Identification, Description, and Characterization of Existing and Alternative Nuclear Energy Systems

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May 9, 2011

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I. Introduction

Fundamentally, a nuclear energy system uses nuclear fission to create heat, which is then available for generating electricity or other applications, including seawater desalination, heating, and production of other fuels. The nuclear energy system as currently deployed in the United States, Figure 1, consists of a number of integrated components, beginning with the natural resources required for nuclear fuel, followed by fissioning of the fuel in reactors connected to electricity generation facilities, and ending with the disposition of all wastes, including used nuclear fuel (UNF). Natural uranium enriched in the fissile isotope ^{235}U fuels the light-water reactors (LWRs). Once the fuel has been fissioned to its design limit, the discharged fuel is stored awaiting final disposition. Power production with a nuclear reactor has virtually no routine emissions to the atmosphere, making it a desirable method of producing electricity. However, other components of the nuclear energy system may have environmental impacts, especially those related to obtaining uranium from the environment, preparing it for use as fuel, and radioactive waste disposal in the environment. Additional concerns with this fuel cycle include proliferation risk and security, safety, resource availability, and cost. In considering the potential future use of nuclear power, it is important to evaluate every component of the fuel cycle, and to consider all of these concerns and any associated impacts.

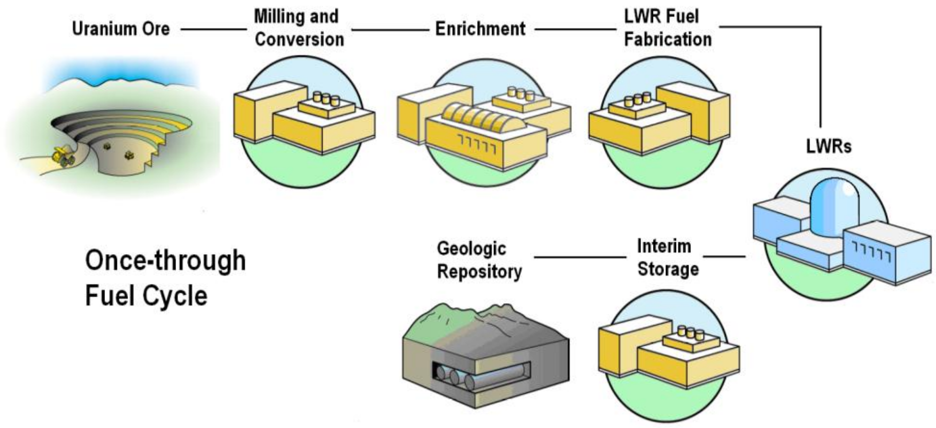

Figure 1. The Integrated Once-Through Fuel Cycle in the United States

Other components can be added to the once-through nuclear energy system, such as the possibility of processing UNF using separations or other treatment technologies, and the use of nuclear breeder reactors to increase the rate at which new nuclear fuel resources are created from either uranium or thorium. Such options have been researched extensively in the U.S. to study the potential for development into commercial systems, although there are concerns associated with these as well, including the total radioactive waste generation from processing activities and the potential for propagating the use of technologies that could be used for obtaining weapons-usable materials. Some of these options have already been implemented in other countries such as France and Japan for the extension of fuel resources leading to future fuel cycles. Appendix A contains a detailed discussion of fuel cycle components, from mining resources to disposal.

The issues of waste management, resource utilization, environmental impact, safety, proliferation risk, security, and economics may need to be addressed for future use of nuclear power. Since the relative importance of these identified concerns to the continued and future use of nuclear power is not known, there is uncertainty about the requirements that future nuclear energy systems will need to meet. However, even with this uncertainty, it is possible to identify the characteristics that a nuclear fuel cycle and the technologies would need to have so that these concerns can be addressed, and such studies have recently been conducted, e.g.[1,2]

II. Nuclear Energy Systems

The basic types of nuclear energy systems use either a “once-through” or “recycle” fuel cycle depending on whether or not there is any recycle of materials obtained from processing UNF. The choice affects the quantities and types of materials that need to be disposed of as radioactive waste, whether UNF, high level waste (HLW), or both, and the amounts and classes of other radioactive wastes. A “once-through” fuel cycle uses nuclear fuel only once, followed by storage and disposal. The UNF can be disposed directly, or processed to facilitate the fabrication of waste forms suitable for disposal, but no UNF content is recycled in new fuel. Alternatively, with “recycle” fuel cycles, the discharged fuel can be reprocessed using separations technologies and one or more of the recovered chemical elements used for recycle in new fuel. This report defines UNF processing and recycling possibilities as follows:

- Processing - any treatment of UNF that alters the intact fuel form
- Reprocessing – processing that uses separations technologies to separate the chemical elements in UNF, either individually or in groups, especially TRU elements from fission products and uranium, with the intention of recycling one or more elements
- Recycle - using one or more of the chemical elements separated in reprocessing UNF as part of new nuclear fuel for reuse in reactors

The addition of 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 UNF, depending on the specific recycle approach.

The example of a once-through fuel cycle shown schematically in Figure 2 [3] corresponds to the diagram in Figure 1, where nuclear fuel is used once, followed by disposal of all UNF. The recent U.S. DOE Nuclear Energy Research and Development Roadmap defines the "Once-Through" fuel cycle, as follows [4]:

> **"Once-Through** – Nuclear fuel makes a single pass through a reactor after which the used fuel is removed, stored for some period of time, and then directly disposed in a geologic repository for long-term isolation from the environment. The used fuel will not undergo any sort of treatment to alter the waste form prior to disposal in this approach, eliminating the need for separations technologies that may pose proliferation concerns. Less than one percent of the mined uranium is utilized in the present once-through fuel cycle."

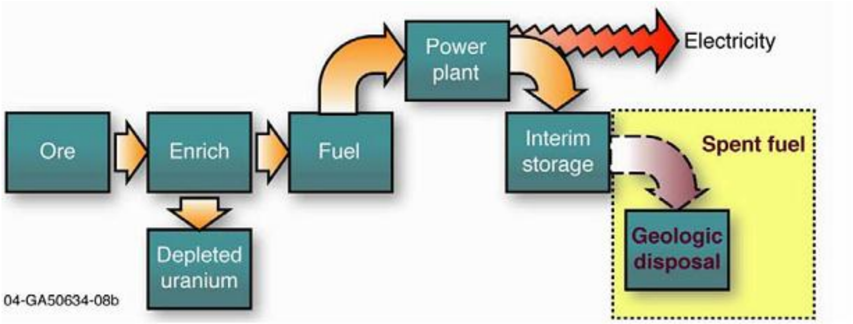

Figure 2. Schematic of a Once-Through Nuclear Fuel Cycle Example

Any fuel cycle that leaves the fuel pins intact is a Once-Through fuel cycle. There are also other once-through fuel cycle variations, such as only processing UNF to facilitate waste disposal without any recycle. The main feature of a Once-Through fuel cycle is that all UNF materials, either intact or after treatment without recycle, are disposed in a repository along with other radioactive wastes that are not suitable for the near-surface disposal used for low-level radioactive wastes.

The recycle fuel cycles logically divide into two major options, "limited recycle" and "continuous recycle," depending on whether all UNF is processed or not. The first option, limited recycle, includes fuel cycles that process UNF and recycle one or more of the recovered elements at least once, but not more than a limited number of times, i.e., limited recycle. An example of the limited recycle fuel cycle option is shown schematically in Figure 3, where it is assumed that the UNF is only processed once for recycle, and then the resulting UNF after recycle is disposed. The example in this figure also assumes that all of the actinides are separated from the reprocessed UNF and are recycled, with the fission products (and process loss amounts of actinides) are in the HLW going to geologic disposal. In general, after one, or a limited number of recycles, the UNF is not processed further, but is disposed.

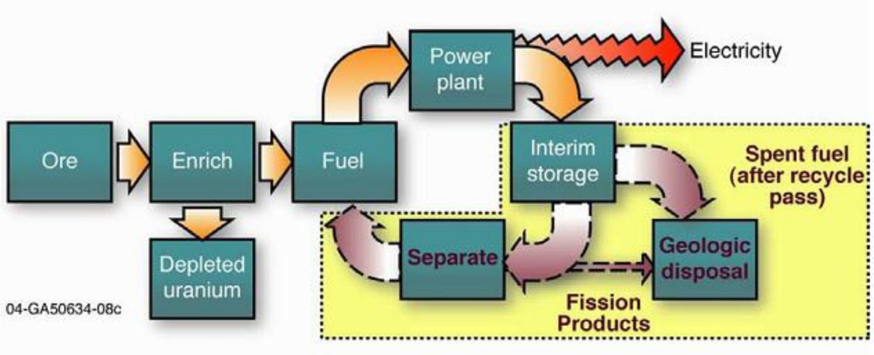

Figure 3. Schematic of a Limited Recycle Nuclear Fuel Cycle Example

The “Modified Open Cycle” fuel cycle defined in the U.S. DOE Nuclear Energy Research and Development Roadmap [4] is approximately equivalent to, or a subset of, limited recycle:

> **“Modified Open Cycle** – The goal of this approach is to develop fuel for use in reactors that can increase utilization of the fuel resource and reduce the quantity of actinides that would be disposed in used fuel. This strategy is “modified” in that some limited separations and fuel processing technologies are applied to the used LWR fuel to create fuels that enable the extraction of much more energy from the same mass of material and accomplish waste management goals.”

While a stated goal of the Modified Open Cycle is to enable extraction of much more energy, the amount of additional energy obtained will be a function of the number of recycles and the performance of fuel cycle components, especially the reactors. There are many variations of the limited recycle fuel cycle, depending on the elements separated and recovered for recycle, and how many recycles occur before the disposal of the resulting UNF. A main distinguishing feature of limited recycle fuel cycles (and the Modified Open Cycle) is that both UNF and HLW are disposed, in addition to low-level radioactive wastes.

The other recycle option is the continuous recycle fuel cycle, as shown in Figure 4, where this example shows all actinide elements being recycled and only fission products (and process loss amounts of actinides) are in the waste. For this option, all UNF is reprocessed after every recycle, so that no UNF is ever disposed.

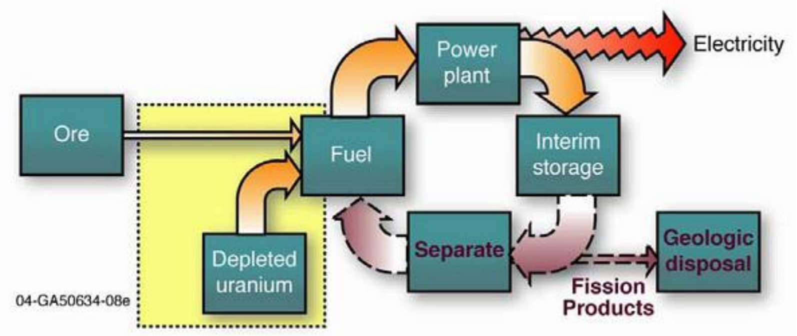

Figure 4. Schematic of a Continuous Recycle Fuel Cycle Example

The example of continuous recycle in Figure 4 also represents an example of the “Full Recycle” fuel cycle described in the U.S. DOE Nuclear Energy Research and Development Roadmap [4]:

> **“Full Recycle** – In a full recycle strategy, all of the actinides important for waste management are recycled in thermal- or fast-spectrum systems to reduce the radiotoxicity of the waste placed in a geologic repository while more fully utilizing uranium resources. In a full recycle system, only those elements that are considered to be waste (primarily the fission products) are intended for disposal, not used fuel. Implementing this system will require extensive use of separation technologies and the likely deployment of new reactors or other systems capable of transmuting actinides.”

The Full Recycle fuel cycle is approximately equivalent to, or a subset of, continuous recycle. Many other variations of continuous recycle are possible depending on the elements separated and recycled. A distinguishing feature of continuous recycle is that only HLW plus other radioactive wastes that are unacceptable for near-surface disposal are disposed in the repository, and unprocessed UNF is never disposed. Similar to the Once-Through and Modified Open Cycle fuel cycles, disposal of low-level radioactive wastes is required.

The following sections summarize the components of each fuel cycle group. Appendix A provides a detailed discussion for each of these components.

A. Once-Through Fuel Cycle

The components of the integrated Once-Through fuel cycle are as follows:

- Uranium Resources – surface mining, in-situ leaching, recovery from phosphate, …
- Milling – chemical leaching
- Conversion – purification and fluorination
- Enrichment – gas centrifuge, gaseous diffusion, …
- Fuel Fabrication – oxide fuel (oxidation and pellet fabrication), metallic fuel, …
- Power Production – thermal or fast neutron reactors, accelerator-driven systems, …
- UNF Storage – on-site storage, interim storage, …
- Disposal – UNF geologic disposal, LLW near-surface disposal, …

Some illustrative examples of Once-Through fuel cycles are:

- LWR with enriched uranium oxide fuel
- LWR with enriched uranium / thorium oxide fuel
- Heavy-water reactor (HWR) with natural uranium oxide fuel
- HWR with enriched uranium oxide fuel
- High temperature gas reactor (HTGR) with enriched uranium oxide fuel
- Sodium-cooled fast reactor with enriched uranium metallic fuel
- Molten salt thermal reactor with enriched uranium oxide fuel

Many more variations are possible for the Once-Through fuel cycle, given the range of reactor and fuel types that are available, but uranium is always required to provide the fissile material (^{235}U) in the fuel, and the uranium almost always needs to be enriched in ^{235}U. With today’s LWRs, uranium enrichment is about 4% ^{235}U to achieve a fuel burnup at discharge in excess of 50 GWd/MTIHM, but uranium fuel utilization is usually very low, about 1% or less. All fission products and other elements created during irradiation are disposed in the UNF.

The focus of recent proposed Once-Through fuel cycles is on increasing uranium utilization, such as by increasing the burnup of the fuel before discharge, although this also requires a higher initial uranium enrichment. However, analyses have shown that the amount of uranium required per unit of energy produced from the reactor is not very sensitive to discharge burnup. For example, increasing discharge fuel burnup of 50 GWd/MTIHM to 100 GWd/MTIHM may slightly increase annual natural uranium usage by about 4%, partly due to the higher ^{235}U enrichment of 8-9%, and partly due to the higher fission product concentration in the UNF causing a higher fissile content at discharge from the reactor. Another suggested approach to changing uranium utilization is to add thorium to the fuel (to create fissile ^{233}U from ^{232}Th), but this will also require higher uranium enrichment since thorium is only a fertile material and not a fissile fuel, and analyses show that thorium use in a Once-Through fuel cycle makes essentially no difference in annual natural uranium usage as compared to using enriched uranium only. Significantly increasing uranium utilization requires nuclear reactors with efficient internal conversion of fertile material to fissile material (creation of ^{239}Pu from ^{238}U), such as once-through fuel use in fast reactors, where uranium utilization of 10% or higher may be possible in principle. Since geologic disposal of all UNF terminates a Once-Through fuel cycle, there are typically only small differences in the content of the UNF in all cases, implying that waste management is likely to be similar for any Once-Through fuel cycle.

B. Modified Open Cycle Fuel Cycle

As discussed above, the category of Modified Open Cycle adds reprocessing or treatment to the Once-Through fuel cycle, but UNF is reprocessed and recycled only one or a few times before the resulting UNF is disposed. Some illustrative examples of Modified Open Cycle using LWRs are:

- UNF processing for reuse in an HWR (DUPIC) after once-through use in an LWR
- Reprocessing UNF with a limited number of recycles of plutonium in LWRs
- Reprocessing UNF with a limited number of recycles of ^{233}U in LWRs started with uranium / thorium fuel
- Reprocessing UNF with a limited number of recycles of TRU in LWRs

Many more variants are possible in the Modified Open Cycle category, including using other reactor types (as listed in the Appendix), using multiple reactor types, or recycle of other individual or groups of actinide elements in the recycle fuel. All Modified Open Cycle options exhibit the same characteristics of using limited recycle for any or all TRU with possible uranium re-enrichment. Since all options will continue to need enriched uranium as a fuel resource, all of the fuel cycle components described in IIA related to obtaining uranium fuel are retained: mining, milling, conversion, uranium enrichment, and fuel fabrication, although some of the parameters may change, such as the initial ^{235}U enrichment.

i. Processing of LWR UNF

One approach processes the used LWR fuel so that the product can be reconstituted into new fuel for another reactor to extend the burnup of the fuel, followed by geologic disposal of the UNF. The processing method is high temperature oxidation and reduction of the LWR UNF to change the solid UNF into a powder suitable for sintering into new solid oxide fuel. In this approach, no reprocessing technologies are used, and any separation of UNF materials is limited to the volatile or gaseous elements lost in processing, but there is no overall separation of fission products, TRU, and uranium. A specific example of this is the DUPIC fuel cycle, where used LWR fuel is reconstituted for further irradiation in an HWR.

ii. Reprocessing of LWR UNF

The addition of recycle to the nuclear fuel cycle creates opportunities to advantageously change the characteristics of the fuel cycle, although there are disadvantages as well. Limited recycle uses reprocessing technologies to separate and recover elements from the spent fuel for recycle, but this is only done once or a few times before the resulting UNF is disposed. As a result, one characteristic of limited recycle is that the HLW from UNF reprocessing and ultimately the UNF itself will require geologic disposal. The preparation and fabrication of the recycle fuel may also be quite different than fabrication of typical uranium fuel, and depending on the elements being recycled, may have to be performed in a remote environment, either with glove boxes to provide isolation from personnel, or hot cells with thick radiation shielding to reduce personnel exposure. As with other Modified Open Cycle fuel cycles, all of the limited recycle options would continue to need uranium fuel, and would include all of the activities listed under the Once-Through category, i.e., mining, milling, conversion, enrichment, and fuel fabrication.

The same reactor, or reactor type, can be used for irradiation of new uranium fuel and recycle fuel, as shown in Fig. 3. It is also possible to use more than one reactor type with Modified Open Cycle fuel cycles, such as having an LWR for the initial irradiation of uranium fuel, and another reactor type specifically intended for using the recycle fuel. Performance of limited recycle options in comparison to Once-Through options depends on the contents of the disposed UNF and HLW with respect to the amount of power generated. The disposed UNF contains fission products, TRU, and uranium. The HLW from reprocessing also contains fission products and may contain the bulk of one or more TRU elements, depending on how many of the TRU elements are recycled, along with losses from reprocessing and recycle fuel fabrication. Recycle activities are likely to produce increased amounts of LLW as compared to a Once-Through option.

All reactor types listed above appear to be suitable for use in Modified Open Cycle fuel cycles, leading to a large number of possible fuel cycle options, especially where more than one reactor type is included in the candidate fuel cycle. Both thermal and fast reactors can be included, as well as externally-driven systems. There are also numerous potential separations technologies, depending on the elements recovered for recycle, which adds still more possible options. Including different fuel types, the possibility of using thorium, and different disposal paths results in a list of specific fuel cycle options that is almost endless. However, limited recycle options all share the same basic characteristics as shown in Fig. 3:

- The need for uranium fuel (natural or enriched, depending on the reactor)
- Reprocessing of UNF once or a few times
- Disposal of both HLW from reprocessing and UNF

The UNF will contain fission products, TRU, and uranium. In particular, recycle may have the potential for maintaining or increasing the amount of fissile TRU such as ^{239}Pu with each recycle, depending on the internal conversion of fertile material in the reactor. Addition of thorium to the fuel enables creation of fissile ^{233}U as well, which can also be recycled as fuel. The UNF destined for disposal will likely contain useful amounts of such fissile materials, which can be viewed as being detrimental to the overall performance of the fuel cycle.

Fission products are created with each use of fuel in the reactor, in proportion to the energy generated by the fuel. Since most fission products are not effectively transmuted by neutron irradiation, the fission product inventory in the disposed UNF and HLW will be approximately proportional to the total energy produced, and will not be very different from the fission product inventory per unit energy production from a Once-Through fuel cycle. However, TRU elements can be effectively transmuted with neutron irradiation, and recycle of TRU can limit the inventory of TRU in the disposed UNF and HLW. Lower TRU inventory per unit of energy produced may be beneficial to waste management, depending on the characteristics of the disposal environment.

C. Full Recycle Fuel Cycle

The definition of full recycle specifies the continuous recycle of all actinide elements that are important to waste management; in this report it is assumed that all continuous recycle options are included in Full Recycle. Since uranium is typically not a dominant contributor to waste management issues for geologic disposal, full recycle normally considers continuous recycle options where all TRU elements are recycled, although uranium may be recycled for other reasons. All UNF is processed, with only HLW going to geologic disposal. The HLW contains the fission products and process loss amounts of uranium and TRU. As in the Modified Open Cycle, two general classes of Full Recycle can be identified, "burners" where insufficient fissile is created during irradiation, requiring continual addition of new uranium fuel to the fuel cycle, and the other where sufficient ("break-even") or excess ("breeders") fissile is created and the need for new uranium fuel can be greatly reduced. In each class, some or all of the TRU may be recycled. Some illustrative examples of full recycle options are as follows:

- TRU burner LWR
- LWR / TRU burner fast reactor
- TRU burner fast reactor
- Break-even fast reactor TRU recycle
- Breeder fast reactor TRU recycle
- Continuous recycle of plutonium in LWRs
- Continuous recycle of ^{233}U in LWRs with uranium / thorium fuel

i. Burner

The burner Full Recycle options are generally intended for consumption of higher actinide elements, and may be done with either thermal reactors or fast reactors, and for either uranium or uranium and thorium fuel. Burner fuel cycles are characterized by having an insufficient level of internal conversion (conversion ratio, CR, of less than 1.0) of fertile materials to fissile materials, or "breeding", so that fissile material from an external source needs to be added with every recycle. As a result, there will be a continuing need for uranium fuel and the activities that support it, including mining, milling, conversion and enrichment. Fabrication of new fuel may include the recycled TRU in all fuel, in which case all of the fuel fabrication must be done remotely in shielded hot cells. Alternatively, it is possible to handle the new uranium fuel and the recycle fuel separately. However, there are also examples where fuel fabrication may not be needed, such as in certain molten salt designs with continuous fuel reprocessing.

ii. Break-even and Breeder

For the break-even Full Recycle fuel cycle, sufficient fissile material is created by internal conversion of fertile material with every recycle so that once started, no new fissile needs to be provided from an external source, i.e., CR=1.0 including losses. This enables complete utilization of the uranium resource, including depleted uranium, greatly reducing the need for uranium to only that required to initially start new reactors once each reactor is up and running in equilibrium. Using uranium in thermal reactors such as LWRs, even though ^{238}U is converted to fissile ^{239}Pu, quantities are insufficient to replace the ^{235}U consumed, and $CR < 1.0$. However, it is possible that thorium is capable of creating sufficient ^{233}U to replace the ^{235}U in the initial startup fuel consumed during operation, or CR ≈ 1.0. Once started, the ^{233}U recovered from the reprocessed UNF becomes the fissile material that supports reactor operation and continues to create ^{233}U from ^{232}Th, i.e., the reactor becomes self-sustaining. Thermal reactors such as molten salt reactors may be well suited for this purpose in a Full Recycle fuel cycle. It also may be possible to achieve sufficient fissile creation using uranium in reactors with a less-thermalized neutron spectrum, such as modified LWRs, but the presence of TRU may hinder effective internal conversion. With fast neutrons, uranium can easily be used since there is greater creation of ^{239}Pu from ^{238}U. Fast reactors such as sodium-cooled fast reactors work well for this purpose. In addition, since the conversion of ^{238}U into ^{239}Pu in a fast reactor is much more efficient than in a thermal reactor, recycle TRU can be accommodated in the reactor while still meeting the fissile creation needs. In this manner, a waste management goal for uranium-based fuel cycles of eliminating TRU from the waste stream, except for process losses, may also be satisfied.

Since all UNF is reprocessed in a continuous recycle fuel cycle, the potential for extending fuel resources with continued breeding of fissile materials is raised, CR > 1.0, simultaneously reducing the need for uranium fuel. Breeding can be done with thermal reactors using a thorium/uranium fuel where ^{233}U is recycled, or more effectively with a fast reactor using uranium fuel where ^{239}Pu is recycled. Options that recycle all of the new fissile materials (certain actinide isotopes) are capable of achieving the maximum breeding potential in the nuclear fuel cycle and the maximum extension of uranium and thorium resources. However, any actinides that are not recycled go to the HLW from reprocessing and may have detrimental waste management impacts depending on the disposal environment. As a result, recycle of all TRU may be desirable. As with limited recycle, introducing reprocessing may create additional LLW, depending on the reprocessing technology. In principle, only some of the reactor types listed above in Section IIA may be suitable for such fuel cycles, and in some cases, complete utilization of uranium and /or thorium is possible. This would greatly reduce the impact of obtaining uranium, including mining, milling, conversion, and enrichment.

Once started, the “breeder” fuel cycle would also displace the need for enriched uranium fuel even for starting new reactors. Waste management goals of eliminating essentially all of the TRU from the waste stream except process losses can also be satisfied. While developing a breeder fuel cycle with thermal reactors operating on uranium/thorium fuel may be theoretically possible in the presence of recycled TRU, the more efficient conversion of uranium into plutonium in fast reactors makes fast reactors a much more suitable choice for the breeder fuel cycle.

With continuous recycle in the Full Recycle category, all UNF is reprocessed, with no UNF being disposed. The elimination of UNF disposal has the potential to greatly reduce the inventory of TRU and uranium destined for geologic disposal, although the importance of such reductions may depend on the isolation characteristics of the disposal environment. While fission product recycle is also possible, as mentioned above, fission products are not amenable to neutron transmutation in general, and this possibility is not normally included in fuel cycle options. The waste management benefit from continuous recycle depends on the waste stream contents, determined by the elements that are not being recycled and processing losses.

III. Performance and Comparison of Advanced Nuclear Fuel Cycles

Evaluations of nuclear energy systems consider the performance of the nuclear energy system with respect to a number of areas, based on the required system performance and concerns associated with implementation of the nuclear energy system. An example of these areas and the measures that can be used for performance comparison are as follows, in alphabetical order:[2]

• **Economics**: Cost analyses and projections of nuclear energy systems have always exhibited high uncertainty, even for mature designs that have already been deployed. Much of the uncertainty is due to factors independent of the nuclear energy system itself, including financing, delays due to regulatory uncertainty, and site-specific issues. For most nuclear fuel cycles, reactor costs dominate total system costs due to the relative expense of nuclear reactors compared to other components of the system, and also because some facilities can support large numbers of reactors. Uncertainty becomes even higher for less mature concepts, where development and demonstration costs are incurred. Important factors include:

1. Research and development costs, including development time, technical maturity and risk
2. First-of-a-kind reactor capital costs
3. Nth-of-a-kind reactor capital costs
4. Levelized cost of electricity
5. Other facility capital costs, including safety and licensing related costs
6. Other costs, including resources, storage, transportation, and disposal.
7. For alternative fuel cycles, similarity to existing infrastructure can affect costs

• **Proliferation risk and security**: The question of proliferation risk is partly highly subjective, with evaluation and resolution of this issue not lending itself to just technical issues, where intent and motivation can dominate the risk, e.g.[5,6] Technical measures for proliferation risk allow judgments to be made as to the relative increase or decrease in proliferation risk as a result of nuclear fuel cycle activities that may alter the amount and availability of SNM, or change the detection probability of attempts at acquiring SNM for weapons use. The measures were developed in recognition of more detailed proliferation risk assessment analysis methodologies and measures, such as in the Gen IV Proliferation Resistance – Physical Protection initiative, and capture the major technical contributors to proliferation risk. [7] They include:

1. Inventory of special nuclear materials (SNM), including in-process, UNF and HLW
2. Material attractiveness
3. Uranium enrichment requirements
4. Safeguardability
5. Inventory of all radioactive materials
6. Ability to provide physical security

• **Resource sustainability:** This is one of the original concerns for nuclear energy, dating back to the beginning of nuclear power in the 1940s. Metrics that address sustainability refer to the availability of natural resources, including fuel and disposal, as follows:

1. Natural resources required per unit of energy produced
2. Natural resources available for use as fuel or fertile material
3. Environmental impact of obtaining fuel resources
4. Natural resources required for disposal, per unit of energy produced
5. Natural resources available for disposal
6. Environmental impact of creating disposal resources

• **Safety**: Safety requirements are, or will be, defined by the NRC so that the operations of nuclear reactors, facilities using nuclear materials, and transportation of nuclear materials can all be conducted without posing an unacceptable risk to workers, public health and safety, and the environment. Satisfying the safety requirements requires the use of reactors, facilities, transportation and activities with sufficient safety features and operational procedures to minimize or eliminate the likelihood of catastrophic events that pose a significant risk to workers and the general public such that all parts of the nuclear fuel cycle are suitable for being licensed. While detailed safety requirements exist for certain nuclear technologies, such as LWRs, the NRC may not have regulations established at this time for other technologies such as advanced reactors, reprocessing facilities, and interim storage. It is expected that the safety goals will remain unchanged regardless of the facility, so that all facilities would need to meet the same safety goals. Important considerations include:

1. Level of difficulty in licensing the facilities and operations, including the potential for introducing new safety issues with alternative fuel cycle strategies and technologies. This measure would assume that each facility would need to achieve the same overall safety goals as stated by the NRC, which may be easier in some cases than others, but in principle is possible with all fuel cycles and technologies. As a result, achieving the safety goals becomes more a question of cost, not a discriminator of safety, and the potential impacts are reflected in the economics section.

• **Waste management**: All radioactive wastes need to properly disposed, including those requiring long-term isolation from the environment (high level waste and disposed used nuclear fuel) and low-level wastes. While the mass of hazardous radioactive materials can be calculated, estimating waste volumes is uncertain and requires assumptions about technologies and other issues, especially when extended to low-level wastes. Calculation of risk to the environment or to the public is also uncertain, due to the difficulty in characterizing the disposal environment and the inherent uncertainty about predicting future conditions or events. Measures for nuclear waste management that can provide insight into the ability to either provide the required isolation or to alter the waste characteristics to reduce the hazard are as follows:

1. Estimated peak dose rate – risk to the biosphere
2. Radiotoxicity of disposed materials – hazard of the disposed materials [8]
3. Mass of radionuclides in used nuclear fuel (UNF), HLW, and LLW
4. Interim (decay) storage
5. Decay heat load – engineering limitation on repository utilization [9]

Considering all of these areas and their associated issues, a comparative evaluation of a nuclear energy system needs to address how important each of these areas may be. This is not an entirely technical decision, and can evolve with time. However, it is possible to provide assessments for each of these areas individually. In this report, the issue of cost is separated from the technical issues and is discussed in the next chapter.

A. Illustrative Examples of Fuel Cycle Performance

Examples of specific Once-Through, Modified Open Cycle, and Full Recycle options are used to illustrate the performance changes that may occur with such alternative fuel cycles, as follows:[1]

Once-Through PWR: this option is similar to the current implementation of nuclear power in the U.S., consisting of the once-through use of enriched-uranium oxide (UOX) fuel in pressurized light-water-moderated reactors (PWRs), where the fuel is irradiated in the reactor until it reaches the desired burnup (typically about 5-6 years), storage of the discharged UNF for an extended period of time (typically 25 years or more to allow for cooling and radioactive decay), followed by disposal of the UNF in an engineered repository in a geologic environment.

Once-Through HTGR: once-through use of enriched-uranium oxide (UOX) fuel in high-temperature gas-cooled graphite-moderated reactors (HTGRs), where the fuel is irradiated in the reactor until it reaches the desired burnup, typically 3-4 years, then storage of the discharged UNF for an extended period of time (typically 25 years or more to allow for cooling and radioactive decay), followed by disposal of the UNF in an engineered repository in a geologic environment.

Once-Through SFR: once-through use of metallic uranium /zirconium fuel (UZr) in sodium-cooled fast reactors (SFRs) once equilibrium operation has been established. Enriched uranium (or other fissile material) is required for the initial startup, but then only natural or depleted uranium is needed. The conversion ratio (fissile created / fissile consumed during irradiation) is 1.26, making this reactor example a once-through fast breeder reactor. The fuel is irradiated in the reactor until it reaches the desired burnup, which in this case is about 50 years (beyond today's technical capabilities), followed by storage of the discharged UNF for an extended period of time (typically 25 years or more to allow for cooling and radioactive decay), and then disposal of the UNF in an engineered repository in a geologic environment.

Modified Open Cycle - PWR/PWR (U/Pu-MOX): use of enriched uranium oxide (UOX) fuel in PWRs followed by one recycle of plutonium as U/Pu-MOX. Fuel is irradiated until discharge burnup is reached (about 5-6 years) The UOX UNF is processed (typically by chemical means) to recover the uranium and plutonium, with the other transuranic (TRU) elements (neptunium, americium, and curium) and the fission products being in the processing waste, with separation of cesium and strontium for separate decay storage. The recovered plutonium and uranium are used for fabrication of part of the new PWR fuel as U/Pu-MOX. The processing waste is stored for an extended period of time (depending on the time of processing, with the total time from discharge to disposal typically 25 years or more to allow for cooling and radioactive decay), followed by disposal of the high-level processing waste (HLW) in an engineered repository in a geologic environment, with other classes of radioactive waste that were created as a result of processing and recycling also requiring appropriate disposal. The used U/Pu-MOX is also disposed in a geologic repository.

Full Recycle SFR: use of metallic uranium fuel (U/Zr) in a sodium-cooled fast reactor until discharge burnup is reached (about 6 years). The fast-neutron reactor conversion ratio of about 1.1, which means that slightly more fissile material is created than destroyed, allowing the reactor to be self-sustaining without the need for any additional fissile other than for the initial startup core, and allowing for processing and fuel fabrication losses. All fast reactor UNF also processed to recover the actinides, which are used as part of the contents of new fast reactor fuel, so that the TRU elements are indefinitely recycled in fast reactors, consuming TRU with each recycle. Processing waste contains fission products, hardware, and process-loss amounts of actinides, is stored for an extended period of time (depending on the time of processing, with the total time from discharge to disposal typically 25 years to allow for cooling and radioactive decay), and is followed by disposal of HLW in an engineered repository in a geologic environment and disposal of other classes of wastes as appropriate.

The performance estimates for each of these examples is listed in Table 1 using the assumptions specified in Ref. 7. For those alternatives that include reprocessing and recycling of the UNF, the total losses of U and TRU are assumed to be 0.1%, and include UNF processing losses, fuel fabrication losses, and losses from all other activities where such losses may occur. Achieving such low losses represents a significant technical challenge. To the extent the challenge is not met greater amounts of U and TRU will be sent to the repository.

As can be seen from Table 1, the performance estimates allow a comparison of each of the alternatives with respect to the current once-through use of enriched uranium in PWRs.

Common features:

- Uranium enrichment for the thermal reactor options, although some alternatives require higher LEU enrichment levels than are currently available commercially. The SFRs also require enriched uranium or equivalent fissile in the first startup core, but after that are self-sustaining on natural or depleted uranium.
- Fabrication of reactor fuel, although in some cases this may have to be done remotely, depending on the hazard presented by the fuel constituents.
- For the alternatives with UNF processing, HLW, LLW-GTCC, and LLW are created, with volume estimates covering a wide range in each case, with large uncertainty.
- Geologic disposal facilities are required in all cases for UNF, HLW, or both, depending on the alternative. This will also include other radioactive wastes, i.e., some GTCC, that may not be acceptable in the near-surface burial used for LLW.
- LLW disposal is also needed in all cases.

Once-Through HTGR as compared to the Once-Through PWR:

- New fuel fabrication technology for HTGR fuel needs to be implemented.
- Uranium resource requirement is essentially the same, although the required LEU enrichment level is higher than commercially available today, at 14%, due to the higher fuel burnup.
- The mass of UNF to be disposed is lower partly due to the higher fuel burnup, but the volume of UNF is higher by about a factor of 2.6 if the fuel compacts can be separated from the hexagonal prismatic blocks, or substantially higher by a factor of 15 if this process is not successful. TRU content is 57% of that for used LWR fuel.
- The thermal load for geologic disposal is lower by a factor of about 1.4.
- The radiotoxicity is lower by a factor of about 2-3.

Table 1. Performance Estimates of Illustrative Once-Through, Modified Open Cycle, and Full Recycle Examples

	Once-Through			**Modified Open Cycle**	**Full Recycle**
				Limited Thermal Recycle	Continuous Recycle
Case Description	PWR	HTGR	SFR at Equilibrium CR=1.26	PWR/PWR (U/Pu-MOX) 1 recycle	SFR with Recycle CR=1.1
Reactor Power Production (GWe-yr/yr)[a]					
LWR–UOX or HTGR–UOX	100 (LWR)	100 (HTGR)	0	90.2	0
LWR–U/Pu-MOX	0	0	0	9.8	0
Fast-Neutron Reactor	0	0	100	0	100
Other Facilities Required					
Enrichment Facility	Yes	Yes	No[b]	Yes	No[b]
Fuel Fabrication Facility	Yes	Yes	Yes	Yes	Yes
UNF Reprocessing Facility	No	No	No	Yes	Yes
Uranium (Natural and Low-Enriched Uranium [LEU]) or Thorium Resource Requirement (Annual)					
Natural U Feed (MT/yr)	19600	22800	324.0	17000	110
LEU (MT/yr)	2170	770	0	1980	0
LEU Enrichment	4.4	14.0	0	4.21	0
SNF/ HLW/TRU Production/Cs/Sr storage/Recovered U storage (Annual)					
Fuel Burn-up at Discharge (GWd/MTIHM)	51	100	277	50 (LWR) 50 (MOX)	66
Net TRU Production (MT/yr)	28	16	29	26	12.4
Amount of TRU to waste (MT/yr)	28	16	29	19	0.16
Mass of UNF to repository (MTIHM/yr)[c]	2170	770	290	215	0
Cs/Sr to decay storage (MT/yr)	0	0	0	10.8	10.0
Recovered U to Storage (MT/yr)	0	0	0	1660	0
Waste Management Metrics					
Volume of UNF to repository, m^3/yr	975	2600 – 14940[c]	450	100	0
Volume of Processing Wastes Classified as HLW to repository, LB; UB, (m^3/yr)[d]	0	0	0	25; 700	40-195; 1560
Volume of GTCC Waste from processing, LB; UB (m^3/yr)[d]	0	0	0	135; 5350	445-500; 12300
Volume of Low-Level Waste from processing; LB: UB (m^3/yr)[d]	0	0	0	13; 20800	210-840; 70600
Thermal Load Reduction Factor (relative to No Action)	1	1.4	1.5	1.1	200
Radiotoxicity Reduction – Time to Decay to Natural U Ore Radiotoxicity (Yr)	240,000	85,000	120,000	170,000	350

Table 1 (Cont'd). Performance Estimates of Illustrative Once-Through, Modified Open Cycle, and Full Recycle Examples

CF = Capacity Factor; ND= No Data Available, UNF = Used Nuclear Fuel

a 100 GWe-yr per year is the assumed power production. Since reactor capacity factors (i.e., the percentage of time that the reactor is producing power) are less than 100%, the installed capacity of the reactors must be greater than 100 GWe. Typical values of reactor capacity factors are 90% or higher for LWRs and other thermal reactors, and are about 80-85% for fast reactors.

b Enriched uranium or other fissile material is only needed for the initial startup fuel. Once equilibrium operation is established, sufficient new fissile is created in the reactor so that additional fissile is not needed on recycle.

c Mass listed is only for the remaining heavy metal and the fission products in the UNF; no hardware or cladding is included

d Lower values represent the "lower bound" (LB) estimates of waste by considering waste from the UNF only, with no consideration of wastes from operations, maintenance, etc. The LB estimate considers potential volume reductions associated with advanced waste forms, decay storage to reduce hazard, and potential reclassification of wastes so that classification and disposal requirements are based on hazard instead of origin, Upper values represent the "upper bound" (UB) and are estimated using projections based on existing technologies and operating experience, and all fission products including gases are considered to be HLW with no allowance for advanced waste management approaches like decay storage of wastes with shorter-lived hazards prior to disposal.

Once-Through Uranium Fuel in an SFR as compared to the Once-Through PWR:

- Uranium resource requirement is substantially lower at about 324 MT/yr, although LEU enrichment is needed for the initial startup fuel at levels higher than today's use.
- The mass and volume of UNF to be disposed is much less at 290 MTHM/yr, reflecting the higher burnup of the UNF.
- The thermal load for geologic disposal is estimated to be lower by a factor of about 1.5 due to the high TRU and fission product content.
- Radiotoxicity is generally moderately lower by about a factor of 1.5 to 2.

Modified Open Cycle - PWR/PWR (U/Pu-MOX) as compared to Once-Through PWR:

- Protected (glovebox) fabrication of the recycle fuel is likely to be required. Processing of the UNF needs to be implemented.
- Uranium resource requirement is about 15% lower due to the use of recycled plutonium, but enriched uranium at 4.2% enrichment is still needed.
- The U/Pu-MOX UNF is disposed, but the mass of the TRU elements in the UNF and HLW is reduced by about 30%. The total mass of UNF disposed is much lower, but disposal of HLW is required.
- The thermal load for geologic disposal is lower by a factor of 1.1.
- Although initially higher, the radiotoxicity of the combined UNF and HLW is slightly lower.

Full Recycle SFR (CR = 1.1) as compared to Once-Through PWR:

- Remote fabrication of fast reactor fuel is required. Processing of SFR UNF needs to be implemented.
- Uranium resource requirement is 2 orders of magnitude lower.
- There is no disposal of UNF, only wastes from processing all UNF. The volume of HLW is less than the volume of UNF, the amount determined by the details of processing, operation, and other factors. The TRU content disposed is about 0.3% of the amount in used PWR fuel.
- The thermal load for geologic disposal is lower by a factor of about 200.

- The radiotoxicity is substantially lower, by a factor of 100-1000 after several hundred years.

There are several general conclusions that can be drawn from these comparisons:

1. Alternate “once-through” strategies provide a small benefit to waste management, up to a factor of 2-3, due to the changes in UNF content and to the assumed higher fuel burnup.
2. Recycle strategies that include the disposal of spent fuel or a significant part of the TRU elements also provide small waste management benefits, up to a factor of 2-3.
3. For large waste management benefits, it is essential to continuously recycle all of the TRU elements to keep them out of the waste stream. Alternatives show the potential benefit of using fast reactors to recycle the TRU elements.
4. For all alternatives, geologic disposal capability is required.
5. For alternatives that require spent fuel processing, the amount of HLW, LLW-GTCC, and LLW can vary widely depending on processing and operational details, potential waste reduction technologies, and the potential for waste hazard reduction prior to disposal. All wastes will require a disposal path, whether for geologic disposal or near-surface burial.

B. Performance of Other Fuel Cycle Options

Table 1 does not include the major groups of fuel cycles that either have high internal conversion to create new fissile, whether for Once-Through or Full Recycle. The main impact of these fuel cycles is in the large reduction in uranium resource needs and the associated fuel cycle activities of mining, milling, conversion, and enrichment. An indication of the reduction in resource requirement can be obtained from the data on Figure 5, which shows uranium utilization as a function of the type of fuel cycle.[10] The Once-Through LWR and HTGR options typically have uranium utilization in the range of 0.4 – 1%. The Once-Through fast “breakeven” SFR shows the potential for greater utilization, as high as 20-30% (although the technology requirements are beyond today’s capabilities), while the Full Recycle SFR breakeven and breeder reactors can achieve essentially 100% utilization, depending on the process losses.

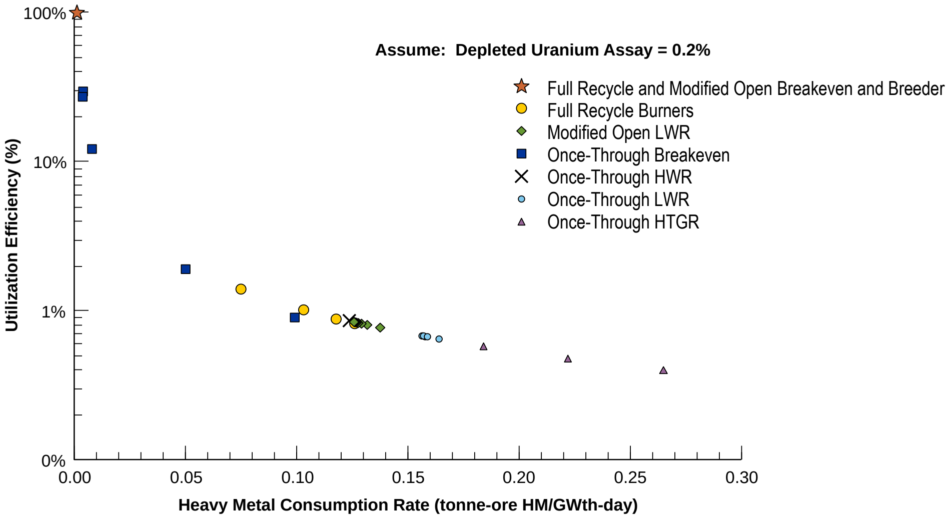

Figure 5. Uranium Utilization for a Range of Fuel Cycle Options

For any recycle fuel cycle, if reprocessing technologies are similar to those used for the examples in Table 1, one would expect the waste management performance to be about the same as for the corresponding cases, e.g., other Once-Through systems that do not have significant internal conversion of fertile material into fissile in both thermal and fast reactors would have performance similar to that for the LWR and HTGR cases shown. Other Modified Open Cycle fuel cycles that dispose of UNF would behave similarly to the PWR/PWR U/Pu-MOX case since all of the contents of UNF are disposed at some point in the fuel cycle. Similarly, other Full Recycle breakeven and breeder fast systems that recycle TRU would also have waste management results similar to the Full Recycle cases with fast reactors shown in Table 1. However, the Once-Through "breakeven" options may dispose of larger quantities of fissile ^{239}Pu in the UNF.

IV. Economics of Alternative Fuel Cycles [2]

The economics of nuclear power, and the fuel cycle in general, have been a primary issue that is raised as both a barrier for the re-establishment of growth in the nuclear enterprise or the adoption of an alternative nuclear fuel cycle, especially if the fuel cycle is more complex as would occur with the recycle option. Nuclear fuel cycle facilities, including reactors and processing plants, are capital-cost intensive with costs exceeding several billion dollars. These costs, in many cases, are comparable to the total market capitalization value of the private sector electric utilities that would have to finance and build these facilities, resulting in a single new investment representing an extreme investment risk, i.e., costing as much or more than the current value of the entire utility. Furthermore, a major factor related to economics is the large uncertainties in the costs of the nuclear facilities based on a lack of recent experience with the deployment nuclear reactors constructed in the U.S., a lack of demonstrated experience in meeting construction schedules, and the need to show that new licensing processes can reduce the regulatory uncertainty that has resulted in delays in the past. This is combined with the uncertainty in the revenue generation of the new nuclear plants, given the electricity market price impact of substantial new supply, the large variations in the cost of competing energy sources (primarily natural gas), strong government incentives supporting alternative energy sources (such as tax credits for wind and solar energy), and uncertainty about the time-frame for implementing carbon control measures that would increase the electricity production price from existing supply, such as cap-and-trade or carbon taxes. In recognition of these issues, the U.S. government is supporting near-term deployment of nuclear reactors and fuel cycle facilities through loan guarantee programs, with one loan guarantee in place for Georgia Power's Vogtle nuclear reactors (2 units, $8B loan guarantee [11]) and one fuel cycle facility (AREVA Eagle Rock enrichment facility with a $2B loan guarantee [12]). Competition between competing facility proposals is complicating efforts to move forward, where the limited funding available in loan guarantees is putting the U.S. Government in a position of having to choose among the proposals, rather than being able to support the market in general.

However, it is very important to note that while the costs of a large nuclear power plant are substantial, typically $4-5 B, the revenue created by the operation of the nuclear plants in producing electricity is also very large. The same 1 GWe LWR produces revenue from the sale of electricity of approximately $750M/yr (based on an average U.S. retail cost of electricity in 2010 of 9.67 cents/kWh [13]), or $45B over the expected 60 year lifetime of the reactor. Similarly, while the latest total life-cycle cost of the proposed Yucca Mountain repository (including transportation) was approaching $100B[14], the revenue generated from the production of electricity by the UNF that would be placed in the repository is greater than $5T (based on 70,000 MTHM UNF, 45 GWd/MTHM, 9.67 cents/kWh).

A. Uncertainties in the Cost of Nuclear Facilities

A key issue in assessing the economics of all nuclear power and fuel cycle concepts is the associated uncertainty in the capital cost of the nuclear facilities. Criteria for assessing costs of an alternative nuclear fuel cycle include:

- Similarity to existing infrastructure
- Capital at risk
- Technical maturity, technical risk, and development time
- Life-cycle costs

Arguably, the first five of these evaluation criteria are measures of economic risk, with life-cycle costs reflecting the actual financial cost. The combination of high capital cost and large uncertainties in schedule from events both internal and external to the design and construction project results in significant financial risk that would not be present if the technology had much lower cost.

An indication of the uncertainty in the cost of nuclear power can be provided by reviewing the available cost data for light water reactors (LWRs), which are by far the most widely deployed nuclear facilities and for which there are significant plans for deployment in the U.S. within the next decade. An evaluation of the costs of LWRs has been performed [15], as well as other studies cited in the Phase I Options Study report,[16] in which a review of the historical and projected costs is performed to provide a range of costs (low, nominal, and high). In the latest edition of the cost database, the total capital cost including financing (LWR, in terms of cost per unit electricity production for an “Nth of a kind” plant) is shown in Figure 6. In comparison to the nominal overnight cost, the low and high costs vary by a range of almost ±40%. Further information is provided in the report for specific plants in terms of an “all-in” (capital + financing). These reported costs show similar cost variations of approximately 40%. The variations in these all-in costs include both variations in the over-night capital cost and in the financing rate that can be obtained and therefore are sensitive to the time that it takes to construct the facility (an evaluation metric). This data shows that even for the most widely deployed nuclear technology, projected costs have a relatively wide degree of variation, which appears partly due to the type of reactor, and which may also be due to external factors such as financing conditions and allowances for contingencies.

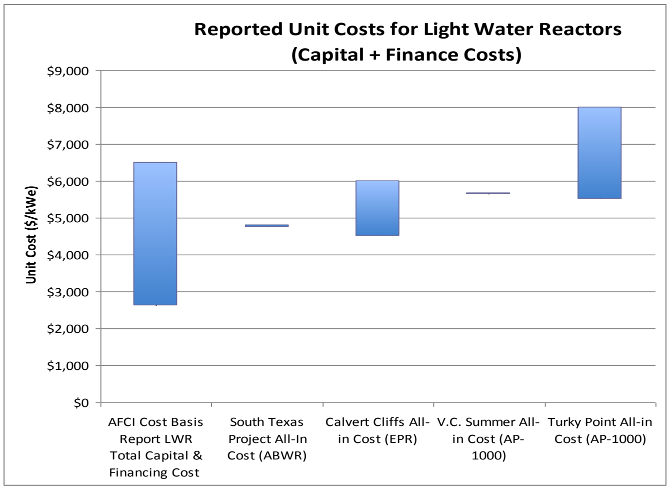

Figure 6. Examples of the reported cost ranges for light water reactors including recommended values from AFCI cost basis report and reported values for three near-term LWR reactors [15]

In the case of more advanced nuclear technology that has not been widely deployed, the expected variations are even larger. For example, the overnight capital cost range provided in AFCI cost data base for fast reactors is $3,000, $4,200 and $7,000/kWe for the low, nominal and high cost. In comparison to the LWR costs, the nominal cost of a fast reactor is 20% higher, but based on the cost ranges for both reactor types, since there is substantial overlap of the cost ranges between an LWR and a fast reactor, it is noted that in principle it may be possible for a fast reactor to have the same cost as an LWR, or even lower. This possibility would depend on whether the factors causing the cost uncertainty are independent between the LWR and the fast reactor, and if the factors causing a higher cost in the fast reactor can be reduced more effectively than those for an LWR.

B. Uncertainties in the Cost of Nuclear Fuel Cycles

In order to evaluate whether there are significant difference in costs for the various nuclear fuel cycles, the cost differential between the options must be significantly larger than the uncertainties in the costs. If the uncertainties are not considered, as Figure 6 illustrates, a comparison of the nominal costs for nuclear fuel cycles can lead to unsubstantiated conclusions. The above considerations of the uncertainties for the cost of nuclear facilities (as well as uncertainties in fuel and operation and maintenance costs) can be incorporated into the cost analysis of the total cost of nuclear fuel cycles that can provide a cost comparison of options that reflect these uncertainties.

As part of the AFCI program, an analysis of the costs of several fuel cycle options was completed. A Once-Through fuel cycle using an LWR, a Full Recycle system that only used fast reactors (called a “one tier” system in references), and a Full Recycle system that included LWRs in a single recycle mode with U/Pu-MOX, followed by the LWR U/Pu-MOX UNF being processed for recycle in fast reactors (a “two-tier” system) were evaluated. Costs of each fuel cycle were calculated including uncertainties due to variations in reactor capital costs, uranium prices, recycle facility costs, variation in waste form costs, and repository costs to obtain cost probability distributions.[17,18] Figure 7 shows these distributions for each of these three fuel cycles.

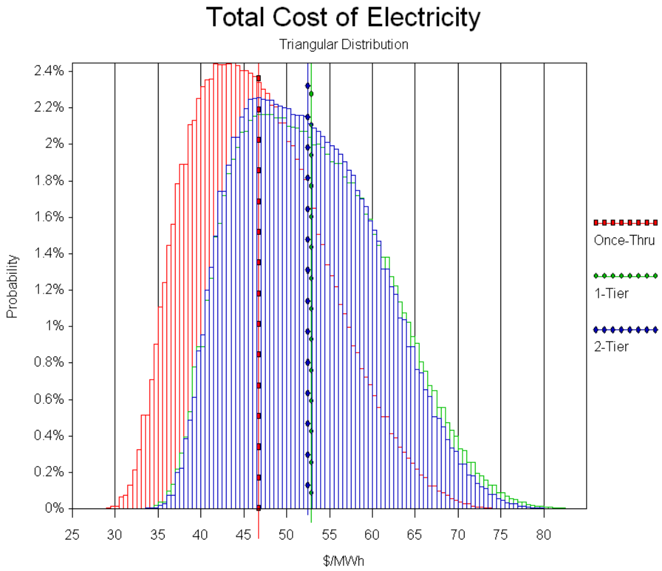

Figure 7. Cost distributions for a Once-Through LWR fuel cycle, a Full Recycle fuel cycle with a fast reactor (“1 Tier”), and a Full Recycle fuel cycle with combined once-through LWR and recycle fast reactor (“2 Tier”) [17,18]

Based on the mean values (indicated by the vertical lines in the figure) the once through fuel cycle cost is approximately 47 $/MWh, while the mean costs for the recycle cases are the same (the cost distributions fully overlap) with a value of 53 $/MWh. Therefore, the recycle cases have a mean cost that is approximately 6 $/MWh, or 10% more than the once-through case. This is generally expected given the increased cost of the fast reactors in comparison to LWRs, and that recycle involves a more complex nuclear fuel cycle with additional facilities. However, both of the distributions have a cost distribution range that is much larger than this difference and, in fact, overlap significantly. Therefore, in terms of the wide cost distributions, it is not clear that one can consider the 10% larger mean estimated cost for the recycle case a significant cost difference from the LWR once-through case.

C. Economics Implications for the Fuel Cycle

The costs of nuclear facilities are very large and can be prohibitive for private industry and utilities to finance given the magnitude of the costs in comparison to the size of the private companies and the risk premium on interest rates. However, this large cost is approximately balanced by a large revenue stream should the facilities be successfully deployed and operated. Therefore, given this balance of both large costs and revenues, the profitability of the nuclear enterprise lies in the uncertainties in the costs and profits. Based on the above discussion and demonstration of the significance of cost uncertainties, in general there are many factors that can impact the cost of deployment and operation of the fuel cycles such that in most cases the differences in costs of particular fuel cycles cannot be demonstrated to be significantly different. Figure 8 shows the cost breakdown for the various components of the fuel cycle for the examples in Figure 7.[18]

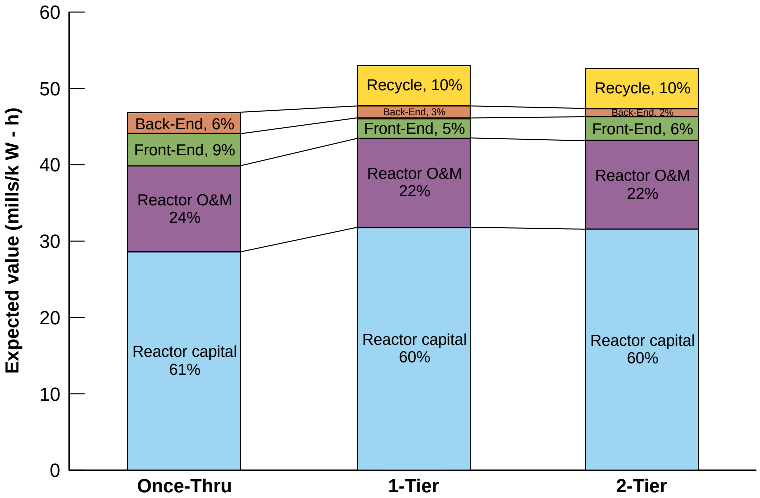

Figure 8. Fuel Cycle Cost Breakdown for Once-Through, and 1-tier and 2-tier Recycle Systems

Figure 8 shows that total costs for recycle systems are impacted partly by the increase in capital expenditures for reactors and the addition of fuel reprocessing, with smaller offsets from reductions in fuel (front-end) and disposal (back-end) requirements. The front-end and back-end values are based on the total amounts needed, or to be disposed with different HLW loading factors, with a cost range based on a unit amount. As Figure 7 indicates, the uncertainties in these costs can dwarf the differences in expected value. Further, estimated reduction in costs for some of the proposed advanced fuel cycles appears to be even more uncertain given their relatively low technical development and demonstration. As a result, it does not appear that one can make definitive statements about a significant cost difference, either more or less expensive, compared to the once-through LWR fuel cycle. However, this observation would imply that one may be able to consider alternative nuclear fuel cycles in which Nth-of-a- kind facilities would not incur a significant cost penalty, although within any fuel cycle option, there are certainly technology options that are expected to be significantly more costly due to obvious complexity or other features.

D. Economics - Observations

As discussed above there are large costs associated with nuclear facilities with associated large uncertainties. The nominal costs for advanced recycle systems are shown to be slightly more expensive than those of a once through fuel cycle, but the difference is within the large uncertainties and are highly dependent upon non-technical considerations such as financing costs and construction duration. In many cases, the financing cost depends upon who is paying for the nuclear facility and taking the financial risk (e.g. government financed versus private financing). Therefore, there is substantial overlap in the costs of the fuel cycle facilities such that a well executed advanced recycle system could have a lower cost than a poorly executed once-through system. For these reasons, it was not possible to unambiguously determine that one fuel cycle option would have significantly different costs than another fuel cycle option in terms of real world costs.

With that said, there are a number of areas in which research and development can reduce the cost uncertainties as well as reduce the overall costs of all fuel cycle options. Small changes in these large costs imply significant financial impacts as the profitability of a nuclear enterprise is based on the balance of the large costs and the large revenues. Cost and uncertainty reductions of the nuclear fuel cycle can provide a significant incentive to support deployment of nuclear energy. While it is unlikely that there will be sufficient resources to reduce the cost uncertainties of all of the fuel cycle options to a level that can be used to differentiate options based on economics alone, there are a number of common features that can be applied across the options that can result in lower costs. These include:

- Reduction of the complexity of the nuclear facilities being utilized. System complexity results in unanticipated costs during construction and operation, increases materials costs, and increases regulatory and licensing costs. All selected fuel cycle systems have potential for reduction in complexity based on optimization of design and operations through R&D to reduce or remove non-essential functions and components.
- Increasing the operational efficiency of the nuclear facilities in terms of products per unit cost. For a reactor system, this means that systems with higher thermal efficiency can provide more electricity generation for nearly the same capital and operating costs. For fuel fabrication and processing facilities this primarily can be achieved through increasing the number of operational days per year.
- The initial capital and financing costs and associated uncertainties can be reduced with nuclear facilities that have short construction durations without delays or schedule extensions. This is one primary reason for interest in Small Modular Reactors (SMR) that use advanced manufacturing approaches including factory fabrication. Another reason is the flexibility of building capacity additions in smaller increments, and therefore smaller capital commitments. Nearly all of the fuel cycle concepts involve reactor systems that could be constructed as SMRs.

V. Analysis of Potential Future Nuclear Fuel Cycles

To assess a complete fuel nuclear energy system (NES), multiple tools are required. The reactor analysis codes generate information on energy generation, fuel requirements, and fuel behavior, including the isotopic content of discharged fuel. This information is used by the system analysis code along with other data such as waste generation to create a simulation of the nuclear fuel cycle. This section summarizes and compares the capabilities of several tools used to assess the NES. These include:

- **CAFCA-SD** (Code for Advanced Fuel Cycle Assessment – System Dynamics) - developed at MIT.
- **COSI -** developed by the French Atomic Energy Commission (CEA)
- **DANESS** (Dynamic Analysis of Nuclear Energy System Strategies) - developed at ANL
- **DESAE** (Dynamic of Energy System – Atomic Energy) - developed for the IAEA
- **VISION** (Verifiable Fuel Cylce Simulation) - developed by a group of DOE laboratories led by INL to support the Fuel Cycle R&D program
- **NUWASTE** (Nuclear Waste Assessment System for Technical Evaluation) - developed for the Nuclear Waste Technology Review Board (NWTRB).

A. Purpose of NES Analyses

Before discussing the characteristics of NES analysis codes, it is important to understand what these codes are used for and what level of accuracy should be expected. NES codes are typically used to understand the behavior of NES systems, especially systems incorporating new technologies, with respect to standard performance indicators. In particular, dynamic simulation models are used to examine systems in transition, such as occurs when a fuel cycle strategy changes to include recycling. Analysis scenarios include assumptions on changes in total energy generation with time, as well as when new technologies become available or when strategy changes are to be initiated. Simulation timeframes are typically 100 years or more.

Analyses provide information on sufficiency of materials for startup of new reactors, capacities and timing of fuel cycle facilities needed to support the growth and/or transition of the NES, and characteristics and quantities of materials throughout the system. The material characteristics and quantities are used to understand changes in material attractiveness (for proliferation risk and security comparisons) and waste parameters (waste loading, decay heat, source terms, etc.).

Appropriate uses of NES analysis results include identifying changes in behavior (inflection points on time plots of parameters) and understanding their drivers and their consequences. The exact timing of when such a change occurs and the magnitude of the change are usually driven by scenario assumptions. Novice users of NES codes often err in assuming higher accuracy of results than is warranted. The result that a code may indicate a total installed base of 53 fast reactors in 2087 can be an unimportant artifact of assumptions, but the trend reported by the code that the commissioning rate of fast reactors is much slower than predicted by static calculations may be an important finding reflecting the impact of system inertia on the relative percentages of different reactor types. When such a trend is identified, sensitivity analyses of input parameters help to better understand the phenomenon.

All modeling is a compromise between accuracy and functionality. Depending on the types of analyses to be performed, more accurate modeling of the real world may result in revealing additional behavior modifiers or may just add random variations to the simulation results that inhibits identification of trend changes. An example is the explicit modeling of individual fuel reloading batches versus just modeling the average annual fuel flow. If the analyses to be performed include detailed assessment of recovered material stocks during a period of transition to recycling, then the timing of reloads may be critical, but if the intent is to understand the impact of recycling on repository loading the average fuel flows provide a cleaner inflection point.

B. Prior Comparisons

All but one of the codes discussed here have been part of one or more formal benchmarking efforts (a benchmarking effort is scheduled to begin shortly with the NUWASTE code). The benchmarking efforts include two efforts using very similar benchmarks conducted by NEA/OECD [19] and IAEA/INPRO and a separate effort led by MIT [20]. In addition, several of the codes have been used in an IAEA/INPRO collaborative effort where participants have analyzed a common set of scenarios and discussed capabilities of the codes.

The results of these efforts indicated that nearly identical results can be obtained from the different codes for very simple scenarios, but only if considerable effort is expended to ensure common interpretation of all assumptions and data. In addition, many of the automated features of the more advanced codes had to be turned off to allow a valid comparison, reducing capabilities to the subset common to all of the codes. This subset includes the primary functions and mass flows, but excludes many of the indicators for waste, economics, and material attractiveness. When the codes were allowed to use their full functionality on more complex scenarios, most provided results that were very similar in general values and trends but were not identical. Differences were primarily due to different approaches in modeling the scenarios, rather than intrinsic differences in the codes.

The other observation from these efforts was that each code had extensions in different areas to provide additional analysis capabilities based on the interests of the developers. These areas of emphasis are noted later when each code is discussed individually.

C. General Characteristics of NES Codes

All of the NES codes are fundamentally mass flow models of nuclear material as it moves from mining, through reactors, and to disposal. Most of the codes model the isotopic content of the material throughout most or all of this flow, although CAFCA-SD dropped this capability when CAFCA was moved from MATLAB to VENSIM to expand systems dynamics modeling capabilities. All are dynamic simulation codes that support modeling of a system in transition from one fuel cycle strategy to another. All of the codes support a scenario-based analysis, where factors such as overall nuclear electricity generation are an input. Each reports on a number of parameters output from the simulations, including total electricity generation, number of reactors, mass of uranium, separative work units for enrichment, mass of fresh and UNF and other inventories and flows.

While all of the NES discussed here have this common theme, each was developed for a different customer and therefore emphasizes different characteristics of the NES. The coding approach also varies in ways that are usually unimportant for general studies but are critical to generation of specific details.

The most significant difference is how information from reactor codes is obtained and used by the system code. Most system codes employ look-up tables containing previously calculated output from reactor codes. These tables contain “recipes” for specific types of fuel that include general burnup, residency and mass information and specific isotopic content of fresh and discharged materials. This approach is computationally efficient and is employed by all of the codes that target simulation run times of a few minutes or less. One drawback of this approach is if the isotopic content of feed material doesn’t match the “fresh” fuel content in one of the recipes, then the discharge content provided by the recipe will be wrong. Some codes use interpolation algorithms to reduce this error, but ultimately it is up to the analyst to determine whether additional recipes are needed. A limited number of nuclear system codes include the option to directly employ detailed reactor codes to perform calculations as needed of fresh material enrichment and discharge material composition based on the isotopic content of the feedstock. This approach is more accurate but requires much faster computers and/or much longer run times and the analyst must confirm that the automated calculations result in fuels that are consistent with reactor safety parameters.

The other primary difference in NES codes is the degree of automation within the code. The simplest codes require manual input of all parameters for each year of the simulation and require the analyst to verify that the results do not violate any physical laws (such a generating negative masses). The more developed codes generally include goal-following capabilities that will automatically commission or retire reactors and fuel cycle facilities as needed to follow a total energy production specification. They will also include physical constraint testing that will prevent operation of reactors in any year that fuel isn’t available, or even prevent ordering of reactors if the fuel supply is not certain.

All of the codes include some type of user interface, including the ability to save input parameters for different scenarios and population of multiple output graphs plotting the simulation results or comparing multiple simulations (used primarily for sensitivity studies). The most common interface is to use Excel spreadsheets. A general trend is the more developed the code, the more complex the inputs and outputs and the more difficult it is to learn.

Specific code descriptions

CAFCA-SD – CAFCA is representative of a number of NES analysis tools developed at universities. The SD version simulates the complete fuel cycle for a range of current and future reactors and fuel cycle facilities using a systems dynamics platform (VENSIM). The code automatically deploys reactors and reprocessing facilities over time based on a user-supplied energy demand curve. The focus is on the fuel cycle back end and the impact of UNF stocks and reprocessing facility capacities on the mix of reactors using mined versus recycled feedstock. The SD version tracks material flows at the elemental level, which limits calculation of metrics requiring isotopic information (decay, material attractiveness, radiotoxicity, decay heat) and also limits the accuracy of modeling of the reactor transmutation behavior. It is intended for educational purposes and provides rapid analyses for comparisons of the general mass flow behavior of different NES systems.

COSI – COSI is a well-developed code used by CEA for a range of analyses. COSI has the ability to link directly to a reactor code (CESAR) to calculate the fuel value of feedstock and isotopic content changes due to irradiation with greater accuracy than the other system codes, which all use some form of a recipe file. However, this greatly impacts run-time performance and has resulted in an option that provides much faster run times by instead performing a ^{239}Pu equivalence calculation to determine fuel value. As a full-featured code, COSI tracks numerous isotopes and generates information on material flows, multiple waste parameters for high and intermediate level waste, and capital and operating costs of facilities. COSI's emphasis area is the composition of materials moving through the reactor and the impact on burn-up and core management.

DANESS – DANESS is another full-featured code that features a mass-flow "physics layer" that includes logic for forecasting the availability of fissile materials and using that information to constrain reactor deployment, a nuclear energy systems layer that can model up to 10 different reactor types in parallel, an assessment layer that generates indicators for sustainability, waste and economics, and a "policy" layer where the user can dictate allowable levels of inventories and capacities that constrain the automated logic of the simulation. Reactor irradiation is modeled via look-up recipes. The code tracks up to 70 isotopes to support calculation of fuel values and metric indicators. DANESS models the front-end fuel cycle services to much more detail than the other codes to support an emphasis on assessment of fuel cycle costs. The user interface is Excel-based.

DESAE – Based on limited author experience, DESAE is not as full-featured as most of the other codes discussed here, and does not contain as many automated features. It supports analysis of the complete fuel cycle with isotopic tracking focusing on the actinides. The emphasis is on modeling transition to closed fuel cycle systems and the user can specify flow logic to model the interaction of up to 5 types of reactors utilizing up to 3 different reprocessing systems. Performance indicators are limited because fission products are treated as a group and isotopic decay is not modeled. Some of the shortcomings of DESAE are made up through the use of another IAEA code, NFCSS (VISTA), which estimates nuclear fuel cycle service and material requirements.

VISION – VISION is a full-featured code used by the DOE-NE fuel cycle R&D program. It is similar to DANESS, in that it has a number of automated goal-seeking capabilities, UNF recipes, models up to 10 reactor types (and up to 10 reprocessing technologies), and employs an Excel-based interface. The code is used to assess a wide range of NES and provides sufficient flexibility to model any type of reactor/transmuter in a multi-tier system. The emphasis is on modeling of transition behavior while providing treatment of overall system performance. VISION generates a number of metrics for material attractiveness and waste decay heat and radiotoxicity and tracks over 80 isotopes/groups for this purpose. It has an extensive recipe library that is user extendable to support new reactor/fuel types.

NUWASTE – The code is more specialized that the others discussed here. The emphasis is on waste, and the model contains considerably more detail on modeling of waste sources, different classifications of waste, and packaged volumes. Where most of the other codes only consider the waste generated by reprocessing, NUWASTE includes wastes generated by enrichment and fabrication, and explicitly models multiple options for uranium recovered from reprocessing. The code explicitly models HLW, LLW, mixed LLW, GTCC waste and mixed GTCC waste. NUWASTE is designed to assess mature NES only, and is only based on reactor types currently deployed in the U.S., so is of limited utility to assess alternate NES based on fast reactors, non-oxide fuel forms, non-aqueous separations technologies, or other novel approaches.

D. Future Nuclear Power Scenarios

Scenarios of future nuclear power include three primary dimensions. The first dimension is the geographic range of the scenario – with a single country (U.S.), a single continent (Europe) or the complete world being the most frequent values. Most scenarios only consider one area and model the area homogeneously, while some scenarios involve separate regions or nuclear technology groups and include assessment of their interactions.

The second dimension is the level of future power generation. Typical options for this dimension include nuclear close-out scenarios where existing plants are retired at end of life or earlier, constant energy generation, constant percent of total energy market, and a range of higher growth cases constrained by resource availability, a maximum practical market share, investment requirements, or other parameters. A subset of this dimension is the analyses that examine nuclear market share based on market economics, including incentives or taxes on different energy sources (e.g. renewables, coal) to reflect legislation or a particular goal such as limiting greenhouse gas emissions. Market economics is not implemented in current generation codes, and instead requires input from market simulators such as the tools used by the DOE Energy Information Administration.

The first two dimensions provide the context for a nuclear power scenario. The third future nuclear power scenario dimension is the technology dimension, which addresses performance of the nuclear power system within the scenario context. The technology dimension includes the fuel cycle strategy (once-through, etc.) and also includes transitions from one strategy to another. This aspect of scenarios is typically driven by the reactor technologies involved, the number of "tiers" in the fuel cycle (where fuel outputs from one reactor type are processed to provide inputs to another reactor type in the next tier), and the timing for transitioning to the new fuel cycle strategy. Fuel types, separation technologies, breeding/conversion ratios, and homogeneous vs. heterogeneous cores provide additional variation.

Using the analysis tools described in the previous section, it is possible to explore many aspects of possible future nuclear energy system deployment and their characteristics. The following examples (generated by the VISION code) illustrate the insights that can be gained from such analyses of the same 2-tier recycle system described in Section IV.B., regarding the fraction of fast reactors in a fuel cycle based on growth rate.[17] When considering nuclear fuel cycles that include more than one type of reactor as in the 2-tier system, the number of such reactors can be affected by the overall growth rate of electricity, but not necessarily in proportion to the growth rate, as shown in Figure 9. Growth rate also affects the relative percentage of electricity generated by the different types of reactors.

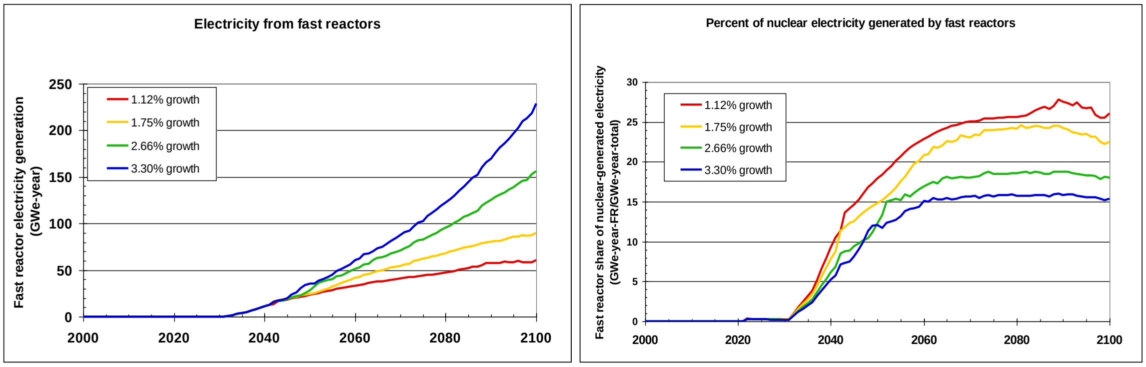

Figure 9. Electricity generation from fast reactors as a function of growth rate [17]

The dynamic analyses show that as the growth rate increases the absolute level of fast reactors also increases, but the relative amount (percent of the fleet) decreases. This is primarily because the impacts of time delays increase with increasing growth rate (e.g. more LWRs are added to meet demand while the used LWR fuel is cooling prior to processing to provide fuel for the fast reactors). It should be noted that legacy UNF inventories also have an impact, but it is only significant at very low growth rates. For growth rates that maintain or increase market share, the legacy fuel inventory is a small percentage of total UNF. This finding has implications on system economics depending on the cost of fast reactors. If fast reactors have a higher cost than LWRs, as is currently projected, at low growth rates, this difference in reactor cost will have a greater impact on the overall cost of the electricity from nuclear energy since the percentage of electricity from fast reactors is highest, but as the growth rate increases, the cost difference decreases.

The conversion ratio of the fast reactor, which reflects the ability of the fast reactor to create new fissile materials, can also have a large influence on the number of fast reactors, as shown in Figure 10. The conversion ratio has a large impact on fast reactor performance for two reasons. First, in the initial core, conversion ratio has virtually no impact on the TRU content of the fuel. However, at each refueling interval, there is a very large difference. With a breakeven fast reactor (conversion ratio of 1,0), no additional TRU would be needed from the reprocessed used LWR fuel, whereas for a conversion ratio of 0.0, roughly 1 MT of makeup TRU would be required per GWe-year of generation. Second, since as the conversion ratio is increased from 0.0 to 1.0, less TRU is needed at refueling from the reprocessed used LWR fuel, so that more fast reactors can be supported by the TRU provided by a given number of LWRs. The result is that at a constant growth rate, a greater percentage of the reactors can be fast reactors, which means fewer LWRs, and less TRU generated overall, i.e., by generating electricity using recycle fuels in the fast reactors instead of UOX in LWRs. Figure 10 shows the impact of conversion ratio on both the total electricity output from fast reactors and the percent output. At higher conversion ratio, both the absolute and relative level of fast reactor generation increases.

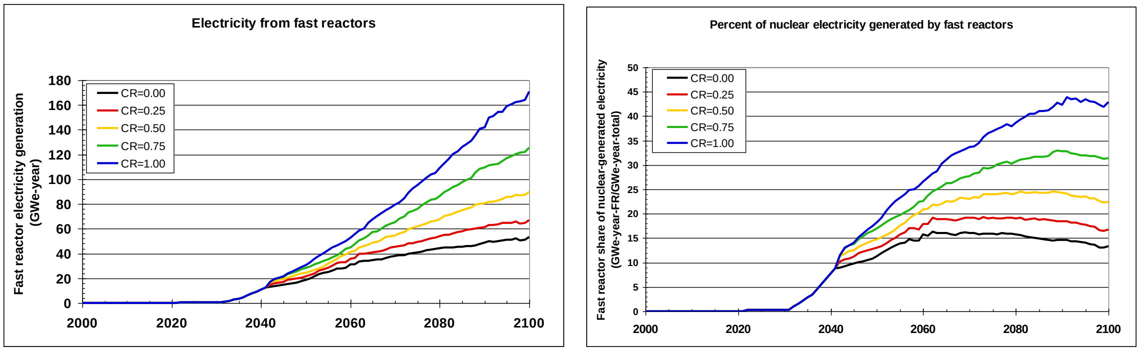

Figure 10. Electricity generation from fast reactors as a function of conversion ratio [17]

As can be seen in these examples, dynamic analyses of electricity growth and the nuclear energy system can depend on many of the detailed characteristics of the system. Most future nuclear power scenarios are used to determine how well performance objectives are met while achieving the desired level of nuclear energy generation. Because current fuel cycles fission less than 1% of the mined uranium, fuel resource utilization improvement is a common theme. Fast spectrum systems perform best on this metric since uranium or thorium utilization can only be substantially affected by breeding of new fissile material, resulting in many scenarios that transition to fast breeder reactors. Reducing long-lived highly radioactive wastes is another common theme, where recycling of plutonium and other transuranic elements is frequently proposed. Achieving waste management objectives may require use of additional fuel types to support higher burnup, and targets and additional transmutation technologies such as molten salt reactors and accelerator driven systems for minor actinide management.

VI. Advantages and Disadvantages of Alternative Nuclear Fuel Cycles

Once-Through, Modified Open Cycle, and Full Recycle categories have been described, with a review of some of the technology options, and estimates of performance and costs. For each of the major performance areas, characteristics were discussed that could be used to advantage, and detrimental aspects were mentioned. However, for some areas, it does not appear to be possible to make distinctions between fuel cycles and as a result, the alternative fuel cycles would have little or no impact in these areas, i.e., they would neither improve or degrade performance. For example, when considering the safety of a nuclear fuel cycle, there can be differences in components of the fuel cycle that could have safety implications, such as new facility types or transportation needs. The question then becomes one of whether or not all parts of the fuel cycle could be licensed, and if the risk of operating such a fuel cycle is acceptable. Overall, there did not seem to be any discrimination in the level of safety that resulted from the choice of the fuel cycle option since all fuel cycle facilities including reactors are strictly licensed and regulated for safety and must meet essentially the same safety goals such as dose limits to the public. However, it was also noted that some technologies had additional safety-related risks that would require more design features for prevention and mitigation measures, where achieving the required level of safety may have negative economic impacts.

In this regard, economics has proven to be a difficult area to reliably assess, mainly due to the high uncertainty and unreliability of cost estimates, as shown in Figure 7. It should also be noted that other social and political aspects can affect fuel cycle decisions, and higher costs may be necessary to meet fuel cycle performance objectives. For these reasons, at this time it is not believed to be credible to use economics as a reliable discriminator between fuel cycles, but only as being qualitatively informative of approximate changes in costs.

The performance for three performance areas that do seem useful in discriminating among fuel cycles, waste management, proliferation risk, and sustainability, is summarized in Table 2 as compared to the current once-through fuel cycle using enriched uranium in LWRs.[16] For waste management, it is seen that only the Full Recycle category can have a significant reduction in the disposed TRU inventory in the HLW and the resulting radiotoxicity due to continuous recycle of all transuranic (TRU) elements, but it should be stressed that this reduction in radiotoxicity may or may not have an impact on estimated peak dose rate since that depends on the geologic disposal environment.[2] Interim storage always appears to have some waste management benefit on decay heat and short-term radiotoxicity. However, all fuel cycles that involve processing, including those with reprocessing, may have the potential to significantly increase the amount of LLW while they reduce the mass of hazardous isotopes in the HLW. Full recycle is also able to lower the decay heat in the disposed wastes, a characteristic that is important to repository design and operation, although it may not have an impact on the isolation performance. The environmental impact of the nuclear fuel cycle arises from front-end and back-end activities, as well as potentially from intermediate steps such as fuel fabrication and UNF processing.

For proliferation risk and security, alternative nuclear fuel cycles and technologies may have differences in some of the technical aspects related to the materials and products. Some fuel cycles may assist in reducing some aspects of the risks from proliferation and terrorism by using technologies that allow effective and efficient implementation of nuclear safeguards and by enabling security at nuclear fuel cycle facilities. This can include reducing the attractiveness of readily-available materials, and by using fuel cycles and technologies that would not contribute to knowledge transfers of sensitive technologies. Overall, from a technical viewpoint, it also appears that there is no difference between using either a thorium/uranium fuel cycle or a uranium/plutonium fuel cycle since both deal with attractive SNM.

However, proliferation risk is not just a technical issue, but involves political and social aspects that are not affected by technical differences, and these may dominate the overall risk, making some of the technical differences between fuel cycles less important. For example, it is difficult to evaluate the relative risk of uranium enrichment as compared to UNF processing in a country, even if SNM is separated. It appears that safeguards can be effectively implemented in all cases, but the risk of proliferation may be determined more by the intent of the nation involved, regardless of the technical issues. In addition, assumptions made about the countries capabilities may also eliminate the differences between fuel cycles, such as the case where clandestine facilities are constructed instead of trying to divert from or misuse commercial facilities.

Table 2. Potential Performance Impact of Alternative Fuel Cycles as Compared to a Once-Through Fuel Cycle using Enriched Uranium in LWRs

Fuel Cycle Category	**Alternative Once-Through**	**Modified Open Cycle**	**Full Recycle**
Nuclear Waste Management			
Estimated Peak Dose Rate from a Geologic Repository	No significant change due to fission product and TRU content of disposed UNF	No significant change due to fission product and TRU content of disposed UNF or HLW	Possibly lower with actinide (TRU) recycle depending on the geologic repository environment
Radiotoxicity of Disposed Materials	No significant change due to TRU content of disposed UNF	No significant change due to TRU content of disposed UNF	Significantly lower with sustained actinide (TRU) recycle and HLW disposal
UNF & HLW Mass for Disposal (Volume proportional to mass as determined by waste form loading)	Similar UNF content for all once-through cycles; less UNF with higher burnup	Somewhat less combined UNF & HLW content due to recycle	No UNF; TRU mass in HLW is significantly lower due to TRU recycle (Volume determined by waste form loading)
LLW Mass for Disposal (Volume proportional to mass, as determined by waste form loading)	No significant change in LLW	Likely to be more LLW due to processing	Likely to be more LLW due to processing
Effect of Interim Storage (as compared to reference case): specific effects compared to not using interim storage	No significant change: Lower near-term radiotoxicity and heat load for UNF	No significant change: Lower near-term radiotoxicity and heat load for UNF and HLW	No significant change: Lower near-term radiotoxicity and heat load for UNF and HLW
Repository Heat Load	No significant change due to UNF disposal	No significant change due to UNF disposal	Significantly lower with sustained TRU recycle, Cs/Sr management, and HLW disposal
Proliferation Risk			
SNM Inventory (^{239}Pu, ^{233}U, ^{235}U)	No significant change	Higher fuel cycle inventory, lower-to-higher SNM inventory in disposed UNF and waste	Higher fuel cycle inventory, significantly lower SNM in disposed wastes with sustained SNM recycle
Material Attractiveness (^{239}Pu, ^{233}U, ^{235}U)	No significant change	Technology and fuel cycle dependent	Technology dependent; may be lower or higher
Uranium Enrichment Needs (^{235}U initial enrichment)	Technology dependent; may be lower or higher	Technology and fuel cycle dependent; may be lower or higher based on recycled elements	Technology dependent; may be lower or higher; may be lower or higher based on recycled elements
Safeguardability (ability to effectively and efficiently implement safeguards)	No significant change	No significant change	No significant change
Sustainability			
Fuel Resources	Possibly significantly lower with breeding (thermal or fast)	Possibly significantly lower with breeding (thermal or fast)	Significantly lower with actinide recycle and breeding
Waste Production and Disposal Needs	No significant change	No significant change	Significantly less disposal space required with actinide recycle and breeding

Possibly significantly: Fuel cycle and technology choices are available that could provide significant (order of magnitude or greater) changes, but may be uncertain at this time

Significantly: Fuel cycle and technology choices are available that will provide significant(order of magnitude or greater) change

For sustainability, the natural resource requirement for fuel can only be addressed with high internal conversion in the reactor to create new fissile materials, whether ^{233}U or ^{239}Pu. For fuel type, either uranium-based or thorium-based, it is only in the case of continuous recycle where these two fuel types exhibit different characteristics, and it is important to emphasize that this difference only exists for a fissile breeder strategy. The comparison between the thorium/^{233}U and uranium/^{239}Pu option shows that the thorium option would have lower, but probably not significantly lower, TRU inventory and disposal requirements, but a higher ^{233}U inventory, with the result that both have essentially equivalent proliferation risks. For these reasons, the choice between uranium-based fuel and thorium-based fuels is seen basically as one of preference, with no fundamental difference in addressing the nuclear power issues. Since no infrastructure currently exists in the U.S. for thorium-based fuels, and processing of thorium-based fuels is at a lower level of technical maturity when compared to processing of uranium-based fuels, costs and RD&D requirements for using thorium are anticipated to be higher. The availability and utilization of thorium-based fuels along with the uranium fuel technology in the U.S. would however make available more nuclear fuel resources for future nuclear expansion.

For reactor or irradiation options, thermal and fast reactors could both be used in a once-through strategy with comparable resource needs and UNF characteristics. The same is likely to be true for any limited recycle strategy, since UNF disposal is part of the integrated system. In both cases, incremental improvements such as higher UNF burnup can be used to reduce the volume of UNF requiring geologic disposal, but with little impact on disposal issues or the merits of alternative nuclear energy system. In principle, the selected reactor systems can be mature technologies or a more innovative approach with higher technical risk, but which usually implies a higher cost. For example, while LWRs have been marketed and built for decades, the less-well-developed fast reactors are widely considered to be more expensive and have seen little commercial use.

However, with continuous recycle, fast neutron irradiation is seen to be preferable to using thermal reactors due to the more favorable transmutation environment, i.e., more surplus neutrons, less disturbance to the system due to the introduction of additional TRU, and more favorable safety characteristics. Either fast neutron reactors or externally-driven sub-critical systems could be used, but due to the increased size, complexity and cost of the latter, any deployment would likely be limited to specialized applications such as minor actinide (part of TRU) transmutation. Fast reactors are capable of continuous TRU recycle for transmutation, and although sodium-cooled fast reactor technology development has been ongoing for decades, it is not without technical risk and only a few experimental facilities have been operated to date. Other fast reactor options are at a lower level of development with significant technical issues remaining and have higher development risk.

Processing is usually only associated with recycle, both Modified Open Cycle and Full Recycle, although it could also be considered for once-through use if the benefit of having a better waste form instead of UNF was high enough to offset all of the added costs. Applicable processing options in any given fuel cycle strategy will be determined by the separations and recovery goals, the types and characteristics of the fuel being processed, relative proliferation risk, and economics. At this time, aqueous-based methods are more technically mature with low technical risk, although some of the alternatives such as electro-chemical processing are continuing to mature with ongoing technical development. A related issue is the possibility for on-site processing as compared to centralized processing with the capability to greatly reduce the impacts of storage and transportation.

For sustainability with respect to disposal resources, it is essential to recognize that waste disposal remains a common element for all nuclear fuel cycle strategies, being required for the disposal of highly radioactive materials, whether from fission products alone or including long-lived TRU. All UNF and HLW disposal options face the same issue of demonstrating the required isolation for these materials. There are also non-technical issues such as political and public acceptance that are likely to dominate the decision-making process for siting and licensing such facilities. Continuous recycle appears to be the only practical fuel cycle strategy that may significantly affect waste management issues for UNF and HLW, but only if there are only fission products and residual amounts of TRU in the HLW. It should also be recognized that interim storage can be effectively used with all categories of fuel cycles.

In summary, only certain fuel cycle and technology options have clearly identifiable advantages that are greater than the uncertainties with respect to the once-through fuel cycle as used today in the U.S. Ref. 8 summarized the candidate fuel cycle options with significant advantages as shown in Table 3. It is clear that alternative nuclear fuel cycles can contribute to "developing sustainable nuclear fuel cycles" by increasing the utilization of fuel resources, which reduces the environmental impact related to obtaining the fuel resource and increases self-sufficiency of the fuel resources. Results show that while this is possible to some extent with a few once-through fuel cycle options using systems with high internal conversion to create fissile material or with externally-driven irradiation systems, recycle options can develop this potential to a much greater extent, and for a wider range of technology options. This observation is consistent with the past focus on continuous recycle in fast reactors as the eventual sustainable nuclear energy system.

From an economics point of view, review of previous studies and estimates resulted in the observation that the overall economics for an alternative fuel cycle did not appear to result in a change that was clearly larger than the uncertainties, i.e., even though there were differences in the estimated mean cost for various fuel cycle options, these differences were well within the overlapping uncertainty distributions for each of the estimates. As a result, it was observed that alternative fuel cycles can be considered without necessarily incurring significantly different overall costs. However, the same is not true for the technologies, where the complexity of the technology may be a significant contributor to the costs, as are the added costs from the new supporting infrastructure.

It should be noted that for three issues it was not possible to clearly identify fuel cycle options that could provide a significant benefit for a variety of reasons: proliferation risk and security (high level of subjectivity), safety (regulation requires all systems to be safe), and economics (uncertainties are larger than the differences). This is not necessarily a negative result since the lack of distinction between fuel cycle options on these issues may be contrary to prevailing perceptions, and may lead to consideration of a wider range of alternative fuel cycles.

Some of the nuclear fuel cycle options and technologies are more well-developed, having been the subject of research for several decades in some cases, since the issues with nuclear power are decades old, with changing emphasis on each issue over time. Other possibilities are quite immature, and would require substantial investment in time and funding (and in some cases a number of revolutionary technical developments) to bring them to a level of maturity sufficient to evaluate their suitability for further development and potential implementation. Consequently, the R&D effort and associated costs and duration cover a wide range of possibilities. Since the goals for each issue associated with nuclear power can be accomplished with numerous specific technology solutions for a given fuel cycle option in many cases, it would appear that the selected technologies from the set of specific technology options may be more a matter of preference rather than one of fundamental technical difference. However, within a given fuel cycle option, technology choices for each part of the fuel cycle may not be independent of one another, such as the implications of the intended environment for deep geologic disposal on the recycle requirements. Once decisions have been made as to the issues that are to be addressed with the fuel cycle option, the time required for development and commercial deployment may also cover a wide range, where more mature technologies can be implemented more quickly, perhaps within a decade or two, while immature technologies accomplishing the same goals would require more time, at least a few decades. As a result, the required R&D covers a wide range. Technology solutions that are barely at the stage of proof-of-principle would require substantial R&D and perhaps even fundamental breakthroughs, while those that are at the pilot-scale demonstration phase would need less R&D, although interestingly not necessarily less funding since demonstration facilities can be expensive.

Table 3. Summary of Fuel Cycle Requirements and Candidate Fuel Cycles

Nuclear Power Issue	Requirements for Providing Significant Benefits	Suitable Nuclear Fuel Cycle Options
Nuclear Waste Management	- Reduce content of actinides and their decay products in UNF and wastes requiring geologic disposal: • Complete consumption of fuel, i.e., essentially no UNF actinide content • Actinide recycle - Reduce decay heat of UNF and wastes to enable disposal in some geologic environments. - Limit LLW generation.	- Recycle options with actinide recycle and no UNF disposal (Full Recycle). - Externally-driven once-through with complete fuel consumption.
Proliferation Risk and Security	- Improved and better integrated fuel cycles and technologies that enable effective and efficient safeguards implementation • Use of existing safeguards technologies and best practices • Materials with lower attractiveness - Fuel cycles that allow effective security implementation	All fuel cycles which: - Enable effective and efficient safeguards. - Have lower material attractiveness for SNM in UNF and products Not a discriminator among alternative fuel cycles
Safety	- Use technologies with no irresolvable safety vulnerabilities.	All fuel cycles Not a discriminator among alternative fuel cycles
Sustainability	- Increase internal conversion of fertile materials to fissile materials, i.e. “breeding” to improve fuel utilization and reduce environmental impact. - Increase utilization of geologic repository space by reducing decay heat of UNF and wastes	- Once-through and recycle fuel cycles with more efficient breeding than LWRs. - Recycle fuel cycles with actinide recycle and no UNF disposal (Full Recycle).
Economics	- Avoid complexity. - Avoid systems with larger waste generation, extreme technical requirements or inherent safety or security vulnerabilities requiring additional design features, or requiring rare resources.	- All fuel cycle options but less complex technologies may have fewer issues with costs. - Improved reliability of components and operations

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Appendix – Nuclear Fuel Cycle and Fuel Cycle Component Description

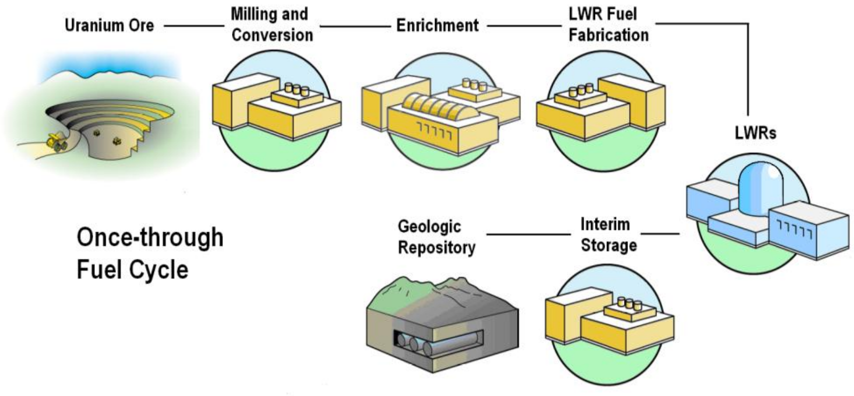

Figure A1. The Integrated Fuel Cycle in the United States

The following discussion briefly describes each component of the existing nuclear energy system in the U.S., also called the once-through nuclear fuel cycle, and its characteristics.

Uranium Fuel Resources – Mining, Milling, and Conversion

The only naturally-occurring fissile material is the uranium isotope ^{235}U. Natural uranium contains about 0.7% ^{235}U, with the remainder being almost entirely ^{238}U. Uranium has been produced from surface mines, underground mines, with in-situ leaching, or from phosphates as a byproduct of fertilizer production. Annual uranium requirement in the U.S. at the current electricity production rate is about 2000 MT of enriched uranium per year, which is produced from almost 18,000 MT of natural uranium, with the majority coming from foreign resources. Considerations for the continuing and future use of this nuclear energy system should include the availability of natural uranium resources and the environmental impacts of recovering those resources. Uranium resource estimates generally indicate that reserves should be sufficient for at least the remainder of this century with today’s usage rate, although it should be recognized that the ongoing availability of uranium for fuel is affected mainly by mining and production capacity, not the amount of resources.[A1] Significant expansion of nuclear power would be expected to reduce the longevity of uranium reserves. Environmental impacts from uranium production activities vary and can depend on the recovery method being used, the uranium content of the uranium ore (ore grade), and the processing technologies, including milling and conversion to UF_6 for enrichment, since radioactive and chemical wastes are generated. These and other factors, including land disturbance and the potential for contamination of water supplies, may affect the ability to develop and use the uranium resources.

The technologies for each part of the front-end of the fuel cycle are as follows:

- **Mining and other methods**
    1. Surface mining
    2. Underground mining
    3. In-situ leaching
    4. Recovery from phosphate
    5. Future possibilities include recovering uranium from seawater and the addition of thorium to the uranium fuel

Uranium exists as uranium oxide, U_3O_8, in nature, in ores of varying quality, e.g., up to 0.5% uranium in Australia and up to 25% in Canada.[A2] Mining technologies that have been used include surface mining and underground mining, where the uranium ore is physically removed from the ground and sent to the milling plant for uranium recovery. Where the uranium ore deposit is sufficiently porous, in-situ leaching (ISL) can be used. ISL (e.g., depending on the ore deposit geologic environment, using either alkali leaching agents such as sodium bicarbonate, ammonium carbonate, or dissolved carbon dioxide, for deposits in geologies such as limestone, or acidic leaching agents such as sulfuric acid, etc., for deposits in other geologies) does not physically remove the uranium ore from the ground, but the leaching liquid is pumped through the ore deposit in place to leach the uranium from the ore. Today, sodium bicarbonate is used in U.S. ISL mining operations and produces 90% of the uranium in the U.S. In some cases, leaching has been used on lower grade uranium ore after the ore has been removed from the ground. Recovery of uranium from phosphates has been done in the past as part of production of fertilizers, detergents, etc., since phosphate rock contains small amounts of uranium in the phosphoric acid, but the cost of obtaining uranium in this manner has prompted termination of these activities in the U.S., at least at this time. If thorium is added to the uranium fuel, the thorium can be obtained as a byproduct of other resource recovery activities since thorium is widely used today for industrial purposes.

- **Milling**
    1. Chemical leaching

- **Conversion**
    1. Solvent extraction and fluorination
    2. Fluorination and fluoride fractional distillation

Milling typically uses either strongly acidic or strongly alkaline leaching agents on uranium ore such as sulfuric acid or ammonium carbonate. The leaching agents are used on the uranium ore after the ore has been crushed to facilitate uranium extraction. Uranium mill tailings (wastes including the ore host rock and impurities) are radioactive, containing radioactive elements that were in the ore deposit with the uranium, which occur naturally due to uranium decay and include thorium, radium, and the remainder of the uranium decay products. Uranium mill tailings are stored as liquids in tailing ponds for evaporation and then the remaining solids are made into large tailings piles. Conversion of the uranium from U_3O_8 to UF_6 is required for the uranium enrichment processes. Two conversion processes are typically used, one a "wet process" that is a combination of solvent extraction (using an approach that is similar to parts of PUREX separations processing, or using tertiary amines) for purification followed by fluorination, and the other a "dry process" that is a combination of fluorination and fractional distillation (similar to fluoride volatility separations processes), although variants of these may used depending on the method used to mine the uranium.[A2,A3]

Uranium Enrichment and Fuel Fabrication

Pressurized water reactors (PWRs) and boiling water reactors (BWRs) are the two reactor types used in the U.S. Both of these reactor types require the ^{235}U content higher than 0.7% to operate, requiring uranium enrichment, typically to about 4-5% ^{235}U. There are two main technologies being used to enrich gaseous UF_6, gaseous diffusion and gas centrifuges. In considering the future use of nuclear power, the main concern with uranium enrichment is that the same technologies have the potential for producing highly-enriched uranium (HEU), where the ^{235}U content is 20% or higher, which is deemed suitable for use in weapons. Uranium enrichment and fabrication produce low-level radioactive wastes containing uranium and its decay products, as does subsequent processing of the enriched UF_6 to produce the enriched UO_2 used for fuel fabrication. The CO_2 emissions from the power plants needed to run the enrichment plants have been raised as an issue, but the use of energy-efficient centrifuge technology mitigates these concerns, and providing power to the enrichment plants from nuclear power or other similar non-emitting sources of electricity should eliminate the CO_2 concern. Another issue is the fate of the uranium that has been depleted in ^{235}U, called depleted uranium (DU), the enrichment plant tailings. Almost 700,000 MT of depleted UF_6 (about 500,000 MT of DU) is in storage in the U.S., which is a hazardous chemical because of its fluorine content. Facilities to convert the depleted UF_6 to the less hazardous uranium oxides for disposal have been build and a contract to begin operations has just been awarded.[A4]

- **Enrichment**
  1. Gaseous diffusion
  2. High-speed centrifuges
  3. Laser-based isotope separation

- **Fuel Fabrication**
  1. Calcination (heating), sintering, and manual assembly of oxide fuels
  2. Future possibilities include fabrication of other fuel types such as metallic fuel, particle fuels (e.g., TRISO), nitride fuel, etc.
  3. Thorium addition to the uranium-based fuel cycle

As described above, natural uranium with 0.7% ^{235}U needs to be enriched to a higher concentration of ^{235}U for use in LWRs and almost all other thermal neutron reactors, in the range of 4-5% ^{235}U for typical discharge fuel burnup. For systems with fast reactors, the uranium enrichment is higher, but still less than the 20% so that it is low-enriched uranium (LEU). Two technologies in use are gaseous diffusion and high speed centrifuges, both of which use UF_6 in a gaseous form, where the high speed centrifuge method is much less energy intensive. Other enrichment technologies are also being commercialized, including the Silex laser-based process that uses UF_6. Other laser-based methods are being studied, again using UF6, and a plasma-based method (plasma separation process) was investigated that used elemental uranium. Following the enrichment process, the UF_6 is converted to UO_2 for fabrication into fuel. For example, in LWRs and HWRs, the ceramic UO_2 is sintered into solid pellets that are loaded into zirconium-alloy tube cladding to make the fuel rods. A cladding is used to separate the fuel from the coolant and to retain all radioactive materials inside the cladding boundary. Due to the relatively low radiation of enriched uranium, the fuel fabrication process is done hands-on without the need for shielding. Hundreds {about 50-60 (BWR) and 200-250 (PWR)} of fuel rods are typically used to make a fuel assembly.

Thorium Addition to Uranium Fuel

Thorium has been considered as a supplement to uranium-based fuel based on considerations of resource utilization (thorium is approximately three times more plentiful than uranium), and more recently as a result of concerns about proliferation and waste management (e.g., reduced production of plutonium and higher actinides, improved physical and nuclear properties for reactor and potential waste management applications). However, it is crucial to understand that since there are no naturally-occurring thorium isotopes that can support fission under reactor conditions, 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 reactors. Thorium is not a replacement for uranium or other fissile fuel. Consequently, a fissile isotope such as ^{233}U, ^{235}U, or ^{239}Pu must be present in sufficient quantities for the reactor to operate. Thorium can be used in the once-through system, but there is far greater potential with recycle options, as there is with uranium as well. The thorium-uranium system allows breeding of ^{233}U (breeding ratio greater than unity) in both types of systems, although the ability to breed effectively in a thermal spectrum generally would require specially designed systems that are different from current commercial LWRs. In considering a thorium-based system, it is essential to recognize the need for fissile material such as ^{233}U, enriched uranium or plutonium to operate the reactor. Given that ^{233}U is also a weapons-usable material, with attractiveness similar to ^{239}Pu obtained from LWR UNF, thorium can be mixed with sufficient uranium in the fuel so that any ^{233}U is isotopically diluted with ^{238}U.

Nuclear Reactors and Other Power Production Facilities

Taken together, PWRs and BWRs are called light-water reactors (LWRs). The LWRs are thermal reactors since normal (light) water is used as to slow fission neutrons so as to allow these reactors to operated on uranium enriched to several percent or less in ^{235}U. The LWRs used in the U.S. have a high reliability, with the average capacity factor (ratio of actual power produced over a time period to the nominal power generating capability over the same time period) for all 104 reactors being in excess of 90%. Capacity factor on average must be less than 100% due to the need to periodically refuel the reactor (about every 18 months) and to perform maintenance activities. Lower electricity demand can also reduce the need for production at less than maximum capacity. Nuclear fuel discharged from the reactor, traditionally known as “spent” fuel but currently labeled as “used” fuel by the U.S. DOE, with a typical burnup of 50 GWd/MTIHM, contains about 5% fission products, 0.8% ^{235}U, 1.2% Pu, other actinide isotopes including minor actinides (Am, Cm, etc.), and over 92% ^{238}U. The ^{235}U and ^{239}Pu in the UNF are fissile isotopes that could be recycled into new fuel, but this would require reprocessing (and re-enrichment in the case of ^{235}U) of the UNF and is not currently done in the U.S.

- **Reactors**
  1. LWRs (PWRs and BWRs)
  2. HWRs
  3. Gas-cooled reactors
  4. Examples of other possibilities
     - supercritical water-cooled reactors (thermal reactor)
     - reduced moderator light water reactors (between thermal and fast reactor)
     - fast reactors with high internal conversion (once-through fast breeder)
     - molten salt reactors with either fixed or flowing fuel (thermal or fast)
     - neutronically-subcritical systems that are driven by external neutron source such as accelerators (thermal or fast)

Thermal Reactors

The thermal reactors used today are LWRs in the U.S., and other reactor types internationally such as heavy-water reactors (HWRs) and gas-cooled reactors, which are all thermal neutron reactors connected to systems for generating electricity, mainly using the heat generated in the reactor to generate steam to power steam turbines with electrical generators. Most of these reactors use enriched uranium for fuel, although some HWRs are operated on natural uranium. At discharge, the fuel contains fission products, transuranic elements (TRU; actinide elements plutonium and higher in atomic number), and uranium. All elements in UNF are contained within the fuel rod cladding, or the equivalent for gas-cooled reactors, which provides a barrier to release of radioactive materials to the reactor coolant. The radiological hazard, as measured by radiotoxicity (the toxic health effects due to radiation, whether ingested, inhaled, or external exposure), is initially mainly from fission products, but is dominated by actinides after about 60 years after discharge. Another issue with UNF is decay heat, where both fission product and TRU actinide elements contribute to the UNF decay heat, which must be managed for safe storage, whether in water-filled storage pools, later in dry casks and during transportation, or ultimately in the repository. Reactor fuels that produce more total energy will have greater fission product and actinide content per assembly.

Fast Neutron Reactors

Fast neutron reactors operate mainly on fast neutrons, i.e., neutrons that have not been slowed down by moderating materials such as water or graphite, which is why fast reactors have been typically cooled with liquid metals such as sodium, and the moderating effect of materials in the reactor core is an important design consideration. Although fast neutron reactors have generally been associated with fuel cycles that recycle fissile materials, they can also be used in a once-through mode using naturally-occurring fuel materials (uranium and thorium) in addition to the initial enriched uranium, where they can be used effectively with high internal conversion to breed new fissile as the initial enriched uranium is consumed. In these systems, it is planned to use driver assemblies containing low enriched uranium fuel and blanket assemblies usually containing uranium to take advantage of the more favorable breeding of fissile ^{239}Pu with fast neutrons. The driver fuel is planned to be irradiated to burnups of 30-40% (beyond today's experience with the technology, where peak burnup is about 20%) while the burnup of the blankets would be lower, though designs with ~20% blanket burnup have been proposed. This compares with the typical 5% burnup that is achieved with LWRs, and could increase the utilization of uranium resources from the less than 1% achieved with today's LWRs to perhaps in excess of 10%, depending on limitations imposed by the capabilities of nuclear fuel and associated materials. While the driver assemblies are initially supporting the core criticality at the beginning of core life, the blankets play a major role at the end of cycle, generating most of the reactor power. 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 more traditional fast reactor designs and demonstrations. Fast "breeder" reactors are distinguished by the coolant, such as

1. Sodium-cooled
2. Lead- or lead/bismuth-cooled
3. Gas-cooled
4. Molten salt with fixed fuel or flowing fuel

As with thermal reactors, it is also possible to use neutronically-subcritical externally-driven systems with fast neutrons in the surrounding blankets, similar to the approach for thermal neutron systems but again with no significant advantages to offset the additional complexities plus the significant cost of the external driver system.

UNF Storage – Interim Storage

Following shutdown of a reactor, the fuel continues to generate heat due to radioactive decay of both fission products and actinides. Removing fuel from the reactor is performed under water so that adequate cooling is provided. The UNF is then stored in a water-filled storage pool. Since the decay heat decreases with time, after sufficient storage time the UNF can be placed in dry casks for further storage. Since water pool or dry cask storage is only intended to be a temporary measure prior to disposal, such storage is usually referred to as interim storage. Currently, there are over 60,000 MT of UNF in interim storage in the U.S.

- **Interim Storage**
  1. UNF storage pool
  2. Dry cask storage
  3. Monitored retrievable storage

As discussed above, interim storage is used to allow time for the decay heat of the UNF to decrease to facilitate transport and disposal of the UNF. Initially, UNF is stored in water-filled pools, and then moved to longer-term dry cask storage. Such storage is currently being licensed to allow for storage until the disposal facilities are licensed and operating. Currently interim storage of UNF occurs at each reactor site, although proposals have been made for centralized interim storage to ease storage limitations at some reactor sites. Monitored retrievable storage could also be developed using below-ground facilities, even in deep geologic environments, with the intent to store materials until a disposal facility is available.

Disposal of Radioactive Materials

All nuclear fuel cycles produce hazardous radioactive materials that require disposal. Due to the significant long-term radiological hazard from UNF and high-level wastes (HLW), and the resulting need to prevent release of these radioactive materials to the biosphere, deep geologic disposal has been judged to be the best approach for providing the required isolation.[A5] In the U.S., no geologic disposal system has been implemented for the disposal of UNF or HLW, although the potential to site a repository at Yucca Mountain has been investigated for decades, with a license application submitted to the U.S. NRC in 2008. The current U.S. administration proposed withdrawing the license application in 2010, and effectively terminated work on the Yucca Mountain repository. It must be recognized that any nuclear energy system also creates other, less hazardous, radioactive wastes, and disposal of low-level wastes (LLW) and other radioactive wastes in the environment also needs to be provided. In projecting the future use of nuclear power, the management of all radioactive wastes must be one of the considerations.

- **Disposal**
  1. Deep geologic disposal of UNF and any civilian HLW
  2. Near-surface burial of LLW

In the Once-Through category, the integrated fuel cycle requires the availability of deep geologic disposal for UNF (and any HLW, always in solid form), whether in mined repositories, deep boreholes, or other similar emplacement. At this time, no technology for the disposal of UNF and HLW has been chosen, although there was a proposal to develop a repository at Yucca Mountain in unsaturated volcanic tuff. Other geologic settings are possible candidates for siting a repository, and are the subject of continued study, as summarized in Ref. 8. For LLW, which must be in solid form, disposal has been performed using near-surface burial in shallow landfills. Classification of waste as LLW by the U.S. NRC is based on content of specific isotopes, including activation and fission products and is not related to total activity. Waste that contains alpha-emitting TRU having a half-life greater than 5y in excess of 100 nanocuries per gram is classified as TRU waste, and is handled separately. Near-surface disposal is judged to be adequate for most LLW disposal, although it should be noted that some LLW may be quite radioactive such as radiation sources used in medicine and industry, and some may require geologic isolation.

Recycle and Separations

Other components are added for recycle nuclear fuel cycles, most notably the possibility of processing UNF using separations or other treatment technologies, and the use of nuclear breeder reactors to increase the rate at which new nuclear fuel resources are created from either uranium or thorium. Such options have been researched extensively in the U.S. to study the potential for development into commercial systems, although there are concerns associated with these as well, including radioactive waste generation from processing activities and the potential for propagating the use of technologies that could be used for obtaining weapons-usable materials. Some of these options have already been implemented in other countries such as France and Japan for the extension of fuel resources. There are numerous separations technologies based on a wide variety of separations principles, including aqueous/organic solvent extraction, molten salt electrochemical, fluorinated gas volatility, etc. They are capable of separating individual chemical elements or groups of elements. As a result, the UNF is processed to result in products, HLW, and LLW, where the masses of hazardous elements in the HLW will be less than that in the UNF. There is also the potential for generating significant quantities of LLW, but this varies with the separations technology and LLW production is amenable reduction by operational best practices and other waste reduction methods.

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