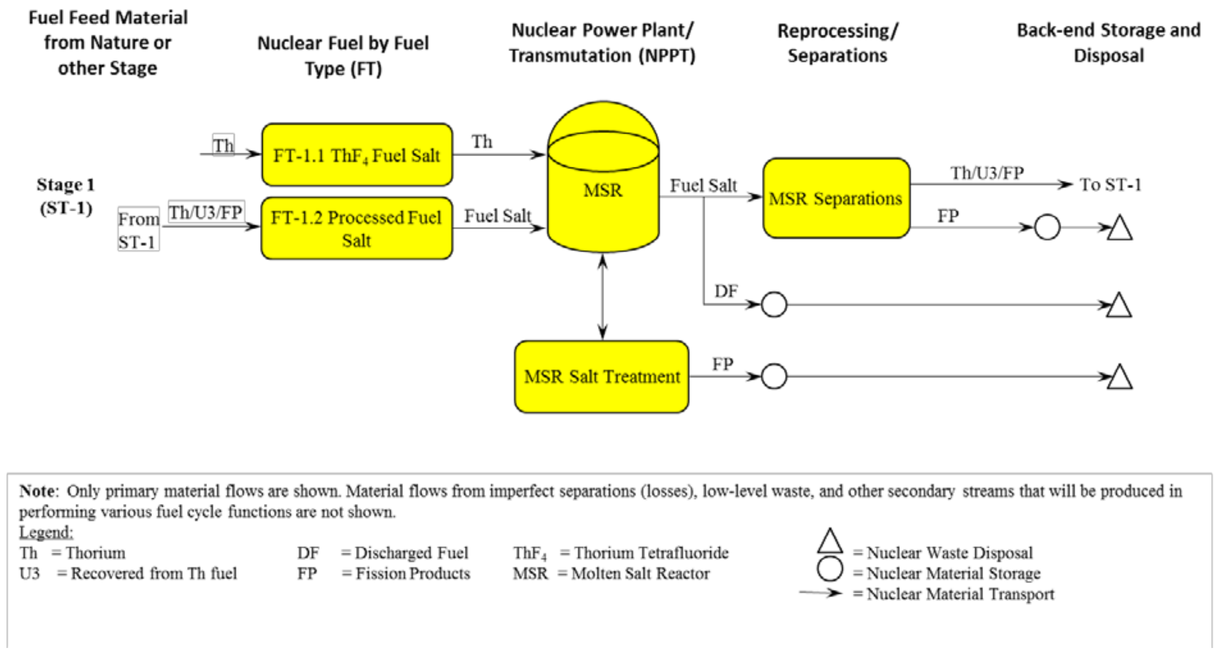


Figure B21. Material Flow Data of Analysis Example for EG10.

Table B32. Reactor and Fuel Information of Analysis Example for EG10.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		MSR	
	Core Configuration		MSR-Th	
	Core Thermal Power, MWth		2250	
	Net Thermal Efficiency, %		44.4	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		ThF_4 Fuel Salt	Processed Fuel Salt
	Purpose		Blanket	Driver/Blanket
	Average Discharge Burnup, GWd/t		n.a. [a)]	101.9 [b)]
	Fuel Composition	Initial Nuclear Material(s)	Th	Th/U3
		(U-235+ U-233)/Total U, %	n.a.	77.0
		Th/Total HM, %	100	98.0
		TRU/Total HM, %	0	<0.01
	Fuel Residence Time in Reactor, EFPY		n.a.	8.8 (avg.) [b)]

a) The average discharge burnup for ThF_4 fuel salt is “not applicable” because it gets chemically mixed into the Processed Fuel Salt.

b) The discharge burnup and residence time values above are calculated based upon time from fresh feed until actual discharge to waste. For a “single pass” of salt entering the MSR until it goes through separations, the average residence time would be 3.0 days and burnup would be 0.095 GWd/t.

Table B33. Mass Flow Data of Analysis Example for EG10.

Stage		1			Sum b)
Technology		Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) a)					
Natural resource	NU				
	Th	-807.0			-807.0
Products from fuel or NPPT technology	DU				
	U3 c)	+17,342.7	-17,342.7		0.0
	Th d)	+849,178.5	-849,178.5		0.0
	Pu	+0.0	-0.0		0.0
	MA	+0.0	-0.0		0.0
	FP e)	+7,669.5	-7,669.5		0.0
	DF f)		+874,190.7	-873,424.0	+766.7
Products from Rep/Sep technology	U3 c)	-17,342.7		+1,7343.3	+0.5
	Th	-848,373.1		+848,373.1	+0.0
	Pu	-0.0		+0.0	+0.0
	MA	-0.0		+0.0	+0.0
	FP	-7,669.5		+7,706.7	+37.2
Loss		+1.6		+1.0 g)	+2.6

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively. For this molten salt system, the mass flows represent flow of material through salt processing systems and subsequent return to the reactor via a small continuous bypass stream; these mass flow rates are extremely high due to the fuel salt continuously circulating in and out of the “core” region. The numbers in this table correspond to the full MSR salt inventory flowing through the system 121.67 times per year.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) U3 in this table is actually the sum of U and Pa; this is approximated in this manner due to the fact that Pa directly decays to U. In addition, U3 is not high quality U-233, but rather simply designates that the uranium is recovered for thorium fuels; the fissile content of the U is noted elsewhere.

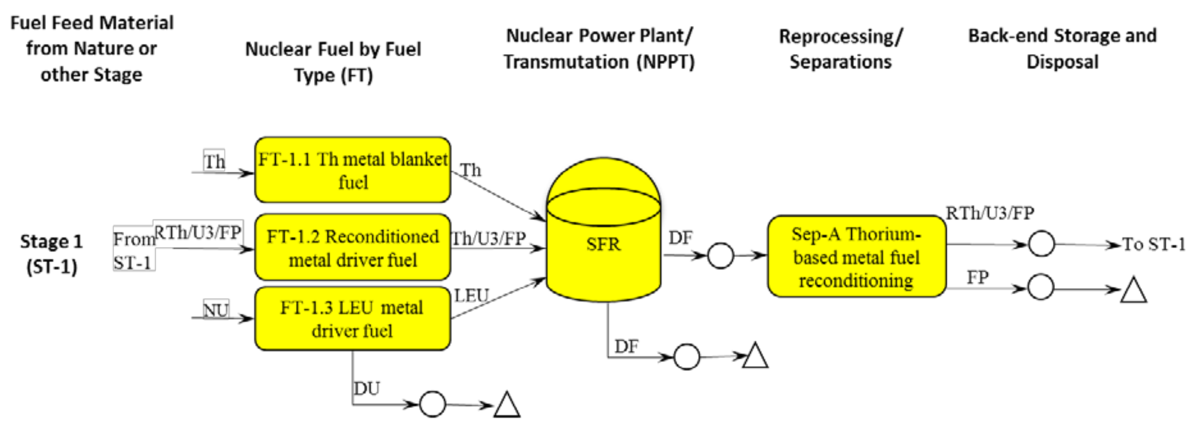
d) Th has been added as a product to account for Th natural resource being used in fuel for NPPT and Th being a product from MSR Separations.

e) Salt treatment that occurs in the NPPT stage of MSR operations adds an FP stream as a product from NPPT technology, accounting for species removed from the fuel in the NPPT stage and sent for waste disposal.

f) The “Sum” for DF includes two separate waste streams: directly discarded fuel (724.4 MT) and FP from salt treatment within the NPPT stage (42.3 MT).

g) Based on MSBR separation process losses.

Evaluation Group EG11



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.
Legend:
NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
U3 = Recovered uranium from thorium stream
DF = Discharged Fuel
FP = Fission Products
TRU = Transuranics
PWR = Pressurized Water Reactor
SFR = Sodium Fast Reactor
UOX = Uranium Oxide
RTh = Recycled thorium
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport
/ = Co-separated products

Figure B22. Material Flow Data of Analysis Example for EG11.

Table B34. Reactor and Fuel Information of Analysis Example for EG11.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		
	NPPT Technology Identifier		SFR		
	Core Configuration		SFR with LEU, Th and Th-U3		
	Core Thermal Power, MWth		3000		
	Net Thermal Efficiency, %		40		
	Electrical Energy Generation Sharing, %		100		
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**1.3**
	Fuel Technology Identifier		SFR-Metallic	SFR-Metallic	SFR-Metallic
	Purpose		Blanket	Driver	Driver
	Average Discharge Burnup, GWd/t		64	[a] 377	130
	Fuel Composition	Initial Nuclear Material(s)	Th	RTh/U3/FP	LEU
		(U-235+ U-233)/Total U, %	0	50-80	19.9
		Th/Total HM, %	100	60-93	0
		TRU/Total HM, %	0	<1.5	0
	Fuel Residence Time in Reactor, EFPY		14.2	7.1-21.4	7.1

a) Average burnup when the fuel is discarded. Burnup accumulated between two reprocessings is <150 GWd/t

Table B35. Mass Flow Data of Analysis Example for EG11.

Stage		1			Sum [b)]
Technology		Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	-8,810.9			-8,810.9
	Th	-169.3			-169.3
Products from fuel or NPPT technology	DU	8,604.2			8,604.2
	Th	545.1	-545.1		0.0
	U	246.4	-246.4		0.0
	Pu	0.0	-0.0		0.0
	MA	0.9	-0.9		0.0
	FP	28.4	-28.4		0.0
	DF		820.7	-479.5	341.2
Products from Rep/Sep technology	RTh	-376.8		376.8	0.0
	U3 [c)]	-40.2		40.2	0.0
	Pu	-0.0		0.0	0.0
	MA	-0.9		0.9	0.0
	FP-recycled	-28.4		28.4	0.0
	FP-removed			28.4	28.4
Loss		1.6		4.8	6.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) Recovered Uranium from Thorium stream (mostly U-233).

Evaluation Group EG12

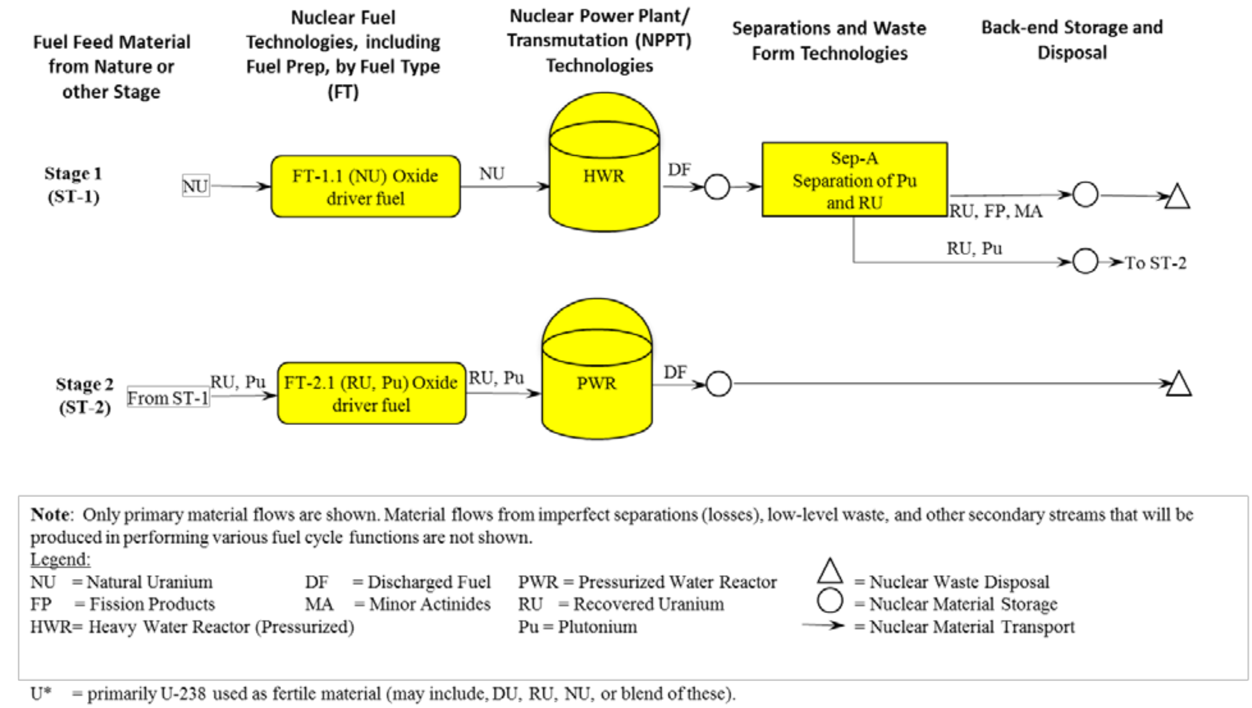


Figure B23. Material Flow Data of Analysis Example for EG12.

Table B36. Reactor and Fuel Information of Analysis Example for EG12.

<table>
<tr><th>Technology category</th><th colspan="2">Parameter</th><th colspan="2">Stage Number</th></tr>
<tr><td rowspan="6">Nuclear Power Plant/ Transmutation (NPPT)</td><td colspan="2">Stage</td><td>1</td><td>2</td></tr>
<tr><td colspan="2">NPPT Technology Identifier</td><td>HWR</td><td>PWR</td></tr>
<tr><td colspan="2">Core Configuration</td><td>HWR with NU oxide</td><td>PWR with RU, Pu</td></tr>
<tr><td colspan="2">Core Thermal Power, MWth</td><td>2084</td><td>3411</td></tr>
<tr><td colspan="2">Net Thermal Efficiency, %</td><td>33</td><td>33</td></tr>
<tr><td colspan="2">Electrical Energy Generation Sharing, %</td><td>76.1</td><td>23.9</td></tr>
<tr><td rowspan="9">Nuclear Fuel</td><td colspan="2">Fuel Type</td><td>1.1</td><td>2.1</td></tr>
<tr><td colspan="2">Fuel Technology Identifier</td><td>HWR NU fuel</td><td>PWR RU, Pu fuel</td></tr>
<tr><td colspan="2">Purpose</td><td>Driver</td><td>Driver</td></tr>
<tr><td colspan="2">Average Discharge Burnup, GWd/t</td><td>7.5</td><td>50.0</td></tr>
<tr><td rowspan="4">Fuel Composition</td><td>Initial Nuclear Material(s)</td><td>NU</td><td>Mixed</td></tr>
<tr><td>(U-235+ U-233)/Total U, %</td><td>0.711</td><td>0.225</td></tr>
<tr><td>Th/Total HM, %</td><td>0</td><td>0</td></tr>
<tr><td>TRU/Total HM, %</td><td>0</td><td>7.995</td></tr>
<tr><td colspan="2">Fuel Residence Time in Reactor, EFPY</td><td>0.63</td><td>3.54</td></tr>
</table>

Table B37. Mass Flow Data of Analysis Example for EG12.

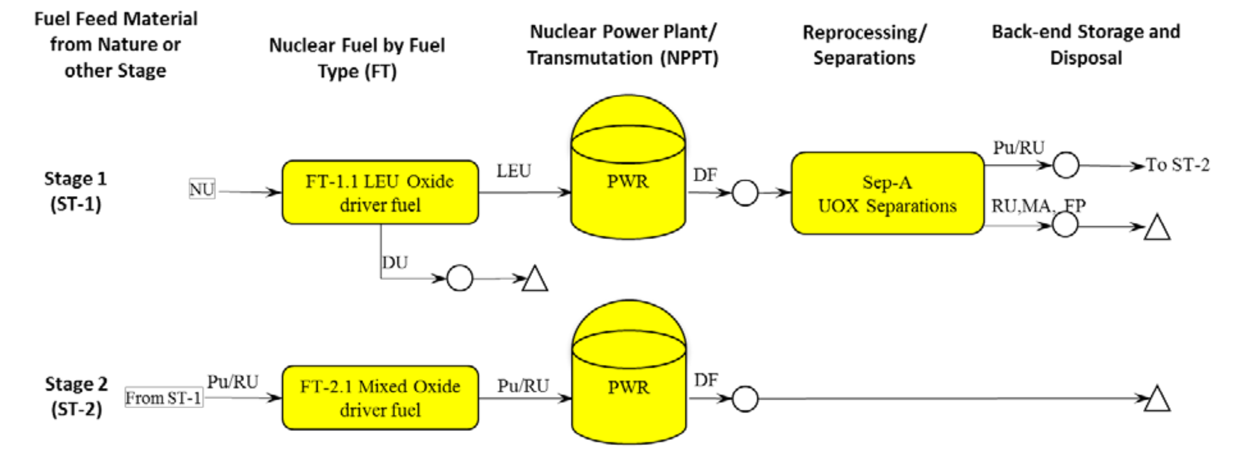
Stage		**1**			**2**			[b] **Sum**
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		76.1			23.9			100.0
Feed or product of nuclear materials (metric ton) [a]								
Natural resource	NU	-11,246.4						-11,246.4
	Th							
Products from fuel or NPPT technology	DU							
	U	+11,224.0	-11,224.0		+486.2	-486.2		0
	Pu				[c] +42.2	-42.2		0
	MA							0
	DF		+11,224.0	-11,224.0		+528.4		+528.4
Products from Rep/Sep technology	RU			+10,982.8	-487.1			+10,495.7
	Pu			+42.3	-42.3			+0
	MA			+0.9				+0.9
	FP			+85.8				+85.8
Loss		+22.4	+0	+112.2	+1.0	+0		+135.6

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) The small amount of Pu-241 decay to Am-241 that takes place while fuel waits to be loaded is not explicitly shown; the fuel could be used promptly since it contains Pu instead of waiting the allowed 0.5 years lag time.

Evaluation Group EG13



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium	DF = Discharged Fuel	PWR = Pressurized Water Reactor	△ = Nuclear Waste Disposal
DU = Depleted Uranium	FP = Fission Products	SFR = Sodium Fast Reactor	○ = Nuclear Material Storage
LEU = Low-enriched Uranium	Pu = Plutonium	UOX = Uranium Oxide	→ = Nuclear Material Transport
RU = Recovered Uranium	MA = Minor Actinides	/ = Co-separated products	

Figure B24. Material Flow Data of Analysis Example for EG13.

Table B38. Reactor and Fuel Information of Analysis Example for EG13.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	PWR
	Core Configuration		PWR with UOX	PWR with MOX
	Core Thermal Power, MWth		3000	3000
	Net Thermal Efficiency, %		33.3	33.3
	Electrical Energy Generation Sharing, %		90.2	9.8
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR-UOX	PWR–MOX
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		50	50
	Fuel Composition	Initial Nuclear Material(s)	LEU	Pu/RU
		(U-235+ U-233)/Total U, %	4.21	0.79
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	10.73
	Fuel Residence Time in Reactor, EFPY		4.1	4.1

Table B39. Mass Flow Data of Analysis Example for EG13.

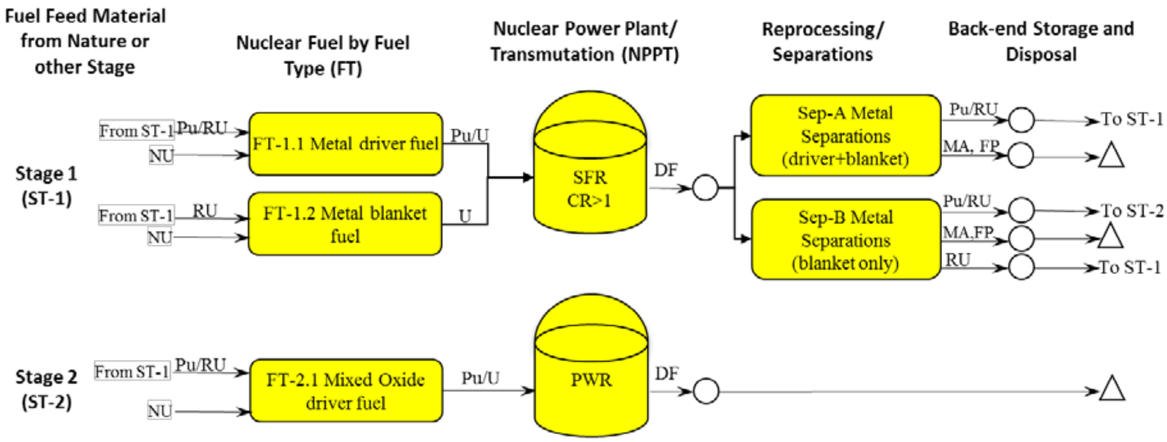
Stage		**1**			**2**			**Sum** [b]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		90.2			9.8			100
Feed or product of nuclear materials (metric ton) [a]								
Natural resource	NU	-16,961.9						-16,961.9
	Th							-
Products from fuel or NPPT technology	DU	+14,983.3						+14,983.3
	U	+1,974.7	-1,974.7		+ 192.2	-192.2		0.0
	Pu				[c] + 23.1	-23.1		0.0
	DF		+1,974.7	-1,974.7		+215.3		+215.3
Products from Rep/Sep technology	RU			+1,827.4	-192.6			+1,634.9
	Pu			+23.1	[c] -23.1			0.0
	MA			+2.5				+2.5
	FP			+ 101.9				+101.9
Loss		+3.9	0.0	+19.7	+0.4			+24.1

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) Pu and its decay daughters.

Evaluation Group EG14



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium	DF = Discharged Fuel	PWR = Pressurized Water Reactor	△ = Nuclear Waste Disposal
DU = Depleted Uranium	FP = Fission Products	SFR = Sodium Fast Reactor	○ = Nuclear Material Storage
LEU = Low-enriched Uranium	TRU = Transuranics	UOX = Uranium Oxide	→ = Nuclear Material Transport
RU = Recovered Uranium	MA = Minor Actinides	MOX = Mixed Oxide	Pu/RU = Co-separated products

U* = primarily U-238 used as fertile material (may include, DU, RU, NU, or blend of these).

Figure B25. Material Flow Data of Analysis Example for EG14.

Table B40. Reactor and Fuel Information of Analysis Example for EG14.

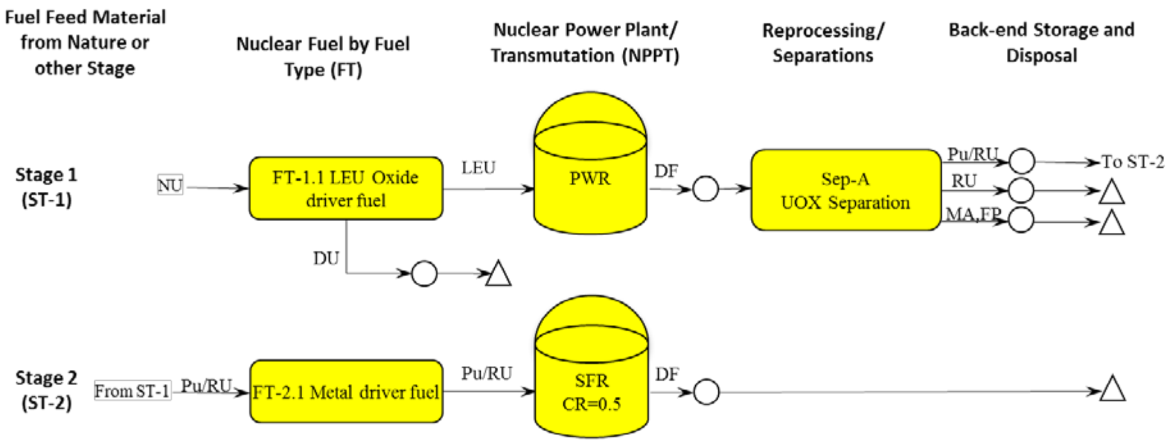
<table>
<tr><th>Technology category</th><th colspan="2">Parameter</th><th colspan="3">Stage Number</th></tr>
<tr><td rowspan="6">Nuclear Power Plant/ Transmutation (NPPT)</td><td colspan="2">Stage</td><td colspan="2">1</td><td>2</td></tr>
<tr><td colspan="2">NPPT Technology Identifier</td><td colspan="2">SFR-Breeder</td><td>PWR</td></tr>
<tr><td colspan="2">Core Configuration</td><td colspan="2">SFR with (UPu) metal fuel</td><td>PWR with (UPu)O_2, i.e. MOX</td></tr>
<tr><td colspan="2">Core Thermal Power, MWth</td><td colspan="2">1000</td><td>3000</td></tr>
<tr><td colspan="2">Net Thermal Efficiency, %</td><td colspan="2">40</td><td>33</td></tr>
<tr><td colspan="2">Electrical Energy Generation Sharing, %</td><td colspan="2">70.6</td><td>29.4</td></tr>
<tr><td rowspan="9">Nuclear Fuel</td><td colspan="2">Fuel Type</td><td>1.1</td><td>1.2</td><td>2.1</td></tr>
<tr><td colspan="2">Fuel Technology Identifier</td><td>SFR-Metal</td><td>SFR-Metal</td><td>PWR-MOX</td></tr>
<tr><td colspan="2">Purpose</td><td>Driver</td><td>Blanket</td><td>Driver</td></tr>
<tr><td colspan="2">Average Discharge Burnup, GWd/t</td><td>96.8</td><td>20.7</td><td>50</td></tr>
<tr><td rowspan="4">Fuel Composition</td><td>Initial Nuclear Material(s)</td><td>Pu/RU/NU</td><td>RU/NU</td><td>Pu/RU/NU</td></tr>
<tr><td>(U-235+ U-233)/Total U, %</td><td>~0.2</td><td>~0.2</td><td>~0.7</td></tr>
<tr><td>Th/Total HM, %</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>TRU/Total HM, %</td><td>21.4</td><td>0</td><td>4.21</td></tr>
<tr><td colspan="2">Fuel Residence Time in Reactor, EFPY</td><td>4.75</td><td>9.5</td><td>3.9</td></tr>
</table>

Table B41. Mass Flow Data of Analysis Example for EG14.

Stage		**1**			**2**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		70.63			29.37			100
Feed or product of nuclear materials (metric ton) [a)]								
Natural resource	NU	-138.3 [c)]			-596.6 [c)]			-734.9
	Th							
Products from fuel or NPPT technology	DU							
	U	+1,297.1	-1,297.1		+622.7	-622.7		
	Th							
	Pu	[f)] +98.5	-98.5		[f)] +27.4	-27.4		
	MA							
	DF		+1,395.6 [d)]	-1,395.6		+650.1 [e)]		+650.1
Products from Rep/Sep technology	RU	-1,161.6		+1,189.0	-27.4			
	Pu	-98.5		+125.9	-27.4			
	MA			+1.7				+1.7
	FP			+65.0				+65.0
Loss		+2.8		+14.0	+1.3			+18.1

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) The use of NU is only necessary when the legacy DU has been fully utilized, i.e. if DU is available it can be used.
d) About 1/3 is driver fuel and 2/3 is blanket.
e) The 650 tons of MOX spent fuel contain about 2.7% of Pu and 0.22% of MA, i.e. about 35% of the Pu initially loaded in the MOX fuel has been transmuted.
f) Pu and its decay daughters.

Evaluation Group EG15



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium	DF = Discharged Fuel	PWR = Pressurized Water Reactor	△ = Nuclear Waste Disposal
DU = Depleted Uranium	FP = Fission Products	SFR = Sodium Fast Reactor	○ = Nuclear Material Storage
LEU = Low-enriched Uranium	TRU = Transuranics	UOX = Uranium Oxide	→ = Nuclear Material Transport
RU = Recovered Uranium	MA = Minor Actinides	MOX = Mixed Oxide	Pu/RU = Co-separated products

U* = primarily U-238 used as fertile material (may include, DU, RU, NU, or blend of these).

Figure B26. Material Flow Data of Analysis Example for EG15.

Table B42. Reactor and Fuel Information of Analysis Example for EG15.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	SFR-Burner
	Core Configuration		PWR with UOX	SFR with (UPu) metal fuel
	Core Thermal Power, MWth		3000	1000
	Net Thermal Efficiency, %		33	40
	Electrical Energy Generation Sharing, %		88.1	11.9
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR-UOX	SFR-Metal
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		51	127
	Fuel Composition	Initial Nuclear Material(s)	LEU	Pu/RU
		(U-235+ U-233)/Total U, %	4.30	~0.8
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	25.9
	Fuel Residence Time in Reactor, EFPY		4.1	3.65

Table B43. Mass Flow Data of Analysis Example for EG15.

Stage		1			2			Sum b)
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		88.1			11.9			100
Feed or product of nuclear materials (metric ton) a)								
Natural resource	NU	-16,837.8						-16,837.8
	Th							
Products from fuel or NPPT technology	DU	+14,921.2						+14,921.2
	U	+1,912.8	-1,912.8		+63.2	-63.2		
	Th							
	Pu				+22.0	-22.0		
	MA							
	DF		+1,912.8	-1,912.8		+85.2 c)		+85.2
Products from Rep/Sep technology	RU			+1,769.6	-63.4			+1,706.2
	Pu			+22.0	-22.0			
	MA			+2.5				+2.5
	FP			+99.6				+99.6
Loss		+3.8		+19.1	+0.2			+23.1

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) At discharge, the 85.2 tons of spent fuel contain about 20% of Pu and 0.6% of MA.

Evaluation Group EG16

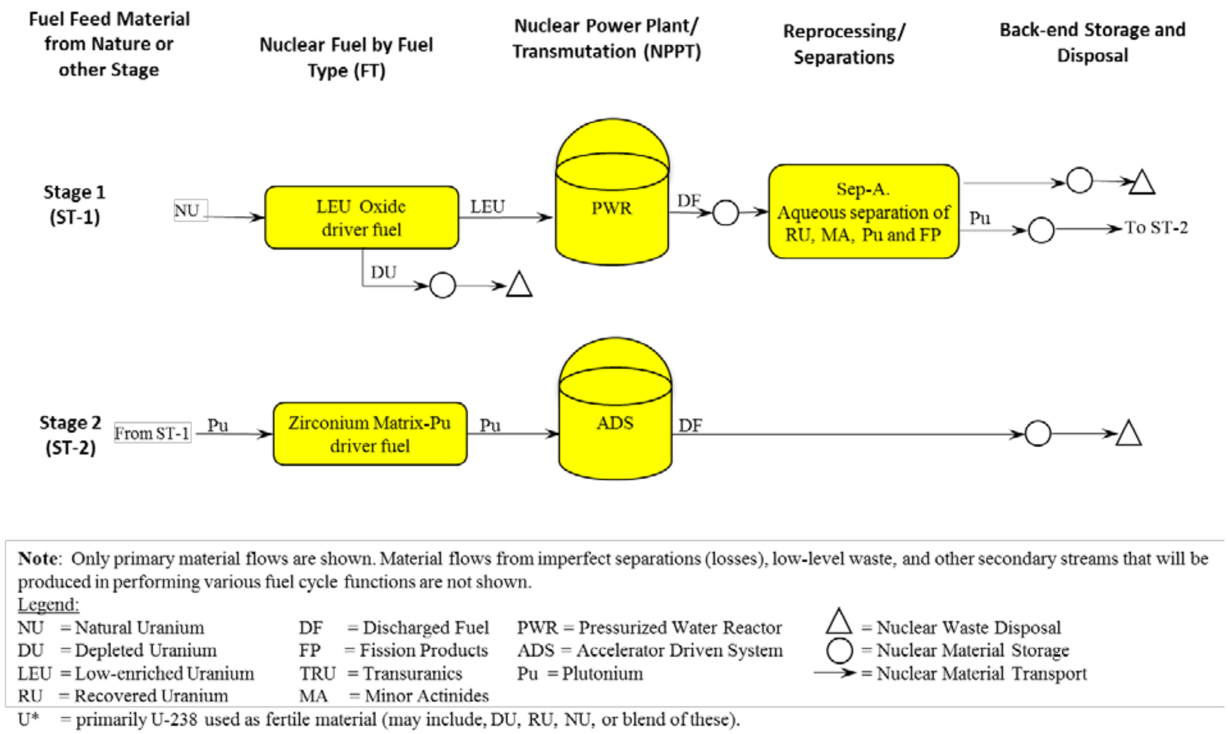


Figure B27. Material Flow Data of Analysis Example for EG16.

Table B44. Reactor and Fuel Information of Analysis Example for EG16.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	ADS
	Core Configuration		PWR with UOX	ADS with Pu IMF
	Core Thermal Power, MWth		3000	840
	Net Thermal Efficiency, %		33	29.9 [a)]
	Electrical Energy Generation Sharing, %		92.56	7.44
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR-UOX	ADS Pu-NFF
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		50	~388
	Fuel Composition	Initial Nuclear Material(s)	LEU	Pu
		(U-235+ U-233)/Total U, %	4.21	n.a.
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	>99.9
	Fuel Residence Time in Reactor, EFPY		4.05	2.56 (avg)

a) The net thermal efficiency was assumed to be 40% without taking accelerator power requirements into account. Since the average accelerator power required is 84.9 MWe, the net thermal efficiency has been adjusted to 29.9%.

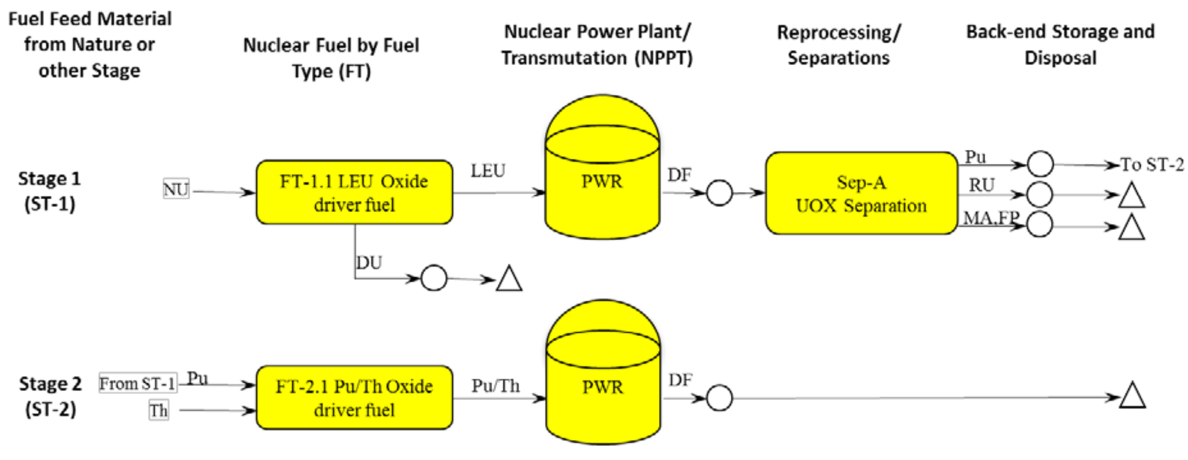
Table B45. Mass Flow Data of Analysis Example for EG16.

Stage		**1**			**2**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		92.56			7.44			100
Feed or product of nuclear materials (metric ton) [a)]								
Natural resource	NU	-17,446.60						-17,446.60
	Th							-
Products from fuel or NPPT technology	DU	+15,415.57						+15,415.57
	U	+2,026.97	-2,026.97		+ 0.009	-0.009		0.0
	Pu				+23.17	-23.17		0.0
	MA				+0.26	-0.26		0.0
	DF		+2,026.97	-2,026.97		+ 23.43		+ 23.43
Products from Rep/Sep technology	RU			+1,877.27				+1,877.27
	Pu			+ 23.48	-23.48			0.0
	MA			+ 2.61				+ 2.61
	FP			+ 103.35				+ 103.35
Loss		+ 4.06		+ 20.27	+ 0.05			+24.38

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG17



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
RU = Recovered Uranium
DF = Discharged Fuel
FP = Fission Products
TRU = Transuranics
MA = Minor Actinides
PWR = Pressurized Water Reactor
Th = Thorium
UOX = Uranium Oxide
MOX = Mixed Oxide
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport
Pu/RU = Co-separated products
U* = primarily U-238 used as fertile material (may include, DU, RU, NU, or blend of these).

Figure B28. Material Flow Data of Analysis Example for EG17.

Table B46. Reactor and Fuel Information of Analysis Example for EG17.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	PWR
	Core Configuration		PWR with UOX	PWR with $(ThPu)O_2$
	Core Thermal Power, MWth		3000	3000
	Net Thermal Efficiency, %		33	33
	Electrical Energy Generation Sharing, %		90.49	9.51
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR-UOX	PWR-Th/Pu
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		50	50
	Fuel Composition	Initial Nuclear Material(s)	LEU	$(Pu/Th)O_2$
		(U-235+ U-233)/Total U, %	4.21	n.a.
		Th/Total HM, %	0	88.95
		TRU/Total HM, %	0	11.05
	Fuel Residence Time in Reactor, EFPY		3.7	3.7

Table B47. Mass Flow Data of Analysis Example for EG17.

Stage		**1**			**2**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		90.49			9.51			100
Feed or product of nuclear materials (metric ton) [a)]								
Natural resource	NU	-17,241.2						-17,241.2
	Th				-187.7			-187.7
Products from fuel or NPPT technology	DU	+15,234.1						+15,234.1
	U	+2,003.1	-2,003.1					
	Th				+187.3	-187.3		
	Pu				+23.3	-23.3		
	MA							
	DF		+2,003.1	-2,003.1		+210.6 [c)]		+210.6
Products from Rep/Sep technology	RU			+1,853.7				+1,853.7
	Pu			+23.3	-23.3			
	MA			+2.7				+2.7
	FP			+103.4				+103.4
Loss		+4.0		+20.0	+0.4			24.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) The 210 tons of ThPu spent fuel contain about 6.1% of Pu and 0.6% of MA, i.e. about 45% of the Pu initially loaded in the ThPu fuel has been transmuted. It also contains about 1.6% of U (90% U-233) produced by neutron captures on Th. It also contains about 5.2% of FP.

Evaluation Group EG18

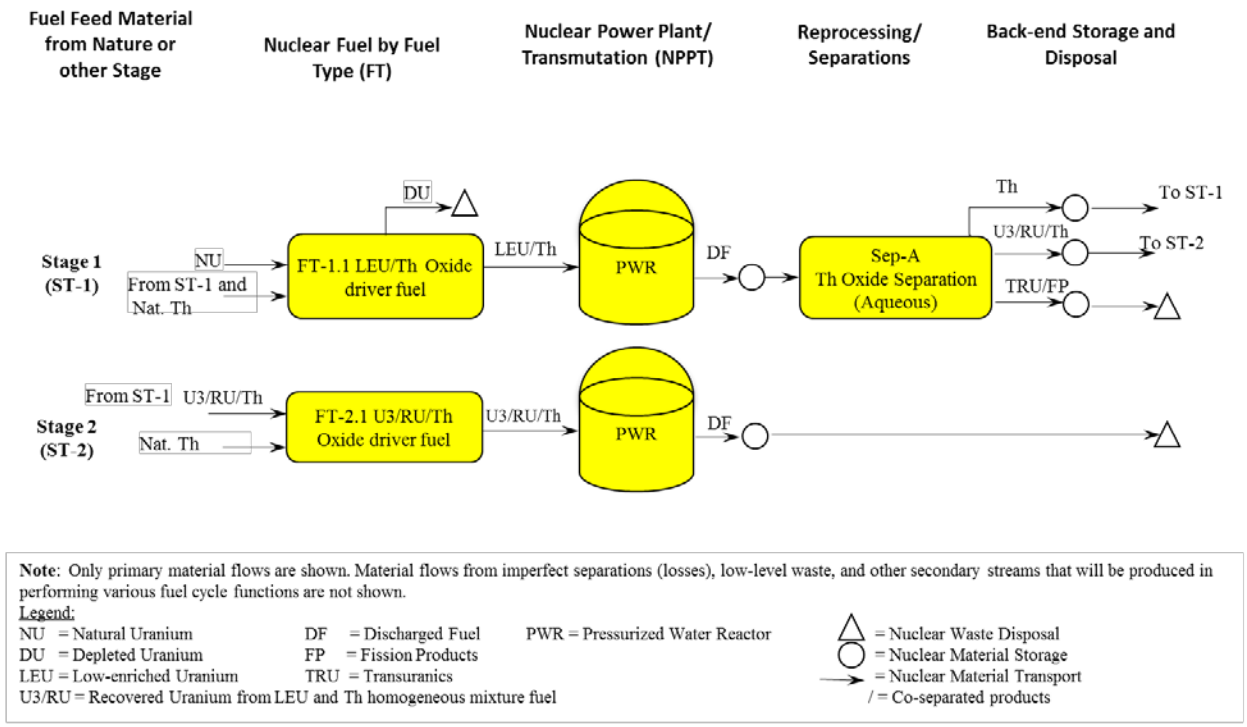


Figure B29. Material Flow Data of Analysis Example for EG18.

Table B48. Reactor and Fuel Information of Analysis Example for EG18.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	PWR
	Core Configuration		LEU/Th oxide	U3/RU/Th oxide
	Core Thermal Power, MWth		3400 [a)]	3400 [a)]
	Net Thermal Efficiency, %		33	33
	Electrical Energy Generation Sharing, %		68.7	31.3
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR(LEU/Th)	PWR(RU/Th)
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		59.6	58.0
	Fuel Composition	Initial Nuclear Material(s)	LEU/Th	U3/RU/Th
		(U-235+ U-233)/Total U, %	20	9.8
		Th/Total HM, %	72.1	48.9
		TRU/Total HM, %	0	0
	Fuel Residence Time in Reactor, EFPY		4.0	4.0

[a)] The higher thermal output reflects the current practice of facilities. The charge mass is dependent only on the discharge burn-up and the thermal efficiency. Thus, the PWR-3000 and PWR-3400 are comparable in terms of charge masses in t/GWe-y, if the fuel accumulates the same discharge burnup.

Table B49. Mass Flow Data of Analysis Example for EG18.

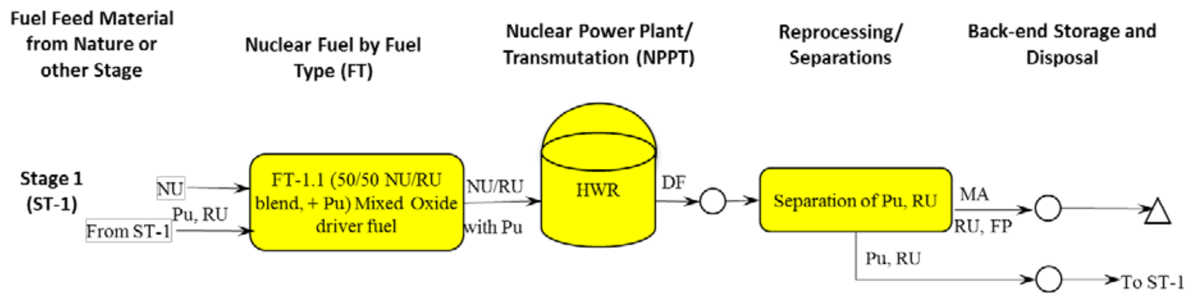
Stage		1			2			Sum b)
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		68.7			**31.3**			100
Feed or product of nuclear materials (metric ton) a)								
Natural resource	NU	-15,215.7						-15,215.7
	Th	-49.0			-293.5			-342.4
Products from fuel or NPPT technology	DU	+14,859.8						+14,859.8
	Th	+919.9	-919.9		+292.3	-292.3		+0.0
	U3/RU c)				+305.7	-305.7		+0.0
	LEU	+355.2	-355.2					+0.0
	DF		+1,275.0	-1,275.0		+598.0		+598.0
Products from Rep/Sep technology	U3/RU c)			+305.7	-305.7			+0
	Th	-872.7		+872.7				+0
	TRU			+7.4				+7.4
	FP			+76.4				+76.4
Loss		+2.6	+0	+12.8	+1.2	+0		+16.5

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) U3/RU consists of the recovered uranium from LEU and Th homogeneous mixture fuel.

Evaluation Group EG19



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend: HWR= Heavy Water Reactor (Pressurized) Pu= Recovered Plutonium

NU = Natural Uranium DF = Discharged Fuel PWR = Pressurized Water Reactor △ = Nuclear Waste Disposal
DU = Depleted Uranium FP = Fission Products SFR = Sodium Fast Reactor ○ = Nuclear Material Storage
LEU = Low-enriched Uranium TRU = Transuranics UOX = Uranium Oxide → = Nuclear Material Transport
RU = Recovered Uranium MA = Minor Actinides MOX = Mixed Oxide / = Co-separated products

Figure B30. Material Flow Data of Analysis Example for EG19.

Table B50. Reactor and Fuel Information of Analysis Example for EG19.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	Stage		1
	NPPT Technology Identifier		HWR
	Core Configuration		EC6 with 37-element fuel assemblies with NU, RU oxide (with recovered Pu oxide) (380 fuel channels, each with 12 fuel assemblies; on-power fueling)
	Core Thermal Power, MWth		2084
	Net Thermal Efficiency, %		33
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		HWR NU
	Purpose		Driver
	Average Discharge Burnup, GWd/t		8.0
	Fuel Composition	Initial Nuclear Material(s)	NU+RU+Pu
		(U-235+ U-233)/Total U, %	0.44
		Th/Total HM, %	0
		TRU/Total HM, %	0.98
	Fuel Residence Time in Reactor, EFPY		0.68

Table B51. Mass Flow Data of Analysis Example for EG19.

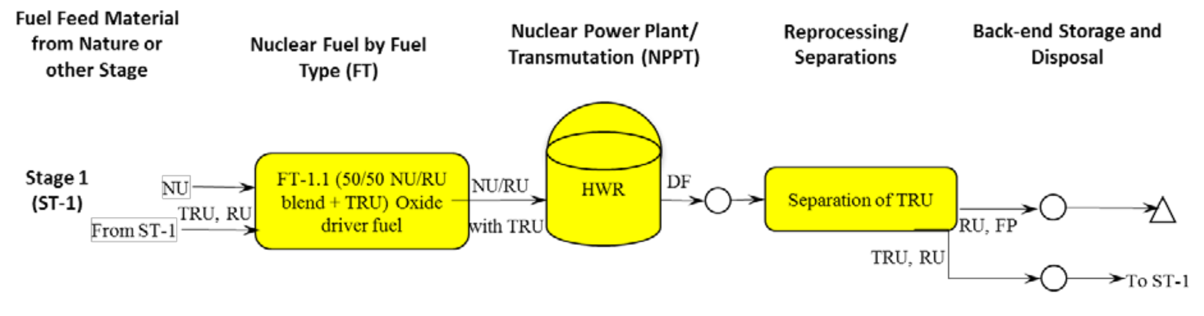
Stage		**1**			**Sum** b)
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) a)					
Natural resource	NU	-6,840.5			-6,840.5
	Th				
Products from fuel or NPPT technology	DU				
	U	+13,653.8	-13,653.8		0
	Pu	+126.5c)	-126.5		0
	MA				
	DF		+13,780.3	-13,780.3	0
Products from Rep/Sep technology	RU	-6,840.5		+13,394.6	+6,554.1
	Pu	-126.7		+ 126.7	0
	MA			+ 6.2	+6.2
	FP			+115.8	+115.8
Loss		+ 27.4	+0	+ 137.0	+164.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) The small amount of Am-241 that could arise from Pu-241 decay during lag time is not explicitly shown. It would be small, and could be zero if the fuel were used right away.

Evaluation Group EG20



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

	HWR= Heavy Water Reactor (Pressurized)		
NU = Natural Uranium	DF = Discharged Fuel	PWR = Pressurized Water Reactor	= Nuclear Waste Disposal
DU = Depleted Uranium	FP = Fission Products	SFR = Sodium Fast Reactor	= Nuclear Material Storage
LEU = Low-enriched Uranium	TRU = Transuranics	UOX = Uranium Oxide	= Nuclear Material Transport
RU = Recovered Uranium	MA = Minor Actinides	MOX = Mixed Oxide	/ = Co-separated products

Figure B31. Material Flow Data of Analysis Example for EG20.

Table B52. Reactor and Fuel Information of Analysis Example for EG20.

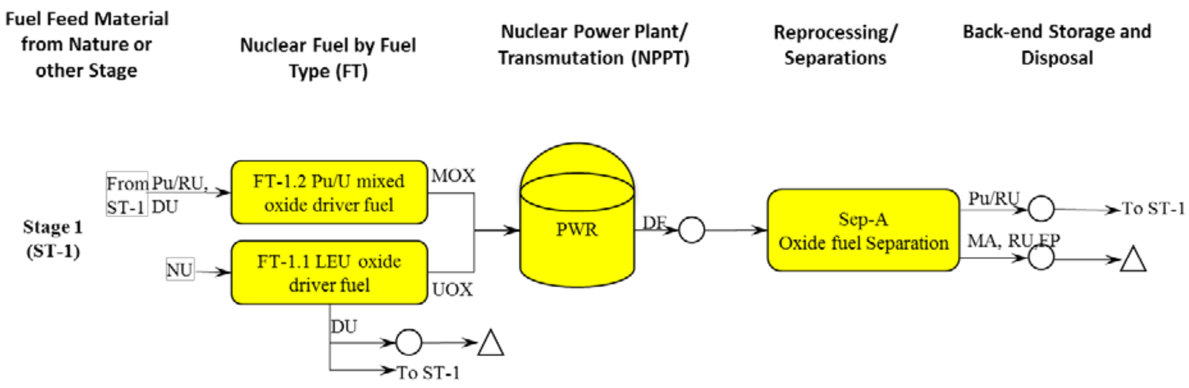
Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	Stage		1
	NPPT Technology Identifier		HWR
	Core Configuration		HWR with NU/RU oxide (with TRU oxide)
	Core Thermal Power, MWth		2084
	Net Thermal Efficiency, %		33
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		HWR TRU fuel
	Purpose		Driver
	Average Discharge Burnup, GWd/t		7.6
	Fuel Composition	Initial Nuclear Material(s)	NU+RU+TRU
		(U-235+ U-233)/Total U, %	0.46
		Th/Total HM, %	0
		TRU/Total HM, %	1.38
	Fuel Residence Time in Reactor, EFPY		0.64

Table B53. Mass Flow Data of Analysis Example for EG20.

Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100.0
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	-7,225.9			-7,225.9
	Th				
Products from fuel or NPPT technology	DU				
	U	+14,422.9	-14,422.9		0
	Pu	+167.0	-167.0		0
	MA	+30.3	-30.3		0
	DF		+14,620.2	-14,620.2	0
Products from Rep/Sep technology	RU	-7,225.9		+14,161.5	+6,935.6
	Pu	-167.3		+167.3	+0
	MA	-30.4		+30.4	+0
	FP			+114.8	+114.8
Loss		+29.3	+0	+146.2	+175.5

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG21



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
MOX = Mixed Oxide
DF = Discharged Fuel
FP = Fission Products
Pu = Plutonium
MA = Minor Actinides
PWR = Pressurized Water Reactor
UOX = Uranium Oxide
RU = Recovered Uranium
/ = Co-separated products
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport

Figure B32. Material Flow Data of Analysis Example for EG21.

Table B54. Reactor and Fuel Information of Analysis Example for EG21.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		PWR	
	Core Configuration		PWR with UOX & MOX	
	Core Thermal Power, MWth		3000	
	Net Thermal Efficiency, %		33.3	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		PWR-UOX	PWR–MOX
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		45.0	45.0
	Fuel Composition	Initial Nuclear Material(s)	LEU	Pu/U
		(U-235+ U-233)/Total U, %	4.62	0.12
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	8.45
	Fuel Residence Time in Reactor, EFPY		3.7	3.7

Table B55. Mass Flow Data of Analysis Example for EG21.

Stage		**1**			**Sum** b)
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) a)					
Natural resource	NU	-15,758.8			-15,758.8
	Th				-
Products from fuel or NPPT technology	DU	+13,455.3			+13,455.3
	U c)	+2,366.0	-2,366.0		0.0
	Pu	d) +67.4	-67.4		0.0
	DF		+2,433.4	-2,433.4	0.0
Products from Rep/Sep technology	RU	-67.4		+2,221.0	+2,153.6
	Pu	d) -67.4		+67.4	+0.0
	MA			+8.5	+8.5
	FP			+112.2	+112.2
Loss		+4.9		+24.3	+29.2

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) Total uranium in UOX and MOX fuels, which consists of LEU in UOX fuel and DU and RU in MOX fuel.

d) Pu, including its decay daughters.

Evaluation Group EG22

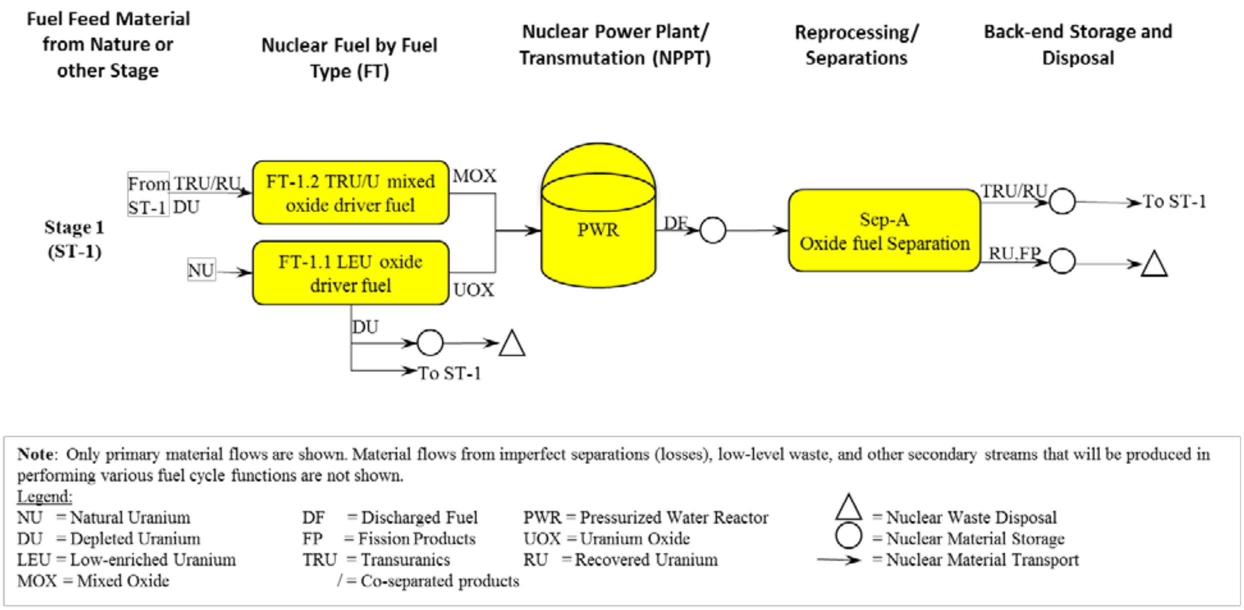


Figure B33. Material Flow Data of Analysis Example for EG22.

Table B56. Reactor and Fuel Information of Analysis Example for EG22.

Technology category	**Parameter**		**Stage Number**	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		PWR	
	Core Configuration		PWR with UOX & MOX-TRU	
	Core Thermal Power, MWth		3000	
	Net Thermal Efficiency, %		33.3	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		PWR-UOX	PWR–MOX
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		45.0	45.0
	Fuel Composition	Initial Nuclear Material(s)	LEU	TRU/U
		(U-235+ U-233)/Total U, %	5.12	0.12
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	20.4
	Fuel Residence Time in Reactor, EFPY		3.7	3.7

Table B57. Mass Flow Data of Analysis Example for EG22.

Stage		1			Sum [b]
Technology		Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) [a]					
Natural resource	NU	-17,526.5			-17,526.5
	Th				-
Products from fuel or NPPT technology	DU	+15,412.9			15,412.9
	U [c]	+2,271.0	-2,271.0		0.0
	Pu	+130.4	-130.4		0.0
	MA	+31.9	-31.9		0.0
	DF		+2,433.3	-2,433.3	0.0
Products from Rep/Sep technology	RU	-162.3		+2,133.5	+1,971.2
	Pu	-130.4		+130.4	0.0
	MA	-31.9		+31.9	0.0
	FP			+113.2	+113.2
Loss		+4.9		+24.3	+29.2

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) Total uranium in UOX and MOX fuels, which consists of LEU in UOX fuel and DU and RU in MOX fuel.

Evaluation Group EG23

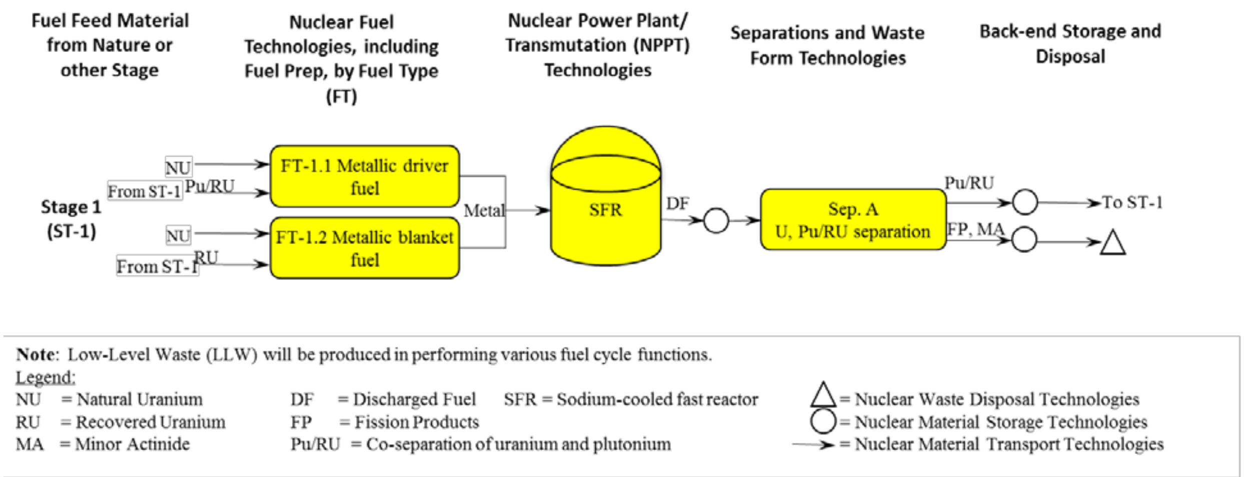


Figure B34. Material Flow Data of Analysis Example for EG23.

Table B58. Reactor and Fuel Information of Analysis Example for EG23.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		SFR	
	Core Configuration		SFR-Pu	
	Core Thermal Power, MWth		1000	
	Net Thermal Efficiency, %		40	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		SFR-Metallic	SFR-Metallic
	Purpose		Driver	Blanket
	Average Discharge Burnup, GWd/t		81.5	23.5
	Fuel Composition	Initial Nuclear Material(s)	Pu/RU	NU
		(U-235+ U-233)/Total U, %	~0	0.71
		Th/Total HM, %		
		TRU/Total HM, %	15.3 [a)]	0
	Fuel Residence Time in Reactor, EFPY		3.6	5.4

a) Average TRU content in driver fuel, including axial blanket.

Table B59. Mass Flow Data of Analysis Example for EG23.

Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	- 110.6			- 110.6
	Th				-
Products from fuel or NPPT technology	DU				
	U	+ 1,095.2	- 1,095.2		0.0
	Pu	[c)] + 162.2	- 162.2		0.0
	MA				0.0
	DF		+ 1,257.4	- 1,257.4	0.0
Products from Rep/Sep technology	RU	- 987.1		+ 987.1	+ 0.0
	Pu	[c)] - 162.2		+ 163.1	[d)] + 0.9
	MA			+ 1.5	+ 1.5
	FP			+ 93.1	+ 93.1
Loss		+ 2.5		+ 12.6	+ 15.1

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) Pu, including its decay daughters.
d) Not zero because Pu breeding ratio is slightly higher than break-even. The extra Pu was treated as HLW.

Evaluation Group EG24

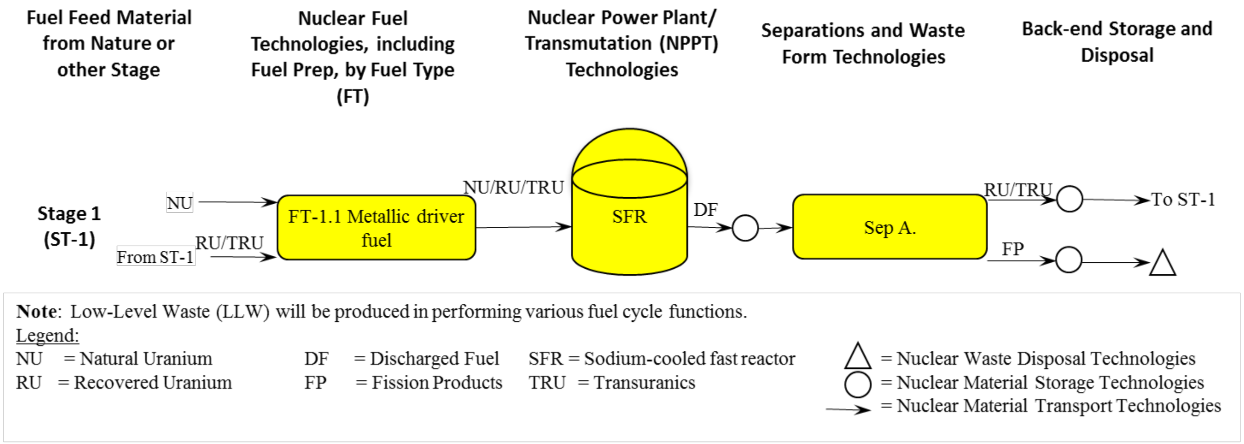


Figure B35. Material Flow Data of Analysis Example for EG24.

Table B60. Reactor and Fuel Information of Analysis Example for EG24.

Technology category	Parameter		Stage Number
Nuclear Power Plant/ Transmutation (NPPT)	Stage		1
	NPPT Technology Identifier		SFR
	Core Configuration		SFR with U-TRU-Zr
	Core Thermal Power, MWth		1000
	Net Thermal Efficiency, %		40
	Electrical Energy Generation Sharing, %		100
Nuclear Fuel	**Fuel Type**		**1.1**
	Fuel Technology Identifier		SFR-Metallic
	Purpose		Driver
	Average Discharge Burnup, GWd/t		73
	Fuel Composition	Initial Nuclear Material(s)	TRU/RU/NU
		(U-235+ U-233)/Total U, %	~0
		Th/Total HM, %	0
		TRU/Total HM, %	13.9
	Fuel Residence Time in Reactor, EFPY		3.6

Table B61. Mass Flow Data of Analysis Example for EG24.

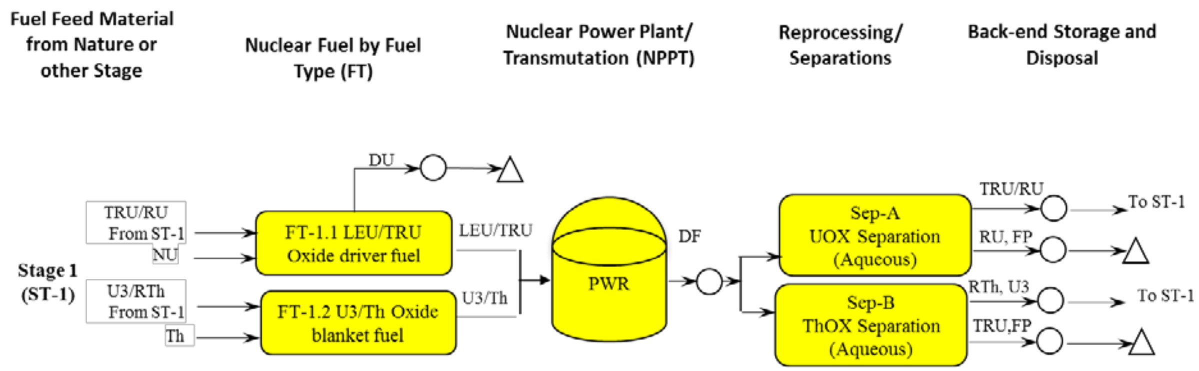
Stage		**1**			**Sum** [b]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) [a]					
Natural resource	NU	-113.2			-113.2
	Th				
Products from fuel or NPPT technology	U	+1,078.7	-1,078.7		0.0
	TRU	+172.5	-172.5		0.0
	DF		+1,251.2	-1,251.2	0.0
Products from Rep/Sep technology	RU	-967.7		+967.7	0.0
	TRU	-172.9		+172.9	0.0
	FP			+98.1	+98.1
Loss		+2.5		+12.5	+15.0

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) Uranium includes recovered uranium (RU) and natural uranium (NU).

Evaluation Group EG25



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
RU = Recovered Uranium
DF = Discharged Fuel
FP = Fission Products
TRU = Transuranics
ThOX = Thorium Oxide
PWR = Pressurized Water Reactor
U3 = U recovered from Th stream
RTh = Recovered Thorium
Th = Natural Thorium
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport

Figure B36. Material Flow Data of Analysis Example for EG25.

Table B62. Reactor and Fuel Information of Analysis Example for EG25.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		PWR	
	Core Configuration		LEU/TRU oxide in seed and U3/Th oxide in blanket	
	Core Thermal Power, MWth		1700	
	Net Thermal Efficiency, %		33	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		PWR(LEU/TRU)	PWR(U3/Th)
	Purpose		Driver	Blanket
	Average Discharge Burnup, GWd/t		49.0	26.4
	Fuel Composition	Initial Nuclear Material(s)	LEU/TRU	U3/Th
		(U-235+ U-233)/Total U, %	4.9	77.7
		Th/Total HM, %	0	97.7
		TRU/Total HM, %	1.65	0
	Fuel Residence Time in Reactor, EFPY		4.7	4.7

Table B63. Mass Flow Data of Analysis Example for EG25.

Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	-11,353.6			-11,353.6
	Th	-84.8			-84.8
Products from fuel or NPPT technology	DU	+10,224.2			+10,224.2
	Th	+2,011.4	-2011.4		+0.0
	U3 [d)]	+47.7	-47.7		+0.0
	LEU	+1,127.1	-1,127.1		+0.0
	TRU	+18.9	-18.9		+0.0
	DF		+3,205.1	-3,205.1	+0.0
Products from Rep/Sep technology	RU			+1,056.5	+1,056.5
	Th	-1,930.6		+1,930.6	+0.0
	U3 [d)]	-47.7		+47.7	+0.0
	TRU	-18.9		+19.2[c)]	+0.2
	FP			+119.1	+119.1
Loss		+6.3	+0.0	+32.1	+38.3

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) This TRU material includes the TRU from the seed and the blanket. The TRU from the seed is recycled. The TRU from the blanket is sent to disposal (treated as nuclear material produced).
d) U mass in blanket, which consists of 35t of U-233 and 12.7t of other uranium isotopes.

Evaluation Group EG26

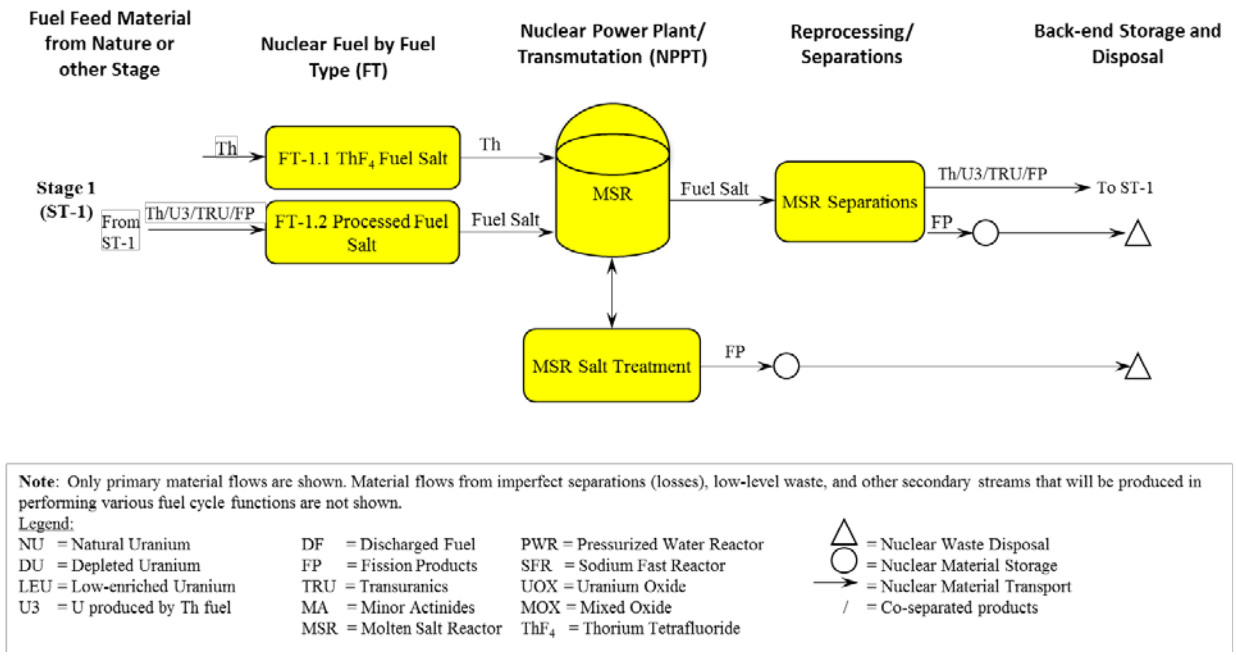


Figure B37. Material Flow Data of Analysis Example for EG26.

Table B64. Reactor and Fuel Information of Analysis Example for EG26.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		MSR	
	Core Configuration		MSR-Th	
	Core Thermal Power, MWth		2250	
	Net Thermal Efficiency, %		44.4	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		ThF_4 Fuel Salt	Processed Fuel Salt
	Purpose		Blanket	Driver/Blanket
	Average Discharge Burnup, GWd/t		n.a. [a)]	884.9
	Fuel Composition	Initial Nuclear Material(s)	Th	Th/U3/TRU
		(U-235+ U-233)/Total U, %	n.a.	69.0
		Th/Total HM, %	100	97.4
		TRU/Total HM, %	0	<0.01
	Fuel Residence Time in Reactor, EFPY		n.a.	n.a.

a) The average discharge burnup for ThF_4 fuel salt is “not applicable” because it is gets chemically and physically mixed into the Processed Fuel Salt.

Table B65. Mass Flow Data of Analysis Example for EG26.

Stage		1			Sum [b)]
Technology		Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU				
	Th	-92.9			-92.9
Products from fuel or NPPT technology	DU				
	U [c)]	+22,990.6	-22,990.6		0.0
	Th [d)]	+849,178.4	-849,178.4		0.0
	Pu	+9.6	-9.6		0.0
	MA	+23.7	-23.7		0.0
	FP [e)]	+13,978.0	-13,978.0		0.0
	DF [f)]		+886,180.3	-886,132.0	+48.3
Products from Rep/Sep technology	U3 [c)]	-22,990.6		+22,991.9	+1.3
	Th	-849,085.7		+849,086.4	+0.7
	Pu	-9.6		+9.7	0.0
	MA	-23.7		+23.7	+0.1
	FP	-13,978.0		+14,020.3	+42.3
Loss		+0.2		g)	+0.2

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively. For this molten salt reactor system, the mass flows indicated represent flow of material through salt processing systems and subsequent return to the reactor via a small continuous bypass stream; these mass flow rates are extremely high due to the fuel salt continuously circulating in and out of the “core” region.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

c) U and U3 in this table are actually the sum of U and Pa; this is approximated in this manner due to the fact that Pa directly decays to U. In addition, U3 is not high quality U-233, but rather simply designates that the uranium is recovered for thorium fuels; the fissile content of the U is noted elsewhere.

d) Th has been added as a product to account for Th natural resource being used in fuel for NPPT and Th being a product from MSR Separations.

e) Salt treatment that occurs in the NPPT stage of MSR operations adds an FP stream as a product from NPPT technology, accounting for species removed from the fuel in the NPPT stage and sent for waste disposal.

f) The mass balance for the DF stream coming from the NPPT stage gives 48.3 MT, which is attributed to the FP stream removed during salt treatment.

g) For MSBR proposed separations, U-233 loss was demonstrated to be extremely low. Since MSR “fuel fab” and separations are integrated, losses are only shown under fuel fabrication.

Evaluation Group EG27

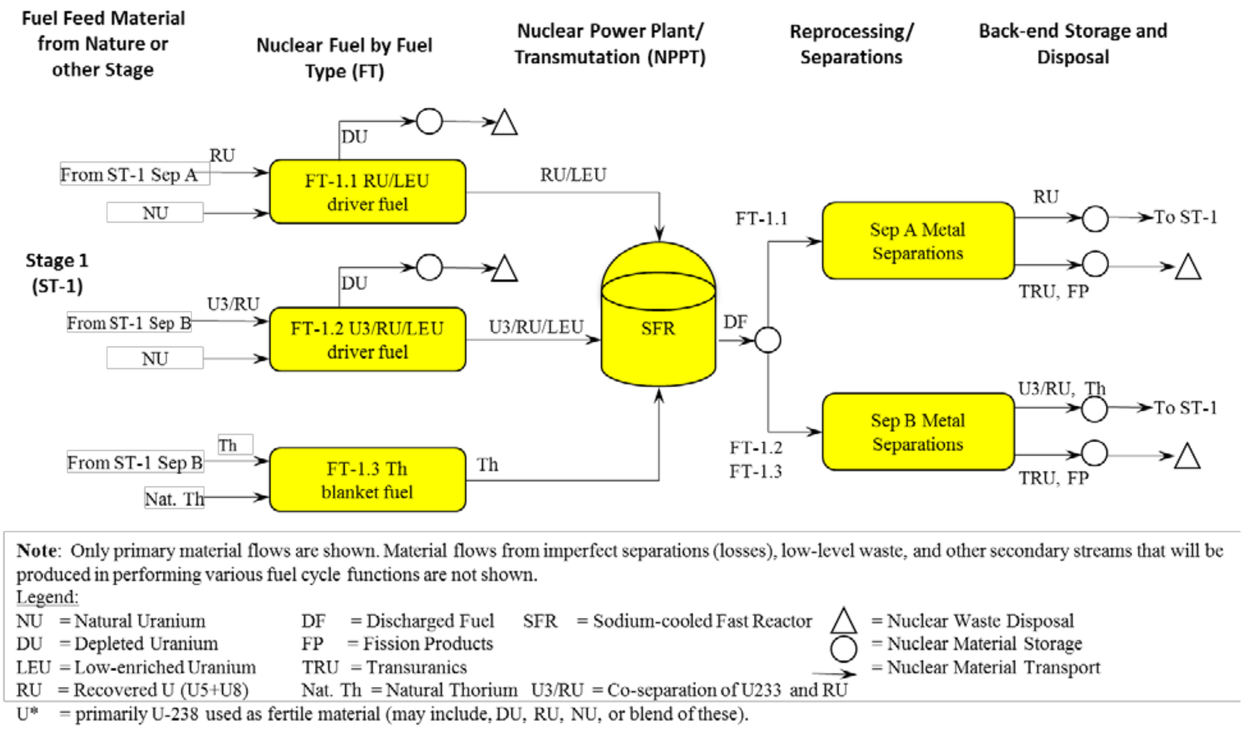


Figure B38. Material Flow Data of Analysis Example for EG27.

Table B66. Reactor and Fuel Information of Analysis Example for EG27.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		
	NPPT Technology Identifier		SFR		
	Core Configuration		RU/LEU and U3/RU/LEU drivers Th blanket		
	Core Thermal Power, MWth		1000		
	Net Thermal Efficiency, %		40		
	Electrical Energy Generation Sharing, %		100		
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**1.3**
	Fuel Technology Identifier		SFR-Metal	SFR-Metal	SFR-Metal
	Purpose		Driver	Driver	Blanket
	Average Discharge Burnup, GWd/t		37.8	36.8	1.4
	Fuel Composition	Initial Nuclear Material(s)	RU/LEU	U3/RU/LEU	Th
		(U-235+ U-233)/Total U, %	19.0	12.6 (3.9+5.2) [a)]	0
		Th/Total HM, %	0	0	100
		TRU/Total HM, %	0	0	0
	Fuel Residence Time in Reactor, EFPY		2.70	2.70	2.70

a) Equivalent ^{235}U enrichment = 12.6% (3.9% ^{235}U + 5.2% ^{233}U/0.6)

Table B67. Mass Flow Data of Analysis Example for EG27.

Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU	-15,396.4			-15,396.4
	Th	-37.0			-37.0
Products from fuel or NPPT technology	Th	1,266.2	-1,266.2		0.0
	U	2,360.6 [c)]	-2,360.6		0.0
	DU	15,017.9			15,017.9
	DF		3,626.7	-3,626.7	0.0
Products from Rep/Sep technology	Th	-1,231.7		1,231.7	0.0
	U	-1,986.7 [e)]		2,209.6 [d)]	222.9 [f)]
	TRU			55.8	55.8
	FP			93.2	93.2
Losses		7.2	0.0	36.4	43.6

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) $^{233}U/^{234}U/^{235}U/^{236}U/^{238}U$ mass ratio in charged fuel = 2.13/0.86/12.97/8.24/75.80
d) $^{233}U/^{234}U/^{235}U/^{236}U/^{238}U$ mass ratio in discharged fuel = 2.29/0.91/10.67/8.86/77.27
e) $^{233}U/^{234}U/^{235}U/^{236}U/^{238}U$ mass ratio in recycled fuel = 2.53/1.00/11.68/9.70/75.08
f) Mass of depleted U tails from re-enrichment of recycled FT-1.1

Evaluation Group EG28

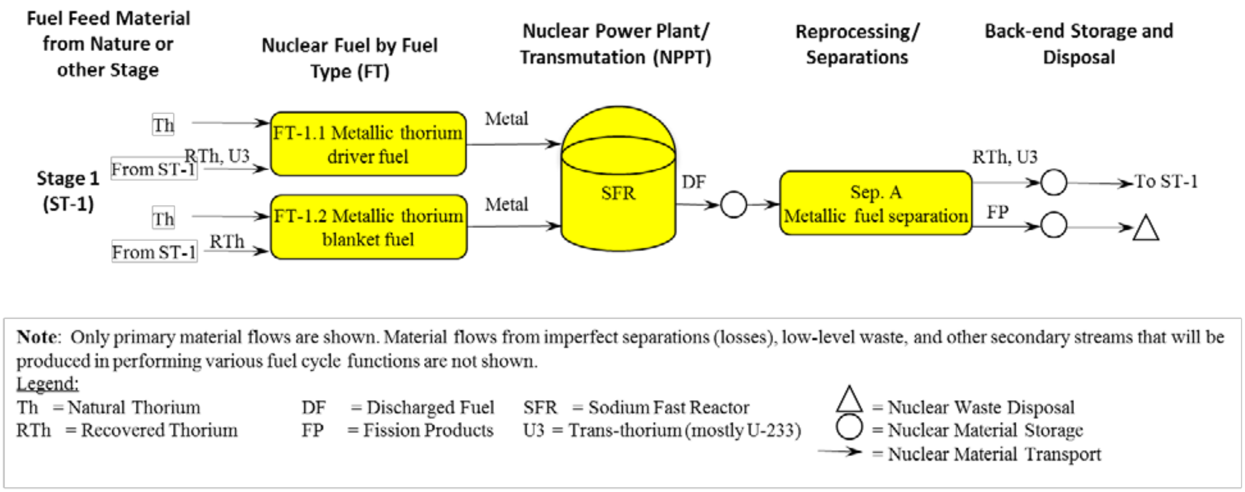


Figure B39. Material Flow Data of Analysis Example for EG28.

Table B68. Reactor and Fuel Information of Analysis Example for EG28.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	
	NPPT Technology Identifier		SFR	
	Core Configuration		SFR with Th-U3 drivers and Th blankets	
	Core Thermal Power, MWth		1000	
	Net Thermal Efficiency, %		40	
	Electrical Energy Generation Sharing, %		100	
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**
	Fuel Technology Identifier		SFR-Metallic Thorium	SFR-Metallic Thorium
	Purpose		Driver	Blanket
	Average Discharge Burnup, GWd/t		63	4
	Fuel Composition	Initial Nuclear Material(s)	U3/RTh	RTh
		(U-235+ U-233)/Total U, %	78.61	~0
		Th/Total HM, %	71.40	100
		TRU/Total HM, %	0.36	0
	Fuel Residence Time in Reactor, EFPY		2.55	2.55

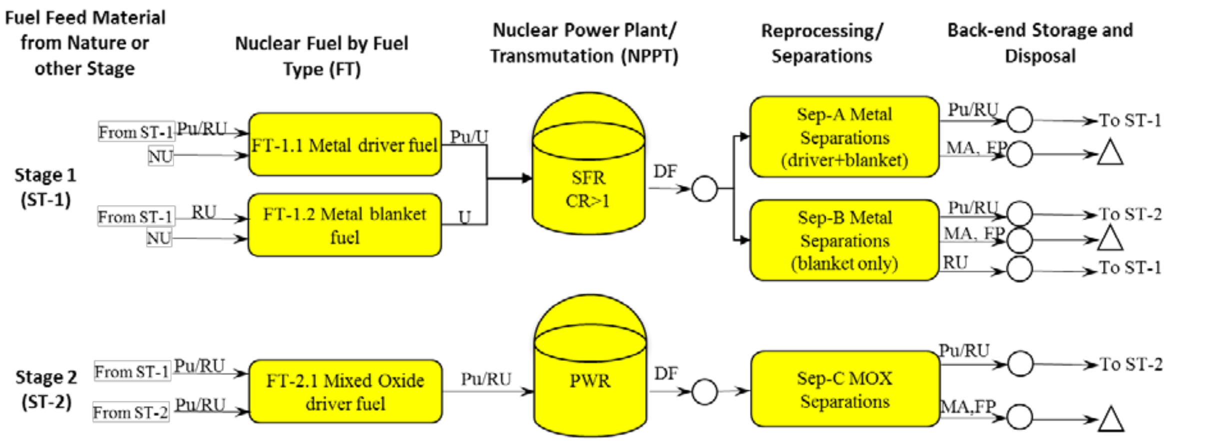
Table B69. Mass Flow Data of Analysis Example for EG28.

Stage		**1**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		100.0			100
Feed or product of nuclear materials (metric ton) [a)]					
Natural resource	NU				
	Th	-138.2			-138.2
Products from fuel or NPPT technology	DU				
	U				
	Th	3,575.5	-3,575.5		
	U3	359.7	-359.7		
	Pu	2.0	-2.0		
	MA	2.8	-2.8		
	DF		3,940.0	-3,940.0	
Products from Rep/Sep technology	RU				
	RTh	-3,444.5		3,444.5	
	U3	-360.4		360.4	
	Pu	-2.0		2.0	
	MA	-2.8		2.8	
	FP			90.9	90.9
Loss		7.9		39.4	47.3

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG29



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium	DF = Discharged Fuel	PWR = Pressurized Water Reactor	△ = Nuclear Waste Disposal
DU = Depleted Uranium	FP = Fission Products	SFR = Sodium Fast Reactor	○ = Nuclear Material Storage
LEU = Low-enriched Uranium	TRU = Transuranics	UOX = Uranium Oxide	→ = Nuclear Material Transport
RU = Recovered Uranium	MA = Minor Actinides	MOX = Mixed Oxide	Pu/RU = Co-separated products

U* = primarily U-238 used as fertile material (may include, DU, RU, NU, or blend of these).

Figure B40. Material Flow Data of Analysis Example for EG29.

Table B70. Reactor and Fuel Information of Analysis Example for EG29.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		**2**
	NPPT Technology Identifier		SFR-Breeder		PWR
	Core Configuration		SFR with (UPu) metal fuel		PWR with (UPu)O2, i.e. MOX
	Core Thermal Power, MWth		1000		3000
	Net Thermal Efficiency, %		40		33
	Electrical Energy Generation Sharing, %		61.1		38.9
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**2.1**
	Fuel Technology Identifier		SFR-Metal	SFR-Metal	PWR-MOX
	Purpose		Driver	Blanket	Driver
	Average Discharge Burnup, GWd/t		96.8	20.7	50
	Fuel Composition	Initial Nuclear Material(s)	Pu/RU/NU	RU/NU	Pu/RU
		(U-235+ U-233)/Total U, %	~0.2	~0.2	~0.2
		Th/Total HM, %	0	0	0
		TRU/Total HM, %	21.4	0	9.11
	Fuel Residence Time in Reactor, EFPY		4.75	9.5	3.9

Table B71. Mass Flow Data of Analysis Example for EG29.

Stage		1			2			Sum [b)]
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		61.08			38.92			100
Feed or product of nuclear materials (metric ton) [a)]								
Natural resource	NU	-133.4 [c)]						-133.4
	Th							
Products from fuel or NPPT technology	DU							
	U	+1,121.8	-1,121.8		+782.9	-782.9		
	Th							
	Pu	+85.1	-85.1		+78.5	-78.5		
	MA							
	DF		+1,206.9 [d)]	-1,206.9		+861.4	-861.4	
Products from Rep/Sep technology	RU	-990.7		+1,028.1	-784.5		+747.1	
	Pu	-85.2		+108.9	-78.6		+54.9	
	MA			+1.5			+7.5	+9.0
	FP			+56.3			+43.3	+99.6
Loss		+2.4		+12.1	+1.7		8.6	24.8

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) The use of NU is only necessary when the legacy DU has been fully utilized, i.e. if DU is available it can be used.
d) About 1/3 is driver fuel and 2/3 is blanket.

Evaluation Group EG30

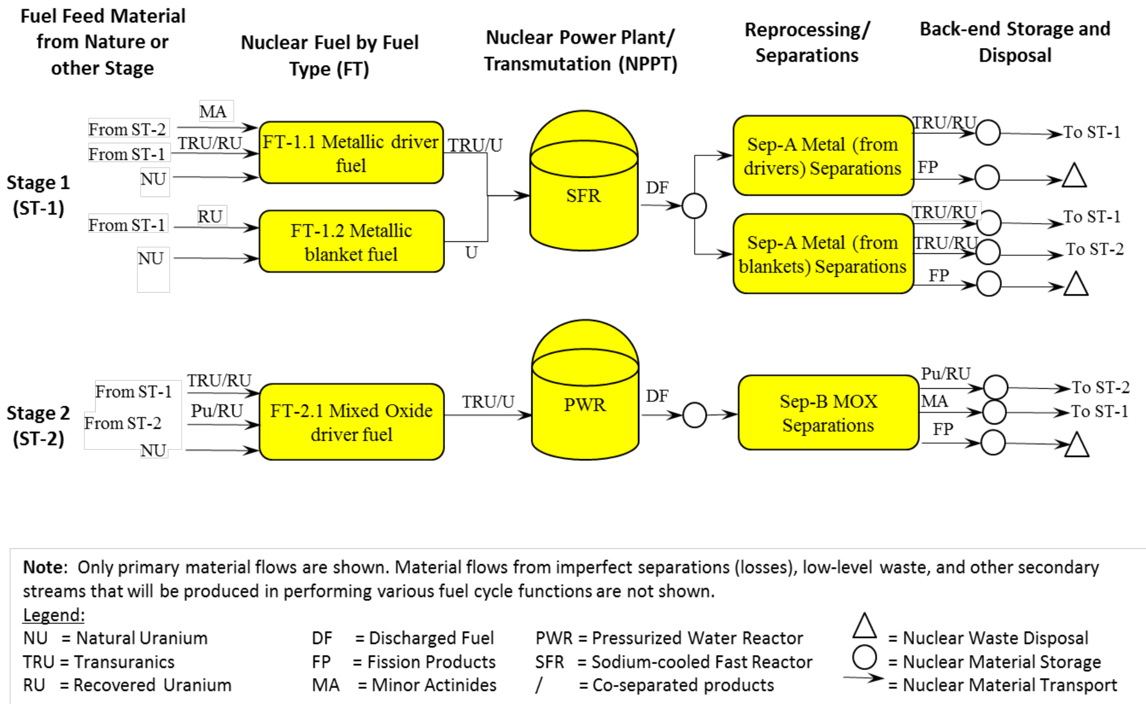


Figure B41. Material Flow Data of Analysis Example for EG30.

Table B72. Reactor and Fuel Information of Analysis Example for EG30.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		**2**
	NPPT Technology Identifier		SFR		PWR
	Core Configuration		SFR with UPuZr		PWR with MOX
	Core Thermal Power, MWth		1000		3000
	Net Thermal Efficiency, %		40		33
	Electrical Energy Generation Sharing, %		87.0		13.0
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**2.1**
	Fuel Technology Identifier		SFR-Metallic	SFR-Metallic	PWR-MOX
	Purpose		Driver	Blanket	Driver
	Average Discharge Burnup, GWd/t		107	23	50
	Fuel Composition	Initial Nuclear Material(s)	TRU/RU/NU	RU/NU	TRU/RU/NU
		(U-235+ U-233)/Total U, %	0.19	0.15	0.04
		Th/Total HM, %	0	0	0
		TRU/Total HM, %	24.4	0.0	10.4
	Fuel Residence Time in Reactor, EFPY		4.9	4.9	4.1

Table B73. Mass Flow Data of Analysis Example for EG30.

Stage		1			2			Sum b)
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		87.0			13.0			100
Feed or product of nuclear materials (metric ton) a)								
Natural resource	NU	-109.9			-3.0			-112.9
	Th							-
Products from fuel or NPPT technology	DU							-
	U	+1,076.3	-1,076.3		+257.3	-257.3		0.0
	Pu	+129.9	-129.9		+29.6	-29.6		0.0
	MA	+12.1	-12.1		+0.1	-0.1		0.0
	DF		+1,218.3	-1,218.3		+287.0	-287.0	0.0
Products from Rep/Sep technology	RU	-968.5		+977.1	-254.8		+246.2	0.0
	Pu	-130.2		+138.7	-29.7		+21.2	0.0
	MA	-12.1		+9.9	-0.1		+2.3	0.0
	FP			+80.4			+14.4	+94.8
Loss		+2.4		+12.2	+0.6		+2.9	+18.1

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG31

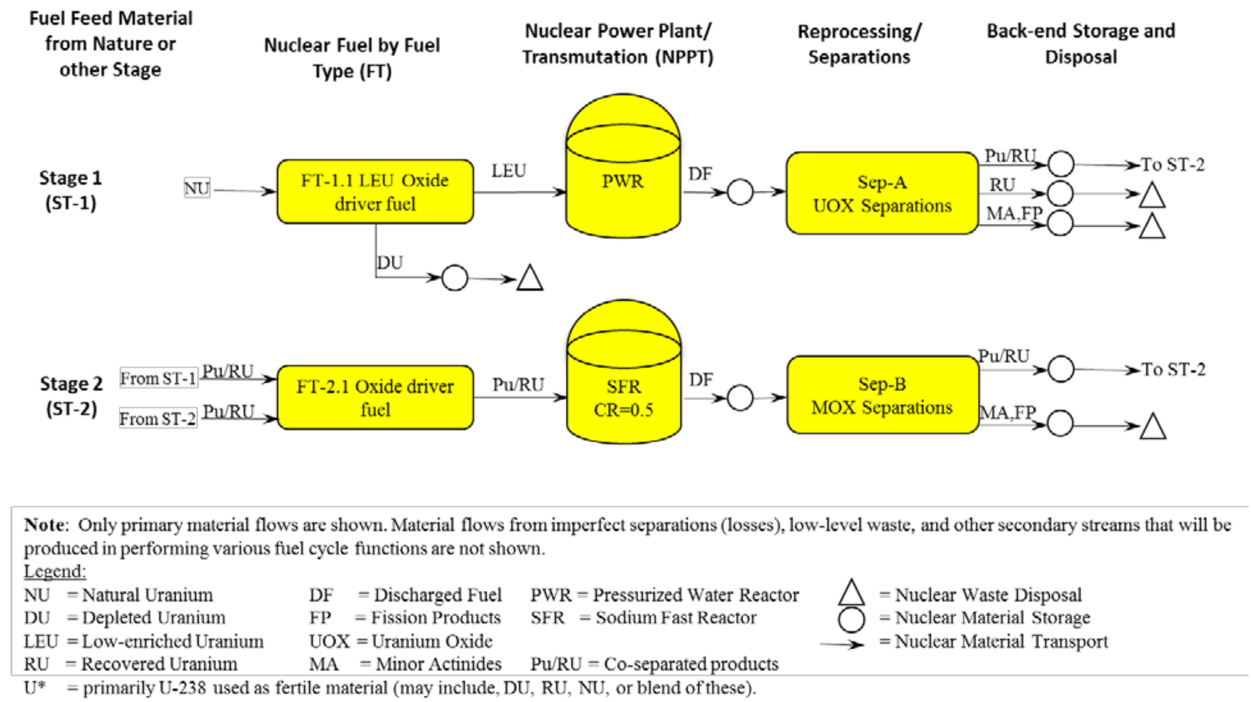


Figure B42. Material Flow Data of Analysis Example for EG31.

Table B74. Reactor and Fuel Information of Analysis Example for EG31.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	SFR-Burner
	Core Configuration		PWR with UOX	SFR with (UPu)O2, i.e. MOX
	Core Thermal Power, MWth		3000	1000
	Net Thermal Efficiency, %		33	40
	Electrical Energy Generation Sharing, %		68.2	31.8
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR-UOX	SFR-Oxide
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		51 [a)]	169
	Fuel Composition	Initial Nuclear Material(s)	LEU	Pu/RU
		(U-235+ U-233)/Total U, %	4.30 [a)]	~0.2
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	36
	Fuel Residence Time in Reactor, EFPY		4.1	5.63

Table B75. Mass Flow Data of Analysis Example for EG31.

Stage		1			2			Sum b)
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		68.2			31.8			100
Natural resource	NU	-13,028.2						-13,028.2
	Th							
Products from fuel or NPPT technology	DU	+11,545.3						+11,545.3
	U	+1,480.0	-1,480.0		+109.7	-109.7		
	Th							
	Pu				+62.4	-62.4		
	MA							
	DF		+1,480.0	-1,480.0		+172.1	-172.1	
Products from Rep/Sep technology	RU			+1,369.0	-109.9		+91.0	+1,350.1
	Pu			+17.1	-62.5		+45.4	
	MA			+2.0			+2.7	+4.7
	FP			+77.1			+31.3	+108.4
Loss		+2.9		+14.8	+0.3		+1.7	+19.7

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG32

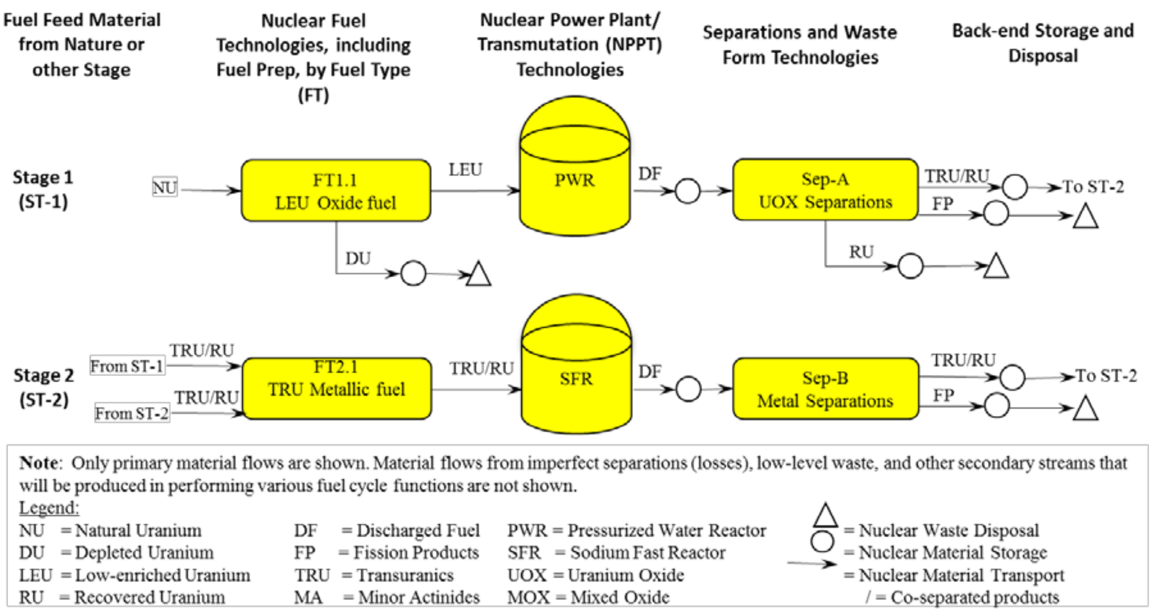


Figure B43. Material Flow Data of Analysis Example for EG32.

Table B76. Reactor and Fuel Information of Analysis Example for EG32.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	SFR
	Core Configuration		PWR with UOX	SFR with U-TRU-Zr metallic
	Core Thermal Power, MWth		3000	1000
	Net Thermal Efficiency, %		33	40
	Electrical Energy Generation Sharing, %		63.41	36.59
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR-UOX	SFR-Metallic
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		50	132
	Fuel Composition	Initial Nuclear Material(s)	LEU	TRU/RU
		(U-235+ U-233)/Total U, %	4.2	~0
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	33
	Fuel Residence Time in Reactor, EFPY		4.0	3.8

Table B77. Mass Flow Data of Analysis Example for EG32.

Stage		**1**			**2**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		63.41			36.59			100
Feed or product of nuclear materials (metric ton) [a)]								
Natural resource	NU	-12,027.2						-12,027.2
	Th							
Products from fuel or NPPT technology	DU	+10,634.8						+10,634.8
	UOX-LEU	+1,389.6	-1,389.6					0.0
	RU				+169.0	-169.0		0.0
	TRU				+84.2	-84.2		0.0
	DF		+1,389.6	-1,389.6		+253.3	-253.3	0.0
Products from Rep/Sep technology	RU			+1,287.2	-169.4		+148.0	+1,265.8
	TRU			+17.6	-84.4		+66.8	0.0
	FP			+70.8			+36.1	+106.9
Loss		+2.8	0.0	+13.9	+0.5	0.0	+2.5	+19.7

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG33

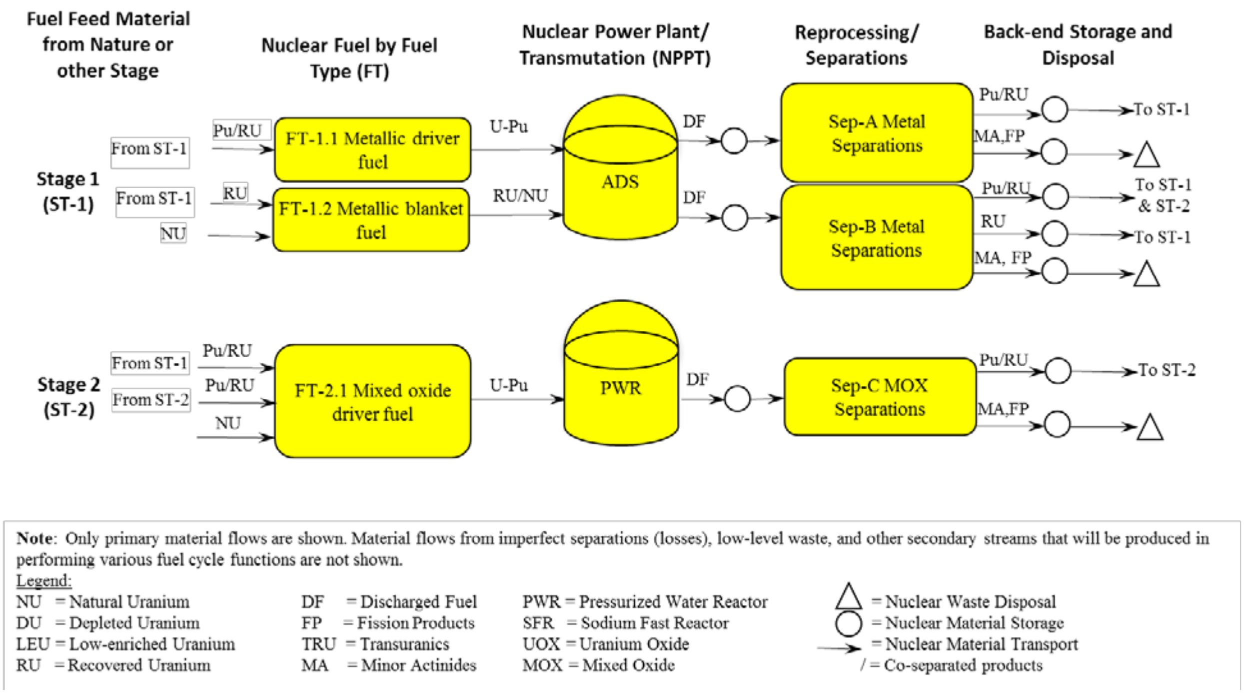


Figure B44. Material Flow Data of Analysis Example for EG33.

Table B78. Reactor and Fuel Information of Analysis Example for EG33.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		**2**
	NPPT Technology Identifier		ADS-Breeder		PWR
	Core Configuration		ADS with metal fuel (Driver/Blanket)		PWR with MOX
	Core Thermal Power, MWth		840		3000
	Net Thermal Efficiency, %		40 (34.5) [a)]		33
	Electrical Energy Generation Sharing, %		83.7		16.3
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**2.1**
	Fuel Technology Identifier		ADS-Metallic driver	ADS-Metallic blanket	PWR-MOX-U/Pu
	Purpose		Driver	Blanket	Driver
	Average Discharge Burnup, GWd/t		77.3	11.3	50
	Fuel Composition	Initial Nuclear Material(s)	RU/Pu	RU/NU	RU/NU/Pu
		(U-235+ U-233)/Total U, %	0.039	0.033	0.035
		Th/Total HM, %	0	0	0
		TRU/Total HM, %	17.29	0	10.15
	Fuel Residence Time in Reactor, EFPY		2.47	2.47	4.1

a) The thermal efficiency was assumed to be 40% without taking accelerator power requirements into account. Since the average accelerator power required is 46 MWe, the net thermal efficiency has been adjusted to 34.5% for use in determining values for the Mass Flow Data Table.

Table B79. Mass Flow Data of Analysis Example for EG33.

Stage		1			2			Sum [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		83.7			16.3			100
Natural resource	NU	-121.5			-14.4			-135.9
	Th							
	Pb/Bi target	TBD	TBD	TBD				
Products from fuel or NPPT technology	DU							0.0
	U	1,497.9	-1,497.9		321.2	-321.2		0.0
	Pu	183.4	-183.4		36.3	-36.3		0.0
	MA	0.1	-0.1		0.0	-0.0		0.0
	DF		1,681.0	-1,681.0		357.5	-357.5	0.0
Products from Rep/Sep technology	RU	-1,379.4		1,379.4	-307.4		307.4	0.0
	Pu	-183.4		194.0	-36.4		25.8	0.0
	MA			2.7			2.8	5.5
	FP			88.1			17.9	106.0
Loss		3.3	0.0	16.8	0.7	0.0	3.6	24.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG34

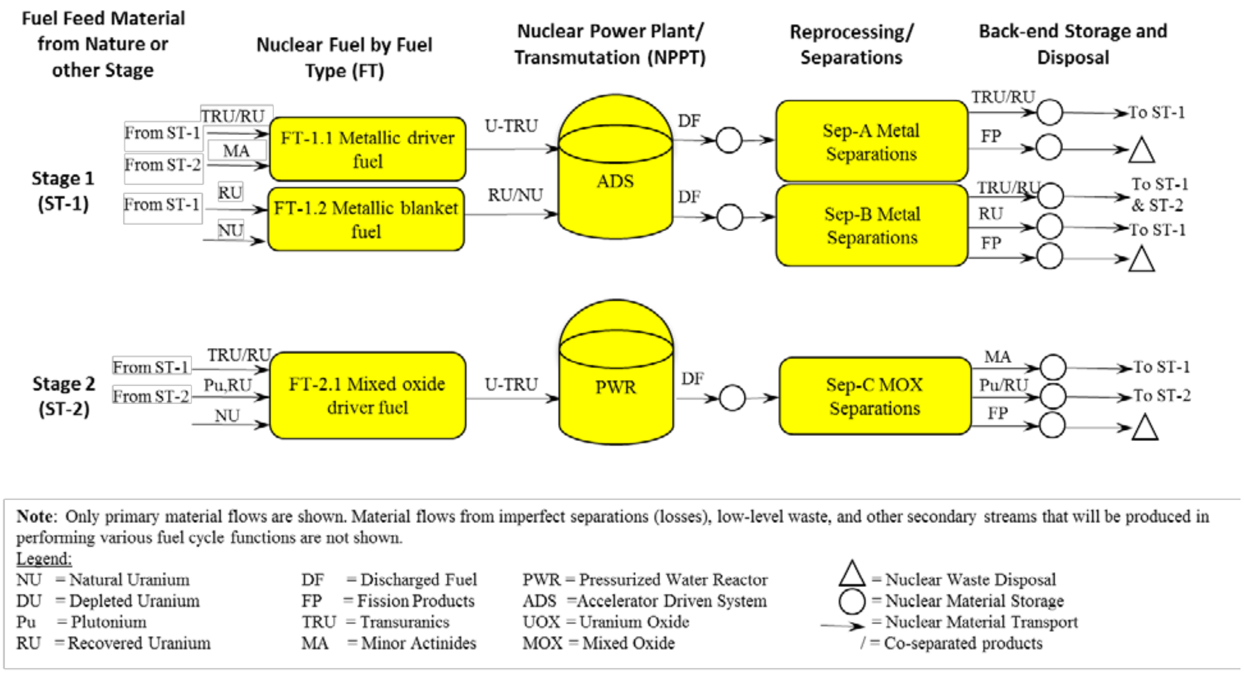


Figure B45. Material Flow Data of Analysis Example for EG34.

Table B80. Reactor and Fuel Information of Analysis Example for EG34.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		**2**
	NPPT Technology Identifier		ADS-Breeder		PWR
	Core Configuration		ADS with metal fuel (Driver/Blanket)		PWR with MOX
	Core Thermal Power, MWth		840		3000
	Net Thermal Efficiency, %		34.8(40) [a)]		33
	Electrical Energy Generation Sharing, %		80.0		20.0
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**2.1**
	Fuel Technology Identifier		ADS-Metallic driver	ADS-Metallic blanket	PWR-MOX-U/TRU
	Purpose		Driver	Blanket	Driver
	Average Discharge Burnup, GWd/t		77.6 [b)]	11.0 [b)]	50
	Fuel Composition	Initial Nuclear Material(s)	RU/TRU	RU/NU	NU/RU/TRU
		(U-235+ U-233)/Total U, %	0.051	0.033	0.035
		Th/Total HM, %	0	0	0
		TRU/Total HM, %	19.31	0	10.22
	Fuel Residence Time in Reactor, EFPY		2.47	2.47	4.1

a) The value between parentheses is the thermal efficiency without subtracting the accelerator power consumption.
b) The average discharge burnup of the ADS at equilibrium is 52.7 GWd/t.

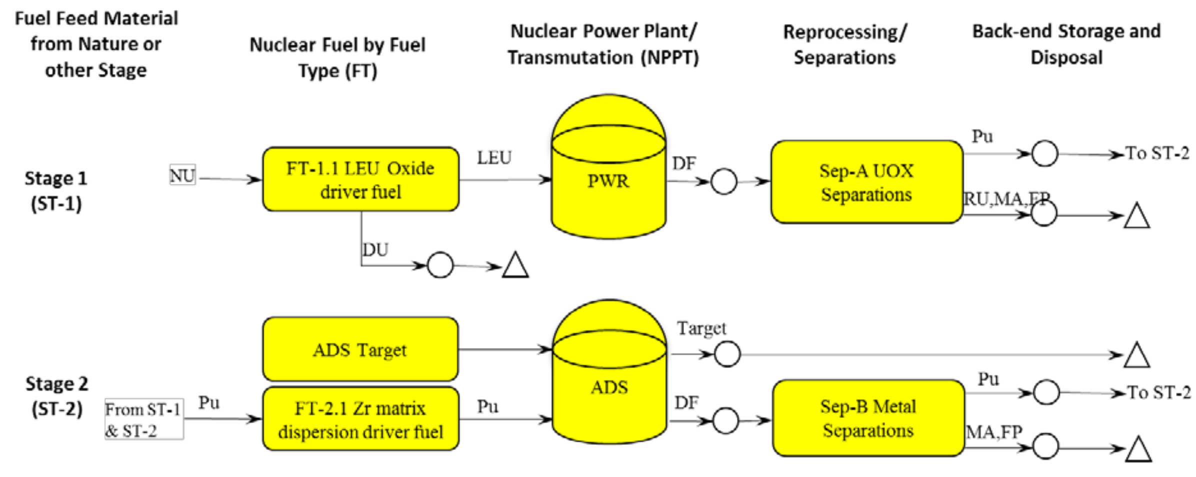
Table B81. Mass Flow Data of Analysis Example for EG34.

Stage		1			2			Sum b)
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		80.0			20.0			100
Natural resource	NU	-112.1			-17.6			-129.7
	Th							-
	Pb/Bi target	TBD	TBD	TBD				
Products from fuel or NPPT technology	DU							0.0
	U	1,399.4	-1,399.4		393.0	-393.0		0.0
	Pu	171.3	-171.3		44.7	-44.7		0.0
	MA	20.3	-20.3		0.05	-0.1		0.0
	DF		1,591.0	-1,591.0		437.8	-437.8	0.0
Products from Rep/Sep technology	RU	-1,290.1		1,290.1	-376.2		376.2	0.0
	Pu	-171.6		184.5	-44.8		31.8	0.0
	MA	-20.4		17.0	-0.05		3.4	0.0
	FP			83.5	0.0		22.0	105.5
Loss		3.1	0.0	15.9	0.9		4.4	24.3

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG35



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:

NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
RU = Recovered Uranium
DF = Discharged Fuel
FP = Fission Products
TRU = Transuranics
MA = Minor Actinides
PWR = Pressurized Water Reactor
SFR = Sodium Fast Reactor
UOX = Uranium Oxide
MOX = Mixed Oxide
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport
/ = Co-separated products

Figure B46. Material Flow Data of Analysis Example for EG35.

Table B82. Reactor and Fuel Information of Analysis Example for EG35.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		PWR	ADS-Burner
	Core Configuration		PWR with UOX	ADS with Pu-IMF
	Core Thermal Power, MWth		3000	840
	Net Thermal Efficiency, %		33	40 (31.1) [a)]
	Electrical Energy Generation Sharing, %		84.7	15.3
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		PWR-UOX	ADS-Metallic
	Purpose		Driver	Driver
	Average Discharge Burnup, GWd/t		50	303
	Fuel Composition	Initial Nuclear Material(s)	LEU	Pu
		(U-235+ U-233)/Total U, %	4.21	2.92
		Th/Total HM, %	0	0
		TRU/Total HM, %	0	99.9
	Fuel Residence Time in Reactor, EFPY		4.1	[b)]2.6/3.0/3.0

a) The net thermal efficiency was assumed to be 40% without taking accelerator power requirements into account. Since the average accelerator power required is 75.0 MWe, the net thermal efficiency has been adjusted to 31.1% for use in determining values for the Mass Flow Data Table.

b) A value is provided for each core region (inner, middle and outer) because they are made of a different number of batches (7, 8 and 8, respectively).

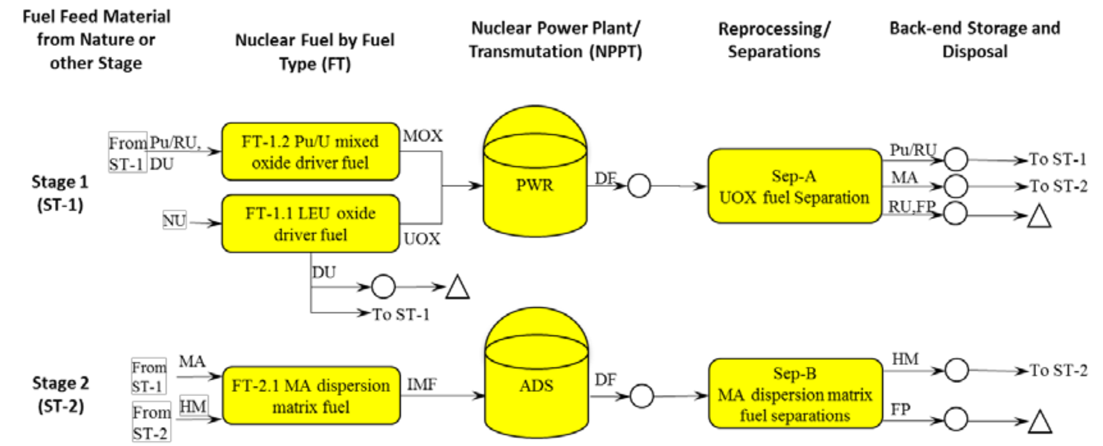
Table B83. Mass Flow Data of Analysis Example for EG35.

Stage		**1**			**2**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		84.7			15.3			100
Natural resource	NU	-15,965.3						-15,965.3
	Th							-
	Pb/Bi target				TBD	TBD	TBD	
Products from fuel or NPPT technology	DU	14,106.8						14,106.8
	U	1,854.9	-1,854.9		0.04	-0.04		0.0
	Pu				58.5	-58.5		0.0
	MA				0.7	-0.7		0.0
	DF		1,854.9	-1,854.9		59.2	-59.2	0.0
Products from Rep/Sep technology	RU			1,717.9			0.1	1,718.0
	Pu			21.4	-59.4		38.0	0.0
	MA			2.5			2.9	5.4
	FP			94.6			17.6	112.2
Loss		3.7		18.5	0.1		0.6	22.9

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group 36



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.

Legend:
NU = Natural Uranium
DU = Depleted Uranium
LEU = Low-enriched Uranium
RU = Recovered Uranium
IMF = Inert matrix fuel
DF = Discharged Fuel
FP = Fission Products
MA = Minor Actinides
MOX = Mixed Oxide
HM = Heavy metal
PWR = Pressurized Water Reactor
SFR = Sodium Fast Reactor
UOX = Uranium Oxide
/ = Co-separated products
= Nuclear Waste Disposal
= Nuclear Material Storage
= Nuclear Material Transport

Figure B47. Material Flow Data of Analysis Example for EG36.

Table B84. Reactor and Fuel Information of Analysis Example for EG36.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		**2**
	NPPT Technology Identifier		PWR		ADS-Burner
	Core Configuration		PWR with UOX and MOX fuels simultaneously (CORAIL-Pu)		ADS with MA-Zr dispersion matrix fuel
	Core Thermal Power, MWth		3000		840
	Net Thermal Efficiency, %		33.3		40.0 (35.0) [a]
	Electrical Energy Generation Sharing, %		93.5		6.5
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**2.1**
	Fuel Technology Identifier		PWR-UOX	PWR–MOX	ADS-Metallic
	Purpose		Driver	Driver	Driver
	Average Discharge Burnup, GWd/t		45.0	45.0	172.0
	Fuel Composition	Initial Nuclear Material(s)	LEU	Pu/RU	MA
		(U-235+ U-233)/Total U, %	4.62	0.3	13.35
		Th/Total HM, %	0	0	0
		TRU/Total HM, %	0	8.45	95.99
	Fuel Residence Time in Reactor, EFPY		3.7	3.7	2.8

a) The thermal efficiency was assumed to be 40%, but the net thermal efficiency has been adjusted to 35% for use in determining values for the Mass Flow Data because 42.0 MWe was used to support accelerator.

Table B85. Mass Flow Data of Analysis Example for EG36.

Stage		1			2			Sum [b]
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		93.5			6.5			100
Feed or product of nuclear materials (metric ton) [a]								
Natural resource	NU	-14,731.1						-14,731.1
	Th							-
Products from fuel or NPPT technology	DU	+12,577.8						+12,577.8
	U	[c]+2,211.7	-2,211.7		+1.6	-1.6		0.0
	Pu	[d] +63.0	-63.0		+14.0	-14.0		0.0
	MA				23.85	-23.85		0.0
	DF		+2,274.7	-2,274.7		39.4	-39.4	0.0
Products from Rep/Sep technology	RU	-63.0		+2,076.0	-1.6		+1.5	+2,013.0
	Pu	[d] -63.0		+63.1	-14.0		+13.9	0.0
	MA			+7.92	-23.85		+16.84	+0.91
	FP			+104.9			+6.8	+111.7
Loss		+4.5		+22.7	+0.1		+0.4	+ 27.8

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) Total uranium in UOX and MOX fuels, which consists of LEU in UOX fuel and DU and RU in MOX fuel.
d) Pu, including its decay daughters.

Evaluation Group EG37

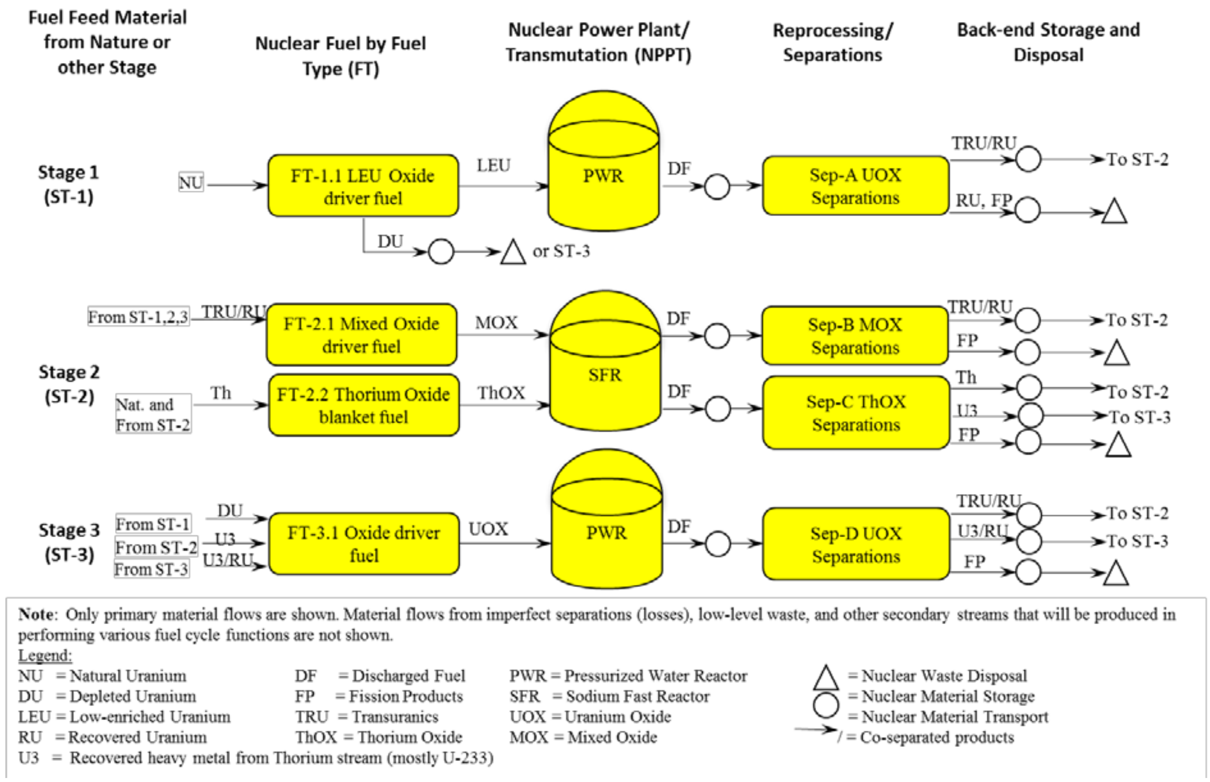


Figure B48. Material Flow Data of Analysis Example for EG37.

Table B86. Reactor and Fuel Information of Analysis Example for EG37.

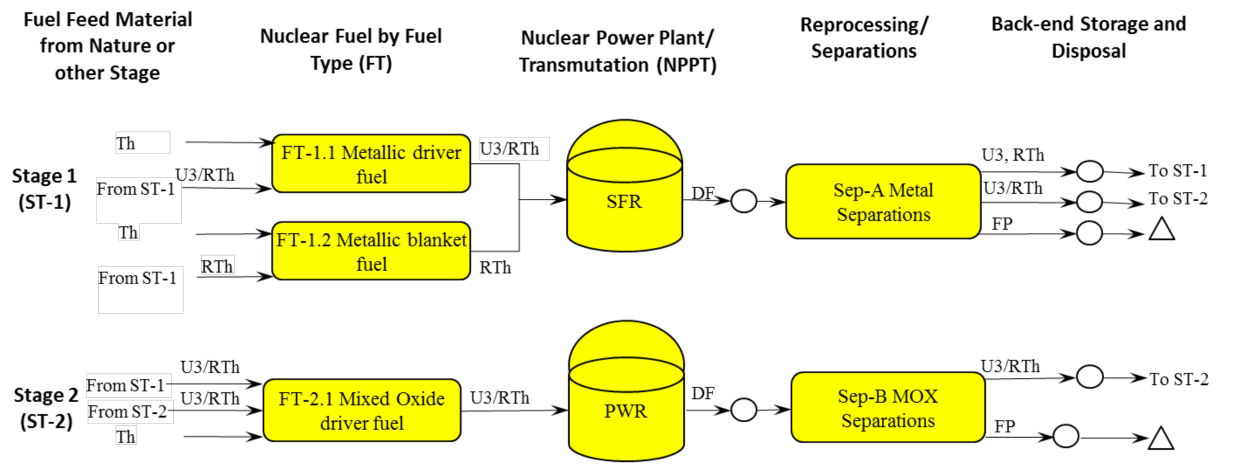
Technology category	Parameter		Stage Number			
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		1	2		3
	NPPT Technology Identifier		PWR	SFR		PWR
	Core Configuration		PWR with UOX	SFR with MOX driver and ThOX blanket		PWR with UOX
	Core Thermal Power, MWth		3000	3000		3400
	Net Thermal Efficiency, %		33.3	40.0		32.4
	Electrical Energy Generation Sharing, %		11.9	50.1		38.0
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**	**2.2**	**3.1**
	Fuel Technology Identifier		PWR-UOX	SFR–MOX	SFR-Th	PWR-UOX
	Purpose		Driver	Driver	Blanket	Driver
	Average Discharge Burnup, GWd/t		50	103	14	55
	Fuel Composition	Initial Nuclear Material(s)	LEU	TRU, RU	Th	U3, RU, DU
		(U-235+ U-233)/Total U, %	4.21	< 1.0	0	3.4
		Th/Total HM, %	0	0	100	0
		TRU/Total HM, %	0	28.6	0	0
	Fuel Residence Time in Reactor, EFPY		4.0	4.1	4.5 – 6	4.1

Table B87. Mass Flow Data of Analysis Example for EG37.

Stage		1			2			3			Sum [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		11.9			50.1			38.0			100
Feed or product of nuclear materials (metric ton) [a)]											
Natural resource	NU	-2,238									-2,238
	Th				-39.4						-39.4
Products from fuel or NPPT technology	DU	1,976.9						-37.5			1,939.4
	Th				552.4	-552.4					0.0
	U3 [b)]							26.7	-26.7		0.0
	U [c)]	260.5	-260.5		267.7	-267.7		753.6	-753.6		0.0
	TRU				107.2	-107.2			0.0		0.0
	DF		260.5	-260.5		927.3	-927.3		780.3	-780.3	0.0
Products from Rep/Sep technology	Th				-514.1		514.1				0.0
	U3 [b)]						24.0	-26.7		2.7	0.0
	RU [c)]			241.1	-268.2		240.7	-717.6		716.1	212.1
	TRU			3.4	-107.4		94.2			9.9	0.1
	FP			13.4			45.1			43.7	102.2
Loss [d)]		+0.52		2.61	1.86		9.27	1.56		7.80	23.6

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Recovered material from thorium stream, mostly U-233 and Pa-233.
c) Recovered uranium from uranium stream.
d) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG38



Note: Only primary material flows are shown. Material flows from imperfect separations (losses), low-level waste, and other secondary streams that will be produced in performing various fuel cycle functions are not shown.
Legend:
Th = Natural Thorium
FP = Fission Products
RTh =Recovered Thorium
U3 = Recovered heavy metal from thorium stream (mostly, U-233)
DF = Discharged Fuel
SFR = Sodium-cooled Fast Reactor
MOX = Mixed U/Th Oxide Fuel
PWR = Pressurized Water Reactor
△ = Nuclear Waste Disposal
○ = Nuclear Material Storage
→ = Nuclear Material Transport

Figure B49. Material Flow Data of Analysis Example for EG38.

Table B88. Reactor and Fuel Information of Analysis Example for EG38.

Technology category	Parameter		Stage Number		
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		**2**
	NPPT Technology Identifier		SFR		PWR
	Core Configuration		SFR with U3/Th, Th		PWR with U3/Th MOX
	Core Thermal Power, MWth		600		3000
	Net Thermal Efficiency, %		40		33
	Electrical Energy Generation Sharing, %		85.5		14.5
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**2.1**
	Fuel Technology Identifier		SFR-Metallic	SFR-Metallic	PWR-MOX
	Purpose		Driver	Blanket	Driver
	Average Discharge Burnup, GWd/t		49	1.3	50
	Fuel Composition	Initial Nuclear Material(s)	U3/Th	Th	U3/Th
		(U-235+ U-233)/Total U, %	84.3	0.0	57.4
		Th/Total HM, %	75.3	100.0	92.6
		TRU/Total HM, %	0.16	0.0	0.36
	Fuel Residence Time in Reactor, EFPY		3.8	3.8	4.1

Table B89. Mass Flow Data of Analysis Example for EG38.

Stage		**1**			**2**			**Sum** [b)]
Technology		**Fuel**	**NPPT**	**Rep/Sep**	**Fuel**	**NPPT**	**Rep/Sep**	
Electricity, GWe-yr		85.5			14.5			100
Feed or product of nuclear materials (metric ton) [a)]								
Natural resource	NU							0.0
	Th	-156.6			-7.9			-164.5
Products from fuel or NPPT technology	Th	+5,173.0	-5,173.0		+298.6	-298.6		0.0
	U3	+352.8	-352.8		+23.1	-23.1		0.0
	Pu	+0.7	-0.7		+0.6	-0.6		0.0
	MA	+1.6	-1.6		+0.5	-0.5		0.0
	DF		+5,528.0	-5,528.0		+322.8	-322.8	0.0
Products from Rep/Sep technology	Th	-5,026.9		+,5033.1	-291.3		+285.1	0.0
	U3	-353.5		+359.8	-23.1		+16.9	0.0
	Pu	-0.7		+0.7	-0.6		+0.6	0.0
	MA	-1.6		+1.6	-0.5		+0.5	0.0
	FP			+77.6			+16.5	+94.1
Loss		+11.2		+55.3	+0.7		+3.2	+70.4

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG39

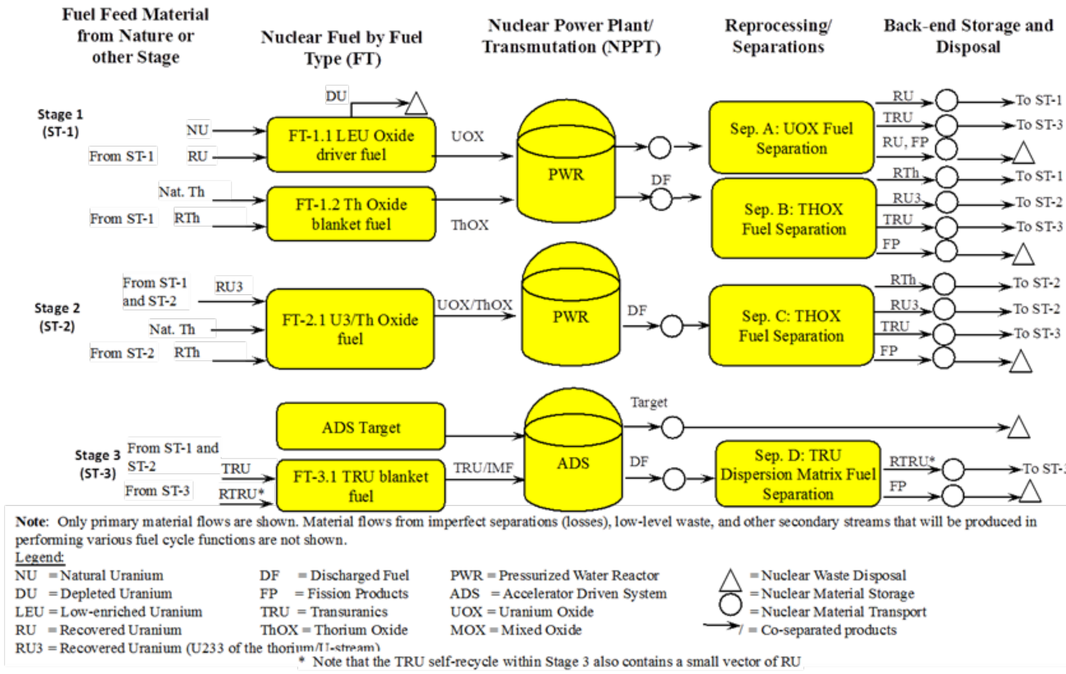


Figure B50. Material Flow Data of Analysis Example for EG39.

Table B90. Reactor and Fuel Information of Analysis Example for EG39.

Technology category	Parameter		Stage Number			
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**		**2**	**3**
	NPPT Technology Identifier		PWR		PWR	ADS-Burner
	Core Configuration		De-rated PWR with LEU seed and heterogeneous ThOX blanket (Seed blanket unit)		PWR fueled with U233/ThOX homogeneous mixture	ADS with TRU-Zr dispersion matrix fuel
	Core Thermal Power, MWth		1500		3000	840
	Net Thermal Efficiency, %		33		33	40 (26) a)
	Electrical Energy Generation Sharing, %		69.64		24.34	6.02
Nuclear Fuel	**Fuel Type**		**1.1**	**1.2**	**2.1**	**3.1**
	Fuel Technology Identifier		PWR-UOX	PWR-ThOX	PWR-Th/UOX	ADS-Metallic
	Purpose		Driver	Blanket	Driver	Driver
	Average Discharge Burnup, GWd/t		61.7	61.7	56.0	194.9
	Fuel Composition	Initial Nuclear Material(s)	LEU	ThOX	ThOX, RU3	TRU
		(U-235+ U-233)/ Total U, %	11.2 b)	0.0	57.0	14.5
		Th/Total HM, %	0.0	100.0	91.9	0.0
		TRU/Total HM, %	0.0	0.0	0.0	94.6
	Fuel Residence Time in Reactor, EFPY		9.67	9.67	4.19	1.92

a) The thermal efficiency assumed was 40%. The electric power required for the accelerator is 120 MWe. Thus, accounting for the accelerator electric power requirements, the net thermal efficiency is 26%.

Table B91. Mass Flow Data of Analysis Example for EG39.

Stage		1			2			3			Sum
Technology		Fuel	NPPT	Rep	Fuel	NPPT	Rep	Fuel	NPPT	Rep	
Electricity, GWe-yr		69.64			24.34			6.02			100.0
Feed or product of nuclear materials (metric ton) [a]											
Natural Resource	U	-11,291.5									-11,291.5
	Th	-50.7			-23.1						-73.8
	Pb/Bi (Target)										
Products from fuel or NPPT technology	DU	11,026.9									11,026.9
	Th	711.8	-711.8		441.7	-441.7					0.0
	U233	0.0	0.0		20.4	-20.4					0.0
	U (other)	536.5	-536.5		18.4	-18.4		2.2	-2.2		0.0
	TRU							41.6	-41.6		0.0
	DF		1248.3	-1248.3		480.6	-480.6		43.8	-43.8	0.0
Products from Rep/Sep technology	RTh	-662.4		662.4	-419.5		419.5				0.0
	U233			11.1	-20.5		9.4				0.0
	RU (other than U233)	-273.1		473.4	-18.5		15.7	-2.2		2.2	197.5
	TRU			8.9			0.5	-41.6		32.3	0.0
	FP			80.0			30.7			9.0	119.8
Loss		2.5		12.5	1.0		4.8	0.1		0.4	21.3

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.

b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.

Evaluation Group EG40

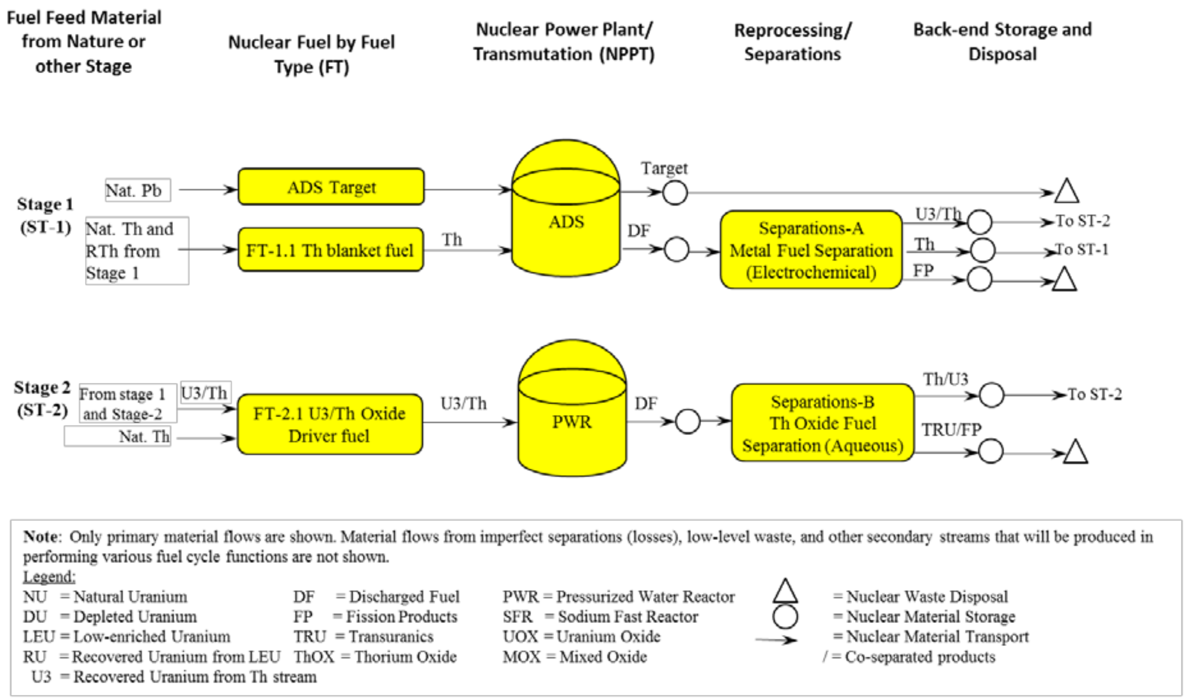


Figure B51. Material Flow Data of Analysis Example for EG40.

Table B92. Reactor and Fuel Information of Analysis Example for EG40.

Technology category	Parameter		Stage Number	
Nuclear Power Plant/ Transmutation (NPPT)	**Stage**		**1**	**2**
	NPPT Technology Identifier		ADS	PWR
	Core Configuration		ADS with Th-Zr Blanket Fuel	U3/Th oxide
	Core Thermal Power, MWth		611.25	3400
	Net Thermal Efficiency, %		40 (23.6) [a)]	33
	Electrical Energy Generation Sharing, %		20.5	79.5
Nuclear Fuel	**Fuel Type**		**1.1**	**2.1**
	Fuel Technology Identifier		ADS(Th)	PWR(U3/Th)
	Purpose		Blanket	Driver
	Average Discharge Burnup, GWd/t		138	62.5
	Fuel Composition	Initial Nuclear Material(s)	Th	U3/Th
		(U-235+ U-233)/Total U, %	0	75.0
		Th/Total HM, %	100	94.1
		TRU/Total HM, %	0	0
	Fuel Residence Time in Reactor, EFPY		18.5	4.1

a) The thermal efficiency assumed was 40 %. The electric power required for the accelerator is 100 MWe. Thus, accounting for the accelerator electric power requirements, the net thermal efficiency is 23.6 %.

Table B93. Mass Flow Data of Analysis Example for EG40.

Stage		1			2			Sum b)
Technology		Fuel	NPPT	Rep/Sep	Fuel	NPPT	Rep/Sep	
Electricity, GWe-yr		20.5			79.5			100
Feed or product of nuclear materials (metric ton) a)								
Natural resource	Pb	-232.2						-232.2
	Th	-66.7			-74.8			-141.5
Products from fuel or NPPT technology	Th	+229.8	-229.8		+1325.6	-1325.6		+0
	Pb-Target	+231.8	-231.8					+0
	c)U3				+83.6	-83.6		+0
	Target(Pb)-Discharge		+231.8					+231.8
	DF		+229.8	-229.8		+1409.2	-1409.2	+0
Products from Rep/Sep technology	c)U3			+30.5	-83.6		+53.1	+0
	Th	+163.6		+163.6	-1253.6		+1253.6	+0
	TRU			+0.0			+0.8	+0.8
	FP			+33.4			+87.6	+121.0
Loss		+0.9d)	+0	+2.3	+2.8	+0	+14.1	+20.1

a) Mass flow in metric ton was developed to produce 100.0 GWe-year from whole nuclear fleet and the signs (-) and (+) indicate the feed and production to or from each technology category, respectively.
b) Summation of each row indicates the required resource (-) or produced nuclear materials (+) per year to generate electricity of 100 GWe-yr.
c) Mainly U233 isotope.
d) Loss includes 0.45 metric tons (assumed to be 0.2%) from target fabrication.

Table B94. Calculation Assumptions for Analysis Examples.

General

- Unprocessed spent nuclear fuel is assumed to be waste and is disposed
- Any depleted uranium (DU) or recovered uranium (RU) produced/recovered and not used is assumed to be waste and is disposed
- No credit is given for generation of excess fissile material to support growth via high conversion ratios. Any such excess material is treated as waste and is disposed
- Fuel cycle facility operating life is assumed to be 50 years (unless otherwise specified)
- There is no constraint on the uranium and thorium resources

Resources

- Natural Uranium mass composition: 0.0054% U-234, 0.711% U-235, 99.2836% U-238
- Natural Thorium mass composition: 100% Th-232

Mining, Milling, Conversion and Deconversion Processes

- Assume no losses in the mining and milling processes, and in the conversion and de-conversion processes

Enrichment

- Depleted uranium tails assay: 0.25%

Fuel Fabrication

- Time between separations product and insertion in reactor – 2 years (not applicable to molten salt reactors with on-line reprocessing)
- Product losses to waste – reference 0.2% by mass

Reactor and Transmuters

- Reactor lifetime: 60 years
- Reactor capacity factor: 90%
- Construction time: 5 years
- Thermal efficiency (used for initial calculations; see Appendix D-1.1 on normalization to 33% for all):
    - Water-cooled = 33%, Sodium-cooled = 40%, Salt-cooled = 44%, Helium-cooled =50%
- For PWR calculations, assume an initial uranium enrichment of 4.21% for the low enriched uranium fuel and an average fuel discharge burnup of 50 GWd/t

Separations/Reprocessing

- Total time from reactor discharge through separations: 5 years
- Separations efficiency (amount retained in the product stream): 99%
- For analyses, assume no carryover impurities
- Facility operational lifetime: 50 years

B-6. Concluding Discussion

The development of the Evaluation Groups used in the E&S involved the following activities:

- Identify the fundamental physics principles and characteristics that affect the performance of a fuel cycle (e.g., spectrum, feed and recycle materials, etc.).
- Create all of the possible fuel cycle option groups based on these principles.
- Combine the fuel cycle option groups based on similarities in need for specific nuclear materials, compositions within the fuel cycle, radioactive materials recycled or requiring disposal, etc.
- Identify a specific Analysis Example for each Evaluation Group for which reactor physics analyses are performed to provide information (primarily mass flows) on resource needs, spent fuel compositions, energy production, and other physics-related fuel cycle characteristics.
- Perform an assessment of the physics-based Evaluation Groups against all nine high-level criteria to ensure that the resulting set of Evaluation Groups is appropriate for the purposes of the E&S.

Forty (40) Evaluation Groups were identified from the above activities, which consisted of eight (8) Once-Through, twelve (12) Limited Recycle, and twenty (20) Continuous Recycle groups. Overall, the resulting list of Evaluation Groups for the E&S and the process for identifying them achieves the following:

- comprehensiveness, i.e., encompasses the entire range of possible fuel cycle characteristics that can affect performance with respect to the high-level evaluation criteria;
- clear explanation of the content of the list of fuel cycle option groups and the corresponding Evaluation Groups;
- identification of an Analysis Example for each Evaluation Group which reflects the focus of the group, for which quantitative data was generated to inform on the metric data as described earlier; and
- the ability to place any proposed new specific fuel cycle option into an existing Evaluation Group, allowing immediate assessment of the potential performance and identification of any benefits that would be associated with such an option.

B-6.1. Description of the Evaluation Groups

The key characteristics of the Evaluation Groups listed in Tables B9-B11 are summarized below. The descriptions include the "focus" of each EG. Note that the resource utilization depends on a number of factors including whether enrichment is employed, the conversion ratio of the irradiation system, burnup, etc. and will therefore be affected by the details of the assumptions made in defining the Analysis Example. The examples noted in the following descriptions are provided to explain the EG and are not necessarily the same as the Analysis Examples.

As noted earlier, the "fuel cycle options" considered in the discussion in Appendix B focus on the "Nuclear Power Alternative" in Figure B1, with the "Fuel Resource Acquisition" and "Nuclear Waste Disposal" components of a complete fuel cycle option considered in a generic fashion. Therefore, only the Nuclear Power Alternative is described here.

<u>Once-Through Fuel Cycle</u>

The once-through fuel cycle uses fuel from natural resources; the fuel is used once and is then discharged; and all spent fuel and LLW is disposed. There are eight (8) Evaluation Groups, as follows:

EG01: The focus of this group is once-through fuel cycles that use enriched uranium fuel in thermal spectrum reactors like those currently used in the U.S., followed by disposal of the spent fuel in a geologic repository. EG01 contains the once-through fuel cycles using low-enriched uranium (LEU) fuel typically with <5 wt.% U-235 in a critical, thermal-spectrum reactor, with the result that about 0.6% of the uranium resource originally obtained for fuel is used for energy production and the remainder is disposed. Since EG01 includes the current planned fuel cycle in the U.S., EG01 serves as the "Basis of Comparison" for this study.

> **Example(s):** A once-through fuel cycle system with current generation, commercial pressurized-water reactors (PWRs) using LEU fuel.

EG02: The focus of this group is once-through fuel cycles that use enriched uranium fuel, in reactors either like those currently used in the U.S. or advanced reactors (critical or driven sub-critical), followed by disposal of the spent fuel. EG02 contains once-through fuel cycles with critical reactors or sub-critical EDS with a thermal or fast-spectrum where the uranium enrichment is generally in the range of 5 - 20 wt.% U-235. This allows the fuel to be used longer in the reactor thereby increasing the discharge burnup, or to increase the multiplication factor and thereby reduce the needed source strength in sub-critical, driven systems. This results in using up to 3% of the uranium resource, the remainder being disposed.

> **Example(s):** Once-through fuel cycle systems using LEU fuel with: 1) critical high-temperature gas-cooled reactors (HTGRs); 2) critical thermal-spectrum light-water/heavy-water cooled/moderated reactors with higher enrichments; 3) fast-spectrum reactors, e.g., sodium-cooled (SFR), lead-cooled (LFR), etc.; and 3) externally driven systems (ADS or FFH) with LEU in a thermal or fast spectrum sub-critical blanket.

EG03: The focus of this group is once-through fuel cycles that use reactor fuel of natural uranium to avoid the need for enrichment and enrichment technology, followed by disposal of the spent fuel in a geologic repository. EG03 contains once-through fuel cycle options that use critical, thermal-spectrum reactors with natural uranium fuel, resulting in up to 3% of the uranium resource being used, and the remainder going to disposal.

> **Example(s):** Once-through fuel cycle systems with: 1) heavy water reactors (HWRs) using natural uranium fuel; 2) gas-cooled graphite moderated reactors using natural uranium fuel.

EG04: The focus of this group is once-through fuel cycles that use uranium fuel without enrichment at equilibrium in fast spectrum critical reactors to high burnup. The once-through fuel cycle options in EG04 use natural uranium fuel or depleted uranium, un-enriched uranium-thorium or thorium as the feed fuel at equilibrium (enrichment may be required at start-up) in critical fast-spectrum reactors to achieve high burnups, resulting in the use of between 3% and 30% of the uranium resource, the remainder being disposed.

> **Example(s):** Once-through systems with natural or depleted uranium, uranium-thorium, or thorium at equilibrium, utilizing: 1) a sodium-cooled fast reactors (SFRs); 2) other critical fast-spectrum reactors.

EG05: The focus of this group is once-through fuel cycles using enriched uranium and thorium in critical thermal reactors to extend natural resources. EG05 contains once-through fuel cycle options that use fuels of enriched uranium and thorium in critical reactors or sub-critical EDS with a thermal or fast-spectrum. Up to 3% of the natural resource is used, with the remainder going to disposal.

Example(s): Once-through fuel cycle system with: 1) HTGRs using thorium and LEU fuel; 2) seed-blanket PWR with an LEU seed and thorium (or LEU plus thorium) blanket.

EG06: The focus of this group is once-through fuel cycles that use thorium to high burnup in a thermal spectrum sub-critical EDS. The fuel cycle options in EG06 utilize thorium or natural uranium and thorium to extend natural resources. The high burnup, and the absence of enriched uranium results in between 30% and 100% of the natural resources being used, with the remainder going to disposal. EG06 contains once through fuel cycle options that use critical reactors or sub-critical EDS with a thermal-spectrum; however, subsequent analyses have demonstrated that critical thermal spectrum systems are not feasible.

Example(s): Once-through fuel cycle systems with: 1) a fission-fusion hybrid (FFH) having a molten-salt-cooled blanket region using thorium fuel; 2) EDS with an accelerator.

EG07: The focus of this group is once-through fuel cycles that use natural uranium to a high burnup in a fast spectrum sub-critical EDS. EG07 contains once-through fuel cycle options that utilize natural uranium fuel in an EDS with a subcritical thermal or fast-spectrum blanket. This system is designed to generate electricity without the need for enrichment starting with natural uranium and breeding fissile material to generate power in the sub-critical blanket. The absence of enrichment, and the potential for high burnup of the fuel results in between 30% and 100% of the uranium resource being used, with the remainder going to disposal.

Example(s): Once-through fuel cycle systems with: 1) an accelerator-driven system (ADS) having a sodium-cooled blanket using natural uranium fuel; 2) an FFH or ADS with a thermal spectrum blanket.

EG08: The focus of this group is once-through fuel cycles that use thorium to a high burnup in a fast-spectrum sub-critical EDS. EG08 contains once-through fuel cycle options utilizing thorium or natural uranium-thorium fuel to extend natural resources in an EDS with a subcritical fast-spectrum blanket. This system is designed to generate electricity without the need for enrichment starting with thorium or natural uranium-thorium and breeding fissile material to generate power in the sub-critical blanket. The absence of enrichment and the potential for high burnup of the fuel results in use of the natural resources of between 30% and 100%, with the remainder going to disposal.

Example(s): Once-through fuel cycle system with a fission-fusion hybrid (FFH - fusion devices with a subcritical fast-spectrum blanket) using thorium fuel.

Limited Recycle Fuel Cycle

The limited recycle fuel cycle uses fuel from natural resources and recycled materials, where at least some discharged fuel is reprocessed and recycled at least once; after one or several recycles, spent fuel/discharged fuel (DF) is disposed along with HLW from reprocessing and recycle fuel fabrication, and LLW. There are three (3) Evaluation Groups for single-stage systems, and seven (7) for multi-stage systems, as follows:

EG09: The focus of this group is limited recycle of U/TRU to high burnup in critical fast reactors without enrichment. The fuel cycle options in EG09 utilize single and multi-stage fast spectrum critical reactor systems, single-stage fast spectrum subcritical EDS, or multi-stage fast spectrum critical reactors and subcritical EDS using fuel(s) of un-enriched natural uranium, or uranium and thorium with recycle of U/Pu or U/TRU. The absence of enrichment and high burnup results in using between 30% and 100% of the natural resource.

> **Example(s):** An example of a fuel cycle in EG09 is SFRs using blanket fuel of natural uranium to create TRU that is recovered by reprocessing and used as driver fuel, with disposal of HLW and SFR DF.

EG10: The focus of this group is limited recycle of U-233/Th in critical thermal reactors without enrichment. Fuel cycle options in EG10 utilize single and multi-stage thermal and/or fast-spectrum critical reactors, single-stage subcritical EDS with thermal or fast spectra, and multi-stage systems with critical reactors and subcritical EDS with thermal and/or fast spectra using fuel(s) of uranium and thorium, thorium, and recycled thorium and uranium (mainly U-233). Between 3% and 30% of the natural resources are used.

> **Example(s):** An example of a fuel cycle in EG10 is molten salt reactors (MSRs) using thorium to create U-233 recovered by reprocessing and used as driver fuel, with disposal of HLW and MSR DF.

EG11: The focus of this group is limited recycle of U/U-233/Th in a critical fast reactor with enrichment. Fuel cycle options in EG11 utilize single and multi-stage fast-spectrum critical reactors and single-stage subcritical EDS with thermal or fast spectra using fuel(s) of thorium and/or enriched uranium, and recycled uranium (mainly U-233), thorium, Pu or TRU. The use of enrichment and limited burnup results in using up to 3% of the natural resource.

> **Example(s):** An example of a fuel cycle in EG11 is SFRs using LEU fuel, and thorium to create U-233 for recycle, with disposal of HLW and SFR DF.

EG12: The focus of this group is limited recycle of U/Pu in a critical thermal reactor without enrichment. Fuel cycle options in EG12 utilize single and multi-stage critical reactors with a thermal spectrum, single-stage subcritical EDS with thermal spectrum blanket, and multi-stage systems with critical fast or thermal reactors and EDS with thermal or fast subcritical blankets using fuel(s) of natural uranium, uranium-thorium, recycled uranium/ thorium, and recycled Pu or TRU. Up to 3% of the natural resource is used.

> **Example(s):** An example of a fuel cycle in EG12 is HWRs (the first stage) using natural uranium fuel and PWRs (the second stage) using fuel of recycled U and Pu from the HWR, with disposal of HLW and all PWR DF.

EG13: The focus of this group is limited recycle of U/Pu in a critical thermal reactor with enrichment. The fuel cycle options in EG13 utilize single and multi-stage thermal-spectrum critical reactors and thermal spectrum sub-critical single-stage EDS using fuel(s) of enriched uranium, recycled uranium, and recycled Pu or TRU. Up to 3% of the uranium resource is utilized.

> **Example(s):** An example of a fuel cycle in EG13 is PWRs (the first stage) using LEU fuel and PWRs (the second stage) using recycled U and Pu from the first stage PWRs, with disposal of HLW and all PWR DF from the second stage.

EG14: The focus of this group is limited recycle of U/Pu with both critical fast and thermal reactors without enrichment. The fuel cycle options in EG14 utilize multi-stage thermal and fast spectrum critical reactors, or critical reactors and sub-critical EDS with thermal and fast spectra using fuel(s) of un-enriched natural uranium, uranium-thorium, recycled uranium/thorium, and recycled Pu or TRU. Between 3% and 30% of the natural resource is used.

Example(s): An example of a fuel cycle option in EG14 is SFRs (the first stage) using driver fuel of recycled U and Pu created from natural uranium blanket fuel in the SFR, and PWRs (the second stage) using fuel of recycled U and recycled Pu from the SFR, with disposal of HLW and all PWR DF.

EG15: The focus of this group is limited recycle of U/Pu with both critical fast and thermal reactors with enrichment. This Evaluation Group is similar to EG14 but the fuel cycle options in EG15 utilize enriched uranium for the feed fuel. The fuel cycle options in EG15 contain multi-stage systems, with thermal and fast spectrum critical reactors, using fuel(s) of enriched uranium, and recycled uranium, Pu or TRU. Up to 3% of the uranium resource is used.

Example(s): An example of a fuel cycle in EG15 is PWRs (the first stage) using LEU fuel, and SFRs (the second stage) using fuel of recycled uranium and Pu from the PWRs, with disposal of HLW and all SFR DF.

EG16: The focus of this group is limited recycle of U/Pu with critical thermal reactors and fast sub-critical EDS with enrichment. This Evaluation Group is similar to EG15, but the fuel cycle options in EG16 contain both critical reactors, and subcritical, driven systems. The fuel cycle options in EG16 contain limited-recycle, multi-stage systems with critical thermal or fast reactors and EDS with thermal or fast spectrum subcritical blankets, using fuel(s) of enriched uranium and recycled uranium, Pu or TRU. Up to 3% of the uranium resource is used .

Example(s): An example of a fuel cycle in EG16 is PWRs (the first stage) using LEU fuel, and fast-spectrum ADSs (the second stage) using fuel of recycled Pu from the PWRs with the Pu as fuel in an inert matrix, and with disposal of HLW and all ADS DF.

EG17: The focus of this group is limited recycle of U/Pu/Th in critical thermal reactors with enrichment. The fuel cycle options in EG17 use enriched uranium and thorium feed fuel to enhance the burning of Pu and TRU by limiting the production of new Pu or TRU during irradiation. Fuel cycle options in EG17 contain limited-recycle options utilizing single-stage thermal spectrum critical reactors, and multi-stage systems with critical, thermal and fast spectrum reactors using fuel(s) of thorium and enriched uranium, and recycled uranium/thorium, Pu or TRU. The group also contains critical thermal or fast spectrum critical reactors with subcritical thermal or fast spectrum EDS using fuel(s) of thorium, enriched uranium, and recycled uranium/thorium, Pu or TRU. Up to 3% of the natural resources is used.

Example(s): An example of a fuel cycle option in EG17 is PWRs (the first stage) using LEU fuel, and PWRs (the second stage) using thorium fuel and the recycled Pu from the first stage PWRs, and with disposal of HLW and all PWR DF from the second stage.

EG18: The focus of this group is limited recycle of U/U-233/Th in critical thermal reactors with enrichment. This Evaluation Group is similar to EG17 except that the recycled element is U (mainly U-233) rather than Pu or TRU. The fuel cycle options in EG18 use enriched uranium and thorium feed fuel, and focus on the recycle of the uranium (mainly U-233) bred from the thorium. Fuel cycle options in EG18 contain limited-recycle options utilizing single-stage thermal spectrum critical reactors, and multi-stage systems with critical, thermal and fast spectrum reactors using fuel(s) of thorium and enriched uranium, and recycled uranium (mainly U-233) and thorium. The group also contains critical thermal or fast spectrum critical reactors with subcritical thermal or fast spectrum EDS using fuel(s) of thorium, enriched uranium, and recycled uranium (mainly U-233) and thorium. Up to 3% of the natural resource is used.

> **Example(s):** An example of a fuel cycle option in EG18 is PWRs (the first stage) using fuel(s) of thorium and LEU, and PWRs (the second stage) using thorium and recycled uranium (from the thorium fuel, mainly U-233) from the first stage PWRs, with disposal of HLW and all PWR DF from the second stage.

Continuous Recycle Fuel Cycle

The continuous recycle fuel cycle uses fuel fabricated from natural resources and recycled materials; the discharged fuel is always reprocessed and recycled; HLW from reprocessing and recycle fuel fabrication, and LLW are disposed. There are ten (10) Evaluation Groups for single-stage systems, and twelve (12) Evaluation Groups for multi-stage systems, as follows:

EG19: The focus of this group is continuous recycle of U/Pu in critical thermal reactors without enrichment. The fuel cycle options in EG19 continuously recycle Pu in thermal-spectrum reactors (single-stage or multi-stage) or single-stage sub-critical systems with a thermal spectrum using fuel(s) of natural uranium, uranium-thorium, recycled uranium/thorium, and recycled Pu. Up to 3% of the natural resources is used.

> **Example(s):** Examples of fuel cycle options in EG19 are systems with: 1) single-stage HWRs using fuel of natural uranium, recycled uranium, and recycled Pu; 2) multi-stage HWRs; 3) graphite-moderated gas cooled reactors; 4) ADS or FFH EDS with sub-critical blankets.

EG20: The focus of this group is continuous recycle of U/TRU in critical thermal reactors without enrichment. This Evaluation Group is similar to EG19 but with recycle of all the TRU instead of just the Pu. The fuel cycle options in EG20 continuously recycle TRU in thermal-spectrum reactors (single-stage or multi-stage) or single-stage sub-critical systems with a thermal spectrum using fuel(s) of natural uranium, uranium-thorium, recycle uranium/thorium, and recycled TRU. Up to 3% of the natural resources is used.

> **Example(s):** Examples of fuel cycle options in EG20 are systems with: 1) single-stage HWRs using fuel of natural uranium, recycled uranium, and recycled TRU; 2) multi-stage HWRs; 3) graphite-moderated gas cooled reactors; 4) ADS or FFH EDS with sub-critical blankets.

EG21: The focus of this group is continuous recycle of U/Pu in critical thermal reactors with enrichment. This Evaluation Group is similar to EG19, except the fuel cycle options in EG21 continuously recycle Pu in thermal-spectrum reactors (single-stage or multi-stage) or single-stage sub-critical EDS with thermal spectra using fuel(s) of enriched uranium, recycled uranium, and recycled Pu. Up to 3% of the uranium resource is used.

> **Example(s):** Examples of fuel cycle options in EG21 are systems with: 1) single-stage PWRs using fuel of LEU, recycled uranium, and recycled Pu; 2) multi-stage PWRs/HWRs; 3) graphite-moderated gas cooled reactors; 4) ADS or FFH EDS with sub-critical blankets.

EG22: The focus of this group is continuous recycle of U/TRU in critical thermal reactors with enrichment. This Evaluation Group is similar to EG21 but recycles all the TRU instead of just the Pu. Fuel cycle options in EG22 use thermal-spectrum reactors (single-stage or multi-stage) or single-stage sub-critical EDS with thermal spectra using fuel(s) of enriched uranium, recycled uranium, and recycled TRU. Up to 3% of the uranium resource is used.

> **Example(s):** Examples of fuel cycle options in EG22 are: 1) single-stage PWRs/HTGRs using fuel of LEU, recycled uranium, and recycled TRU; 2) multi-stage thermal spectrum reactors (e.g., PWRs, HTGRs); 3) ADS or FFH EDS with sub-critical blankets.

EG23: The focus of this group is continuous recycle of U/Pu in critical fast reactors without enrichment. This Evaluation Group is similar to EG19 except that the critical and subcritical systems employ a fast spectrum versus a thermal spectrum in EG19. Fuel cycle options in EG23 use critical single and multi-stage fast-spectrum reactors or single-stage sub-critical EDS with fast spectra using fuel(s) of natural uranium, uranium-thorium, recycled uranium/thorium, and recycled Pu. The absence of enrichment, recycle, and high burnup allows use of between 30% and 100% of the natural resources.

> **Example(s):** Examples of fuel cycle options in EG23 are: 1) SFRs using fuel of natural uranium, recycled uranium, and recycled Pu; 2) other fast-spectrum reactors (e.g., lead-cooled, gas-cooled).

EG24: The focus of this group is continuous recycle of U/TRU in critical fast reactors without enrichment. This Evaluation Group is similar to EG23 except that all of the TRU is recycled instead of just the Pu. It is also similar to EG20 with a fast spectrum versus a thermal spectrum in EG20. Fuel cycle options in EG24 use critical single and multi-stage fast-spectrum reactors or single-stage sub-critical EDS with fast spectra using fuel(s) of natural uranium, uranium-thorium, recycled uranium/thorium, and recycled TRU. The absence of enrichment, recycle, and high burnup allows use of between 30% and 100% of the natural resources.

> **Example(s):** Examples of fuel cycle options in EG24 are: 1) SFRs using fuel of natural uranium, recycled uranium, and recycled TRU; 2) other fast-spectrum reactors (e.g., lead-cooled, gas-cooled).

EG25: The focus of this group is continuous recycle of U233/Th in critical thermal reactors with enrichment. This Evaluation Group contains continuous recycle fuel cycle options initially fuelled with enriched uranium and thorium to extend natural resources. Fuel cycle options in EG25 use critical single and multi-stage thermal-spectrum reactors or single-stage sub-critical EDS with thermal spectra using fuel(s) of thorium and enriched uranium, recycled uranium (from the LEU and mainly U-233 from Th), recycled thorium, and recycled Pu or TRU. Up to 3% of the natural resources is used.

> **Example(s):** An example of a fuel cycle option in EG25 is PWRs using driver fuel of LEU and blanket fuel of recycled uranium and thorium.

EG26: The focus of this group is continuous recycle of U233/Th in critical thermal reactors without enrichment. This Evaluation Group contains continuous recycle fuel cycle options initially fuelled with thorium or uranium-thorium to extend natural resources. Fuel cycle options in EG26 use critical single and multi-stage thermal-spectrum reactors or sub-critical EDS with thermal spectra using fuel(s) of uranium, thorium, recycled uranium (mainly U-233)/thorium. Between 30% and 100% of the natural resource is used.

> **Example(s):** An example of a fuel cycle option in EG26 is MSRs using fuel of thorium, and recycled uranium.

EG27: The focus of this group is continuous recycle of U233/Th in critical fast reactors with enrichment. This Evaluation Group contains continuous-recycle options initially fuelled with enriched uranium or enriched uranium and thorium. Fuel cycle options in EG27 use critical single and multi-stage fast-spectrum reactors or single-stage sub-critical systems with fast spectra using fuel(s) of enriched uranium or enriched uranium and thorium, recycled uranium (from the LEU and mainly U-233 from the Th), recycled thorium, and recycled Pu or TRU. Up to 3% of the natural resources is used.

Example(s): An example of a fuel cycle option in EG27 is SFRs using fuel of thorium, LEU, and recycled uranium.

EG28: The focus of this group is continuous recycle of U233/Th in critical fast reactors without enrichment. This Evaluation Group contains continuous-recycle options initially fuelled with uranium-thorium or thorium. Fuel cycle options in EG28 use critical single and multi-stage fast-spectrum reactors or single-stage sub-critical EDS with fast spectra using fuel(s) of uranium-thorium, thorium and recycled uranium (mainly U-233)/thorium. Since primarily thorium is used initially, and no enrichment is needed, between 30% and 100% of the natural resource can be used.

Example(s): An example of a fuel cycle option in EG28 is SFRs using fuel of thorium and recycled uranium.

EG29: The focus of this group is continuous recycle of U/Pu with both critical fast and thermal reactors without enrichment. The fuel cycle options in EG29 utilize multi-stage critical, thermal and fast spectrum reactors using fuel(s) of thorium and/or enriched uranium, recycled uranium/thorium, and recycled Pu. Continuous recycling of the uranium/thorium, and the absence of enrichment allows between 30% and 100% of the natural resource to be used.

Example(s): An example of a fuel cycle option in EG29 is SFRs (the first stage) using fuel of natural uranium, recycled uranium, and recycled Pu from the SFRs, and PWRs (the second stage) using recycled uranium and recycled Pu from the SFRs.

EG30: The focus of this group is continuous recycle of U/TRU with both critical fast and thermal reactors without enrichment. This Evaluation Group is similar to EG29 but recycles all of the TRU instead of just the Pu. Therefore, only losses from reprocessing require geologic disposal. Comparison to EG29 shows the effect of recycling of the MA. The fuel cycle options in EG30 utilize multi-stage critical, thermal and fast spectrum reactors using fuel(s) of natural uranium, uranium-thorium, recycled uranium/thorium, and recycled TRU. Continuous recycling of the uranium/thorium, and the absence of enrichment allows between 30% and 100% of the natural resource to be used.

Example(s): An example of a fuel cycle option in EG30 is SFRs (the first stage) using fuel of natural uranium, recycled uranium, and recycled TRU from the SFRs and recovered minor actinides (MA) from PWRs (the second stage) using fuel of recycled uranium and recycled Pu from the SFRs.

EG31: The focus of this group is continuous recycle of U/Pu with both critical fast and thermal reactors with enrichment. This Evaluation Group is similar to EG29 but utilizes enriched uranium as feed fuel. The fuel cycle options in EG31 utilize multi-stage critical, thermal and fast spectrum reactors using fuel(s) of enriched uranium, recycled uranium, and recycled Pu. Up to 3% of the natural resource is used.

Example(s): An example of a fuel cycle option in EG31is PWRs (the first stage) using LEU fuel, and SFRs (the second stage) using fuel of natural uranium, recycled uranium, and recycled Pu from the PWRs and SFRs.

EG32: The focus of this group is continuous recycle of U/TRU with both critical fast and thermal reactors with enrichment. This Evaluation Group is similar to EG31 but continuously recycles all the

TRU instead of just the Pu in addition to the uranium. Therefore, only losses from reprocessing require geologic disposal. Comparison to EG31 shows the effect of recycling of the MA. The fuel cycle options in EG32 utilize multi-stage critical, thermal and fast spectrum reactors using fuel(s) of enriched uranium, recycled uranium, and recycled TRU. Up to 3% of the natural resource is used.

> **Example(s):** An example of a fuel cycle option in EG32 is PWRs (the first stage) using LEU fuel, and SFRs (the second stage) using fuel of recycled uranium and recycled TRU from the PWRs and SFRs

EG33: The focus of this group is continuous recycle of U/Pu with both fast EDS and critical thermal reactors without enrichment. This Evaluation Group is similar to EG29 but includes multi-stage systems containing both critical reactors and EDS sub-critical systems. The fuel cycle options in EG33 contain continuous-recycle, multi-stage fuel cycle systems with critical thermal or fast spectrum reactors and EDSs with thermal or fast spectrum subcritical blankets, using fuel(s) of natural uranium, uranium-thorium, recycled uranium/thorium, and recycled Pu. Continuous recycling of the uranium/thorium, and the absence of enrichment allows between 30% and 100% of the natural resource to be used.

> **Example(s):** An example of a fuel cycle option in EG33 is a fast-spectrum ADSs (the first stage) using natural uranium, recycled uranium, and recycled Pu fuel, and PWRs (the second stage) using fuel of recycled uranium and recycled Pu.

EG34: The focus of this group is continuous recycle of U/TRU with both fast EDS and critical thermal reactors without enrichment. This Evaluation Group is similar to EG33 but recycles all the TRU instead of just the Pu. Therefore, only losses from reprocessing require geologic disposal. Comparison to EG33 shows the effect of recycling of the MA. The fuel cycle options in EG34 contain continuous-recycle, multi-stage fuel cycle systems with critical thermal or fast spectrum reactors and EDSs with thermal or fast spectrum subcritical blankets, using fuel(s) of natural uranium, uranium-thorium, recycled uranium/thorium, and recycled TRU. Continuous recycling of the uranium/thorium, and the absence of enrichment allows between 30% and 100% of the natural resource to be used.

> **Example(s):** An example of a fuel cycle option in EG34 is a fast-spectrum ADSs (the first stage) using natural uranium, recycled uranium, and recycled TRU fuel, and PWRs (the second stage) using fuel of recycled uranium and recycled TRU.

EG35: The focus of this group is continuous recycle of U/Pu with both critical thermal reactors and fast EDS with enrichment. This Evaluation Group is similar to EG33 except that enriched uranium is used. The fuel cycle options in EG35 contain continuous-recycle, multi-stage fuel cycle systems with critical thermal or fast spectrum reactors and EDSs with thermal or fast spectrum subcritical blankets, using fuel(s) of enriched uranium, recycled uranium, and recycled Pu. Up to 3% of the natural resource is used.

> **Example(s):** An example of a fuel cycle options in EG35 is PWRs (the first stage) using LEU fuel and fast-spectrum ADSs (the second stage) using fuel of recycled Pu in an inert matrix from the PWRs in order to maximize the burning of Pu.

EG36: The focus of this group is continuous recycle of U/TRU with both critical thermal reactors and fast EDS with enrichment. This Evaluation Group is similar to EG35 but recycles all the TRU instead of just the Pu. Comparison to EG35 shows the effect of recycling of the MA. The fuel cycle options in EG36 contain continuous-recycle, multi-stage fuel cycle systems with critical thermal or fast spectrum reactors and EDSs with thermal or fast spectrum subcritical blankets, using fuel(s) of enriched uranium, recycled uranium, and recycled TRU. Up to 3% of the natural resource is used.

Example(s): An example of a fuel cycle option in EG36 is PWRs (the first stage) using fuel of LEU, recycled uranium, and recycled plutonium, and fast-spectrum ADSs (the second stage) using fuel of recycled minor actinides from the PWRs in an inert matrix to maximize burning of the MA.

EG37: The focus of this group is continuous recycle of U/U-233/TRU/Th with both critical fast and thermal reactors with enrichment. This Evaluation Group is similar to EG31 and EG32 but contains continuous-recycle options initially fuelled with enriched uranium and thorium. The addition of thorium extends the use of natural resources. The fuel cycle options in EG37 contain continuous recycle, multi-stage critical reactors with thermal and fast-spectra using fuel(s) of thorium and enriched uranium, recycled uranium (uranium from LEU and mainly U-233 from Th)/, recycled thorium, and recycled Pu or TRU. This results in a use of natural resources between 3% and 30%.

Example(s): An example of a fuel cycle options in EG37 is PWRs (the first stage) using LEU fuel, SFRs (the second stage) using recycled uranium and recycled TRU as driver fuel, with thorium blankets, and PWRs (the third stage) using recycled uranium from LEU and recovered uranium (mainly U-233) from the thorium blanket of the SFRs.

EG38: The focus of this group is continuous recycle of U-233/Th with both critical thermal and fast reactors without enrichment. This Evaluation Group is similar to EG29 but uses thorium instead of/in addition to uranium to extend natural resources. The fuel cycle options in EG38 utilize multi-stage critical, thermal and fast spectrum reactors using fuel(s) of uranium-thorium, thorium, recycled thorium and recycled uranium (mainly U-233). Continuous recycling of the thorium and uranium allows between 30% and 100% of the natural resource to be used.

Example(s): An example of a fuel cycle option in EG38 is SFRs (the first stage) using fuels of thorium and recycled uranium (mainly U-233) driver fuel with a thorium blanket, and PWRs (the second stage) using fuel of thorium and recycled uranium from the SFR.

EG39: The focus of this group is continuous recycle of U/U-233/TRU/Th with both critical thermal reactors and fast EDS with enrichment. This Evaluation Group is similar to EG37 and includes sub-critical EDS whereas EG37 had only critical reactors. The fuel cycle options in EG39 contain continuous-recycle, multi-stage fuel cycle systems with critical thermal or fast spectrum reactors and EDSs with thermal or fast spectrum subcritical blankets, using fuel(s) of thorium and enriched uranium, recycled uranium (mainly U-233), recycled thorium, and recycled Pu or TRU. Up to 3% of the natural resources is used.

Example(s): Examples of fuel cycle options in EG39 are: 1) PWRs (the first stage) using fuels of thorium (blanket) and LEU (driver), other PWRs (the second stage) using fuel of thorium and recycled uranium (mainly U-233) from the first stage PWRs, and fast-spectrum ADSs (the third stage) using fuel of recycled TRU from the PWRs and the ADSs in an inert matrix.

EG40: The focus of this group is continuous recycle of U-233/Th with both fast EDS and critical thermal reactors without enrichment. This Evaluation Group is similar to EG33 but uses thorium instead of/in addition to uranium to extend natural resources. The fuel cycle options in EG40 contain continuous-recycle, multi-stage fuel cycle systems with critical thermal or fast spectrum reactors and EDSs with thermal or fast spectrum subcritical blankets, using fuel(s) of natural thorium, natural uranium-thorium, recycled thorium, and recycled uranium (mainly U-233). Continuous recycling allows between 30% and 100% of the natural resource to be used.

<u>Example(s):</u> An example of a fuel cycle option in EG40 is fast-spectrum ADSs (the first stage) using thorium fuel and breeding U-233 for PWRs (the second stage) using fuel of recycled uranium (mainly U-233) and thorium.

B-6.2. Relationship to Results of Pilot Demonstration

The FY 2010-2011 Pilot Study [B1] used lists of example fuel cycle options, fuel cycle groups, high-level evaluation criteria, and metrics to test the concept of E&S. Fuel cycles considered in the Pilot Study (PS) were identified as having potential fuel cycle performance improvements that are of "minor benefit," "modest potential," or "most promising," as compared to a once-through fuel cycle with LWRs (today's implementation in the United States). Conduct of the PS uncovered a number of limitations, and lessons learned in the evaluation process were addressed for this E&S. However, even with these limitations identified in the PS, it was possible to identify a number of fuel cycle options (representing about 20% of the options considered in that study) that consistently only provided at most a minor change in fuel cycle performance, and consequently were evaluated as being of "minor benefit." Subsequently, the program determined that these options were "not worthwhile to pursue for long-term R&D."

The "minor benefit" fuel cycles included both once-through and limited recycle fuel cycles, and uranium and uranium/thorium fuels, as indicated in Tables B95 and B96. These groups of options that were evaluated as having minor benefit and proposed as "not worthwhile to pursue" in the Pilot Study are included in the comprehensive list of Fuel Cycle Option Groups developed in the current study, but these specific options were not further analyzed or evaluated.

The groups shown in Tables B95 and B96 that were evaluated as having minor benefit and proposed as "not worthwhile to pursue" are included in the comprehensive list of Fuel Cycle Options Groups shown in Tables B9-B11. The Analysis Example selected for each of these Evaluation Groups is different from the "option" considered in the PS, and is generally a better performing "option" than the one identified in the PS.

Because of the definitions of the Fuel Cycle Option Groups and the methodology for combining these groups to obtain the Evaluation Groups as described in this Appendix, the "minor benefit" options from the PS are included with options that have significantly better potential performance with respect to all the criteria than the "minor benefit" option. Therefore, it would not be appropriate to eliminate an Evaluation Group from consideration simply because it includes a minor benefit option from the PS.

Table B95. Minor Benefit Once-Through Fuel Cycle Options from Pilot Study.

Reactivity	Spectrum	Incoming Feed Fuel Material	Requires Enrichment @ Equilibrium?	Fuel Cycle Option	Option Described: Transmuter [Startup]Driver; Blanket; Waste Matls.)
Critical	Thermal	UTh	Yes	Thermal Thorium Homogeneous Breeder	LWR once-through Thorium breeder, homogeneous, LEU
Group-ID OT-C-T-UTh-Y		**This group is included in EG05; the Analysis Example is an HTGR**			
Critical	Intermediate	U	Yes	Intermediate Spectrum LEU Burner	Reduced-moderation once-through water reactor (RMWR), LEU
				Intermediate Spectrum U Blanket Breeder	RMWR, once-through Uranium breeder, LEU
Group-ID OT-C-F-U-Y		**This group is included in EG02; the Analysis Example is an HTGR**			
Critical	Intermediate	UTh	Yes	Intermediate Spectrum Thorium Blanket Breeder	RMWR, once-through Thorium breeder, LEU
				Intermediate Spectrum Denatured Thorium Blanket Breeder	RMWR, once-through denatured Thorium breeder, LEU
Group-ID OT-C-F-UTh-Y		**This group is included in EG05; the Analysis Example is an HTGR**			
Sub-Critical	Thermal	U	Yes	EDS LEU Burner	ADS thermal spectrum once-through, LEU
				EDS LEU-U Breeder	ADS thermal spectrum, once-through Uranium breeder, LEU
Group-ID OT-S-T-U-Y		**This group is included in EG02; the Analysis Example is an HTGR**			

Table B96. Minor Benefit Limited Recycle Fuel Cycle Options from Pilot Study.

Reactivity	**Spectrum**	**Incoming Feed Fuel Material**	**Recycled Elements**	**Requires Enrichment @ Equilibrium?**	**Fuel Cycle Option**	**Option Described: Transmuter ([Startup]Driver; Blanket; Waste Matls.)**
Critical	Thermal	U	Pu	Yes	Thermal Single-Stage MOX Limited Recycle	LWR U/Pu-MOX limited recycle with MA and FP disposal
Group ID SL-C-T-U-Pu-Y			**This group is included in EG13; the Analysis Example is PWR → PWR**			
Critical	Fast & Thermal	U	Pu	Yes	Fast-Thermal 2-Stage Uranium Breeder/Burner	SFR Uranium breeder + LWR U/Pu-MOX limited recycle
Group ID ML-C-F/T-U-Pu-Y			**This group is included in EG15; the Analysis Example is PWR → SFR**			
Critical	Thermal	U	TRU	Yes	Thermal 2-Stage DUPIC UNF Burner	LWR LEU + HWR with DUPIC limited recycle
Group ID ML-C-T/T-U-TRU-Y			**This group is included in EG13; the Analysis Example is PWR → PWR**			
Critical	Thermal	U	TRU	Yes	Thermal 2-Stage TRU Burner	LWR LEU + HTGR U/TRU deep burn, limited recycle
Group ID ML-C-T/T-U-TRU-Y			**This group is included in EG13; the Analysis Example is PWR → PWR**			
Critical/ Subcritical	Thermal & Fast	U	TRU	Yes	Thermal/EDS 2-Stage TRU Burner	HTGR LEU + EDS fast spectrum TRU burner limited recycle
Group ID ML-C/S-T/F-U-TRU-Y			**This group is included in EG16; the Analysis Example is PWR → ADS**			

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B3. Forsberg, C., "Implications of Plutonium Isotopic Separation on Closed Fuel Cycles and Repository Design," Proceedings of Global 2013, Salt Lake City, Utah, September 29-October 3, 2013