Comparing Nuclear Fuel Cycle Options

Observations and Challenges

A report for the Reactor & Fuel Cycle Technology Subcommittee of
the Blue Ribbon Commission on America's Nuclear Future

by Paul P.H. Wilson

1 Introduction

The comparison of different nuclear fuel cycle options has become an integral element to any analysis of the future prospects for nuclear energy, in the United States and around the world. Concerns for supply security and price volatility of fossil fuels, combined with growing resolve to reduce the emissions of greenhouse gases, have caused a general shift in attitudes towards nuclear energy. However, there are lingering sustainability concerns for nuclear energy – long term uranium supply and environmental impact – as well as concerns about the proliferation of nuclear weapons.

Advanced fuel cycles are often considered as a means to address these concerns. Although they can take on many forms, they generally involve the chemical separation of spent nuclear fuel into various constituents, some of which can be recycled into other nuclear reactors and the remainder destined for long term storage or disposal. Like recycling of any commodity, this is designed to reduce the consumption of primary resources, namely uranium, and reduce the quantity (mass, volume or both) and hazard of material destined for disposal in the biosphere. As such, different combinations of technologies are often combined to achieve some combination of these aims. However, as is also true of other commodities, the ability of a given strategy to achieve these aims is not always clear and choosing between different options becomes a matter of policy.

1.1 Purpose of report

This report is intended to provide a high-level comparison of different fuel cycle options with respect to the most common socio-political measures of their performance. The report begins with a discussion of the sources of hazards in nuclear fuel cycles. After acknowledging the inherent challenges in doing a robust comparison of speculative technologies, a variety of measures and metric will be adopted for conducting this comparison. Various fuel cycle options will then be compared to a reference once-through fuel cycle.

This report is not intended to provide detailed quantitative analysis of each of the nuclear fuel cycles discussed here. The comparison is framed by the results of the recent “AFCI Options Study” [Wigeland2009a, Wigeland2010a] and Congressionally mandated “AFCI Comparison Report[s]” [AFCIComp2003a,AFCIComp2006a], which draw upon previously executed studies by the US Department of Energy and it laboratories, ranging from analyses of individual fuel cycle options to summary comparisons of various fuel cycle options. Metrics for each fuel cycle are described as being either ***substantially the same*** as the once-through reference cycle, ***slightly different*** or ***significantly different***. Where there are differences, they can either be positive or negative in nature and some discussion of the differences will be provided. Additional quantitative information is drawn from the Draft Programmatic Environmental Impact Statement for the Global Nuclear Energy Partnership [GNEPPEIS2008a].

This report is also not intended to be comprehensive across all possible technology options. Instead, it will focus on three main alternative strategies and assume general technology options within each strategy. The first strategy is a modified once-through cycle that focuses primarily on very high-burnup with no reprocessing. The second strategy is a limited recycle of some minor actinides (usually plutonium) while the final strategy is a continuous recycle of some (or all) minor actinides. Where there is a wide discrepancy in performance among technology options within a given strategy, extra discussion will be provided.

Finally, this report will provide a brief overview and comparison of systems analysis tools that have been created by various institutions to provide comparisons of different fuel cycle options using some of the metrics used here.

1.2 Source of Nuclear Fuel Cycle Hazards

Nuclear fuel cycles are different from other industrial processes due to the radioactive nuclides that are involved at every phase of the fuel cycle. Therefore, some measures and metrics of nuclear fuel cycle performance are unique to the nuclear energy industry as they assess the impact of these radioactive nuclides. Furthermore, certain characteristics of these nuclides, either related to their radioactivity or in addition to it, result in unique hazards at different phases of potential fuel cycles. This section enumerates some of those characteristics to facilitate the discussion of the measures and metrics below.

1.2.1 Origin

It is often convenient to classify radioactive nuclides by their origin in the nuclear fuel cycle. Although their behavior and likelihood of becoming a hazard is governed by other properties described below, this classification helps to understand where in the fuel cycle they can become a concern. ***Uranium*** is naturally occurring in the earth's crust and is mined for use in nuclear fuel cycles. Since it is naturally radioactive, ***uranium daughter products*** also occur naturally and some are released during the mining and milling processes. The fission process can split a large atom, such as uranium, into two smaller ***fission products***, most of which are radioactive. During irradiation in a reactor, most nuclides can be transmuted to some other nuclide by capturing a neutron, often becoming radioactive. Those nuclides heavier than uranium are usually classified as ***transuranic nuclides (TRU)*** and those lighter than uranium will be classified here as ***transmutation products***.

1.2.2 Physical form

The physical form of radioactive nuclides is important for understanding the potential for release to the environment. The phase (solid, liquid, gas) of a nuclide at standard conditions can determine how that nuclide must be handled to avoid release to the environment. Some elements are ***gaseous*** in a wide range of conditions and others are considered ***volatile***, existing in some combination of liquid and gaseous state at a wide range of conditions. Both can increase the risk of release to the environment.

1.2.3 Chemical behavior

The chemical behavior of radioactive nuclides is also important for understanding both the potential for release and its behavior following release. Very reactive elements can often be captured and contained by engineered or natural barriers. If an element is not very reactive, with noble gases being an extreme, it can be more challenging to capture and contain them.

Many nuclear fuel cycle facilities are chemical engineering facilities that rely on this chemical behavior to create compounds that are either liquid or gaseous themselves, or can be dissolved in liquids, to facilitate the chemical processing. Similarly, natural environments can result in chemical reactions that change the behavior of the elements involved. These chemical transitions can change the risk of release.

1.2.4 Half-life

The half-life of an nuclide characterizes how long it takes, on average, before it decays to become another nuclide and is an immutable property of an isotope. Although a ***long-lived*** nuclide has a low level of radioactivity, it can be a hazard that must be managed for centuries or longer. ***Short-lived*** nuclides are intensely radioactive, but their hazard is quickly diminished. The time frame for considering a nuclides to be either short- or long- lived may depend on the application. For long term storage/disposal, short-lived is usually used to describe nuclides with half-lives of about a decade or less, and long-lived is usually used to describe nuclides with half-lives of about a century or more.

1.2.5 Decay type

The type of particle emitted during radioactive decay determines the pathways by which the nuclides can become hazards. Those that emit ***alpha*** and ***beta*** particles are typically only hazards to inhalation and ingestion. Those that emit ***gamma*** rays or ***neutrons*** are typically hazards simply to do proximity and possibly also due to inhalation and ingestion.

1.2.6 Decay heat

During radioactive decay, the emitted particles carry with them some energy that is eventually converted to heat in the surroundings. When nuclides have a ***high decay heat***, they can require special consideration for handling, storage and disposal.

1.2.7 Biological impact

Some nuclides have a more important biological impact than others because of the way that the human body processes them, generally as radioactive isotopes of elements that are either important to human physiology, or are chemically similar to such elements. This behavior leads to a ***biological half-life*** that characterizes how long an element stays in the human body. Some radioactive nuclides move quickly through the human body, with little time to cause any harm, while others accumulate in the body for time scales similar to their radioactive half-life.

1.2.8 Fissile/fissionable nature

Whether or not the nuclide is ***fissile*** or ***fissionable*** is important for determining whether it can be used in a nuclear reactor as well as an assessment of the proliferation characteristics of a material. Fissile nuclides are those that easily undergo fission when hit by a neutron of any energy, making them very useful for any fission application, peaceful or otherwise. Fissionable nuclides are those that can be made to undergo fission when hit by a neutron with high enough energy. Fissionable nuclides can be used in nuclear reactors, but are less valuable for nuclear explosives. It is also possible for nuclides to undergo ***spontaneous fission*** without being hit by a neutron at all, a characteristic that makes the material difficult to handle for most applications.

1.3 Overview of Challenges

Many challenges arise when comparing the performance and outcomes of these different fuel cycle technologies. In general, such comparisons must be based on the analyses performed by the designers of that cycle and must rely on the data they provide. This results in variability of the underlying assumptions used in the analysis, a lack of consistency in the data reported, an incomplete assessment of the systems impact of a given technology on the whole nuclear fuel cycle, and an inherent bias based on the underlying values of the analysts. These challenges are all exacerbated by a substantial uncertainty in our predictive understanding of systems that have never been deployed.

Two forms of standardization that could mitigate these challenges have not yet been put into place: standardization of reporting requirements including assumptions and results, and standardization of fuel cycle systems analysis tools.

1.3.1 Variability in assumptions

Each nuclear fuel cycle analysis is constrained by a series of assumptions made in establishing the analysis. While many of these assumptions are stated explicitly by the analysts, there are often implicit assumptions that are not even recognized as such. In some cases, once identified, the assumptions can be accommodated in making a comparison. However, it is also common for an incompatibility in these assumptions to effectively prevent any useful comparison. Rather, the only outcome of such a comparison may be to compare the assumptions themselves rather than differences in technologies.

Some important assumptions arise in the design of the nuclear fuel cycle and related deployment strategies, including:

- growth rate of nuclear electricity
- date of introduction of new technologies and facilities
- constraints on spent fuel interim storage capacity
- constraints on spent fuel storage/cooling times
- constraints on quantity of separated plutonium
- relative priority of different fuel cycle paths
- supply vs. demand flow control at each fuel cycle stage

In addition, to the extent that the performance parameters of individual facilities are considered assumptions for a full systems analysis study, the uncertainty in those quantities introduces another source of variability in those assumptions.

1.3.2 Consistency and Completeness of Reporting

Even when similar assumptions are used for the basis of an analysis, the outcomes of that analysis may be reported in very different ways. Results are generally reported in a summary form that masks some of the details, and each analyst’s choice of those summary forms is different. Direct comparisons are difficult and there is insufficient detail to perform a more careful comparison of the data that composes the summaries. For example, where one analysis may report the reduction in transuranics (TRU) that is sent to a geologic repository, another analysis will report the total amount of transuranics in the fuel cycle.

In some reports, missing data goes beyond a lack of detail. In these cases, when a given analysis is focused on a particular fuel cycle metric, it will fail to provide other metrics entirely, as they were outside the scope of the original study. In general, it is rare to find two analyses prepared by different groups that lend themselves to straightforward comparison.

1.3.3 Systems impact

Not all analyses provide a complete assessment of the impact of a given technology or fuel cycle choice on the nuclear energy system as a whole. In some cases, a fuel cycle technology can be analyzed in a “sandbox” without considerations for how the waste streams for that technology will be accommodate by other stages in the fuel cycle. This makes it difficult to assess the full costs and benefits of the technology in question.

It is also common to analyze a fuel cycle by considering its performance once it reaches an equilibrium state in the full nuclear energy system. However, some fuel cycles may take decades or even centuries to reach these equilibrium conditions, in which case the dynamic transition behavior is more important than the equilibrium behavior. Interpolating from the equilibrium results to the transition results is, in general, not possible.

1.3.4 Uncertainty

Most advanced fuel cycle technologies have never been constructed or operated at a commercial scale, and many exist only in paper studies or small scale laboratory experiments. As a result, the behavior of these systems when deployed at a large scale is subject to large uncertainties and extrapolation from existing technology. Furthermore, even existing reprocessing technologies deployed at commercial scales in France, UK and Japan, have large uncertainties in their economic metrics. As a consequence, most fuel cycle systems analyses produce results with large uncertainty bands, whether explicitly indicated or not, and are best used for a comparative analysis than a predictive estimate of their absolute performance.

1.3.5 Value bias

Finally, the underlying biases of the analysts are also a factor, at times contributing to the above challenges. These biases, derived from a legitimate difference in values-based assessment of the importance of performance metrics, result in analyses that focus on a narrow set of fuel cycle metrics and summarized results, and are often framed to highlight the benefits of a given technology while paying little attention to the disadvantages.

2 Measures & Metrics

Notwithstanding these challenges, there are a number of important measures and metrics that can be used to compare nuclear fuel cycle options. Article 3.(a) of the Advisory Committee Charter for the Blue Ribbon Commission on America's Nuclear Future states:

> Evaluation of existing fuel cycle technologies and R&D programs. Criteria for evaluation should include cost, safety, resource utilization and sustainability, and the promotion of nuclear nonproliferation and counter-terrorism goals.

These broad criteria manifest themselves in a long list of individual metrics when comparing nuclear fuel cycles. Most of these metrics are normalized by the total amount of electricity generated for comparison purposes.

2.1 Cost

Cost is often a primary metric for comparison of nuclear systems and fuel cycles. Often attempts are made to characterize other metrics in economic terms due to the attractiveness of performing a simple economic comparison, but this generally ignores differences in the way that stakeholders value the impacts of these other metrics. Because most advanced fuel cycle facilities have rarely, if ever, been constructed and deployed in a truly open market setting, there is high uncertainty in most cost projections for future nuclear technologies.

- total cost of electricity [$/MWh] including the costs of all aspects of delivering nuclear energy. This metric is interesting when examining the system impacts of introducing different reactor technologies that have different capital/construction costs.
- capital at risk [$] measures the amount of capital that must be invested before a technology

begins generating revenue. This metric is of interest when considering the ability for a corporation (or a small nation) to generate enough funds to build a new technology, independent of the long-term profitability of that technology.

- fuel cycle cost [$/MWh] excluding the capital/construction costs and non-fuel operation and maintenance costs. This metric is often used to capture the impact of advanced fuel cycles on the costs of fuel alone.
- disposal costs [$/MWh] representing the costs to the system for disposal of high-level radioactive waste, determined either by legislation (as in the Nuclear Waste Fee) or by other analysis. This can be used to estimate savings in the disposal of radioactive waste, but is rarely useful without consideration of other fuel cycle costs.

2.2 Safety

Safety of individual facilities is rarely used as a primary distinguishing feature between nuclear fuel cycles and systems. There is an argument to make that safety is not a matter of comparison. Safety standards will be established by regulators and systems will incur costs to meet those standards, turning this into an economic category. However, when considering the complete nuclear fuel cycle, safety issues related to the transportation of radioactive materials introduces a distinguishing measure.

- accident frequency [1/yr] represents the probability that an accident at a facility will occur in any given year of operation. This frequency is independent of the consequences that are measured with some of the metrics below.
- core damage frequency [1/yr] representing the probability that an incident at a reactor will result in an unplanned geometric change to the nuclear reactor core.
- occupational radiation dose [person-rem/MWh] measures the cumulative amount of radiation received by a nuclear energy workforce. While the dose to any individual worker is limited by regulation, the cumulative dose received by all workers measures how much additional risk is assumed by the nuclear energy workforce.
- population radiation dose [person-rem/MWh] measure the cumulative amount of radiation received by the public. This metric can be estimated for nnormal operation as well as for
- maximally exposed individual dose [mrem/yr] measures the annual radiation dose received by the member of the public subjected to the largest radiation dose.
- latent cancer fatalities measure the estimated number of additional cancer deaths that will occur due to a given technology. This can be applied to the occupational workforce or the general public, and can also be attributed to either normal operation or accidents. Calculation of this quantity is based the application of the population linear non-threshold theory of determining the consequence of radiation exposure. Because of the time span between exposure and the onset of the disease, it is difficult to attribute any individual case to the radiation exposure.
- transportation safety metrics: In addition to applying some of the above metrics to the operation of radioactive waste transportation, it is also useful to estimate the number of individual shipments of radioactive waste under different scenarios.

2.3 Resource Utilization

Resource utilization is generally focused on the consumption of uranium ore as the long-term availability of uranium is seen as a potential constraint on the continued use of nuclear energy. Various models for the price of uranium have been proposed, including an upper limit defined by the cost of extracting U from seawater, in an attempt to make this an economic factor rather than a resource factor. Although some cycles suggest thorium fuels to alleviate this, the rate of thorium consumption is rarely used as a distinguishing characteristic of a nuclear fuel cycle. Similarly, the consumption of other natural resources has not been seen as a constraint on the continued use of nuclear energy, with the exception of fresh water consumption, a rapidly emerging concern.

- uranium consumption [kg U_3O_8/GWh] indicating the total amount of uranium that must be mined. This is usually expressed as a system average since some technologies require no direct mining of uranium and act to reduce the system average uranium resource requirements. This metric is important because it measures the consumption of the fissile uranium isotope, assuming that there is nothing that can replace it in the fuel cycle.
- water withdrawals [gal/kWh] measures the amount of water temporarily withdrawn from the fresh water resources, some of it returned.
- water consumption [gal/kWh] measures the the amount of water removed from the fresh water resources but not returned to the same river, lake, or aquifer. This water is ultimately returned to biosphere, but is unavailable for other consumers of water on that system.
- disposal space [ha/GWh] measures the amount of space required for the final disposal of all nuclear fuel cycle waste streams. This metric is governed primarily by the heat load of waste material, but varies regarding which isotopes are most important. For a given repository design, this may be better expressed in another measure of space, such as the length of drift tunnel that needs to be mined.
- total land use [ha/GWh] measures the amount of land disrupted in the process of generating nuclear energy. This measure is not generally used to compare nuclear energy technologies, but can be used to compare nuclear energy to other technologies. It is dominated by factors that relate directly to uranium consumption and disposal space.

2.4 Sustainability (Nuclear Waste Management)

Sustainability covers a wide array of measures and metrics that relate to the environmental impacts of the nuclear fuel cycle and its facilities. While it could encompass resource utilization as well, in this context it will be constrained to measures that relate to the management of materials emitted/released/produced by the nuclear fuel cycle. There are many possible waste streams and a handful of ways to characterize those streams, resulting in an expansive list of measures and metrics in this category.

- Estimated peak dose rate [mrem/yr]. This metric describes the hazard to the maximally exposed individual at the perimeter of a HLW repository and assumes that the repository remains undisturbed throughout its designed lifetime. Although calculating the value itself requires detailed knowledge of a specific repository design, qualitative assessments can be made in many cases for generic repository systems. In most cases, this metric is dominated by a small number of long-lived fission products.
- High-level waste disposal volume [m^3/GWh]. A variety of considerations is included in

determining the volume of HLW destined for a repository, particularly the impacts of its chemical form and decay heat on the stability of the waste form. These are often dominated by short-lived fission products, but transuranics may also be important. This measure will include waste classified as “Greater Than Class C” [GTCC] and therefore cannot be disposed of as low-level waste.

- High-level waste disposal mass [kg/GWh]. Historically, HLW has been measured by its mass, although this measure is of limited utility as the technology of HLW disposal is only weakly related to its mass and more closely related to its volume.
- Radiotoxicity of high-level waste streams. This measures the radiological hazard potential of the HLW at any point in time in the future and is useful for considering situations where the repository is disturbed (by human intrusion or natural disaster) during its lifetime. In most cases, this metric is dominated by both transuranics and fission products.
- Mass of depleted uranium [kg/GWh]. The byproduct of uranium enrichment must be managed for reasons of environmental health and security.
- Low-level [solid] waste volume [m^3/GWh]. Different fuel cycle processes result in the production of waste streams that are not considered high-level waste and can be disposed of in near-surface burial facilities.
- Radioactive liquid release volumes [m^3/GWh]. Some fuel cycle processes include the release of small amounts of radioactive liquids to the local aquifers as part of normal operation, subject to regulation, and expected to quickly become dilute in those aquifers. Of particular interest are nuclides with a higher biological impact such as tritium, iodine, cesium and strontium.
- Radioactive gaseous release volumes [kg/GWh]. Some fuel cycle processes include the release of small amounts of radioactive gases to the local atmosphere as part of normal operation, subject to regulation, and expected to quickly become dilute in those locations. Of particular interest are noble gases that can be inhaled.
- Life-cycle emissions for conventional pollutants [kg/GWh]. Over the entire life cycle of a nuclear energy system, the operation of that system is responsible for the direct and indirect emission of conventional pollutants, including carbon dioxide (or equivalent) emissions. While comparison of this metric among nuclear energy systems is traditionally less common than comparison of all nuclear energy systems with other energy systems, it could become a distinguishing factor in the future.

2.5 Non-proliferation

- mass of special nuclear material [kg/GWh] measures the quantity of special nuclear material[1] [SNM] that exists in different forms at different stages in the fuel cycle. This material must be safeguarded to ensure it is not misused. When it exists in large quantities, there can be concerns about accounting uncertainties that may lead to substantial quantities of material becoming lost from the accounting system.

---

[1] "Special nuclear material" (SNM) is defined by Title I of the Atomic Energy Act of 1954 as plutonium, uranium-233, or uranium enriched in the isotopes uranium-233 or uranium-235. The definition includes any other material that the Commission determines to be special nuclear material, but does not include source material. The NRC has not declared any other material as SNM. [USNRC, 2011]

- required enrichment capacity [kgSWU/GWh] measures the total amount of enrichment services that are needed to support a fuel cycle.
- attractiveness of separated materials is a qualitative measure of how useful a given inventory of material is for undesired uses such as the proliferation of nuclear weapons. When many different streams/inventories of separated material exist, the attractiveness of each would be assessed independently.
- mass of separated plutonium [kg/GWh] measures the inventory of separated plutonium that exists in the fuel cycle at any one time (or possibly the maximum inventory over some time domain of analysis). In some sense, this is a combination of two other metrics – mass of special nuclear material & attractiveness of separated materials – because separated plutonium is considered by most to be a particularly attractive special nuclear material, deserving of its own metric.

2.6 Additional considerations

Even if credible assessments for all these metrics were possible, combining them into a single metric with which to evaluate and directly compare nuclear fuel cycles is not generally possible. Different value systems of various stakeholders can lead to additional metrics, a different expression of some metrics (e.g. different units and evaluation methodologies) and a different relative importance of those metrics.

This is particularly true when specific sites and technologies are selected. For example, some stakeholders may be interested in socio-economic impacts of a specific technology being deployed at a specific site and demographic implications of the process of siting such facilities. Collectively, assessments rooted in social science may have a significant role in decision making even if they are difficult to express generically. The political and legal effort involved in siting a new nuclear facility is not easily measured, but has proven to be important for comparing options.

Also important are legitimate technical disagreements on how to calculate a particular metric. For example, some stakeholders may have differing opinions on how to aggregate or disaggregate individual metrics into summary metrics. Additionally, the assumptions that go into the analyses that determine the metrics are subject to legitimate differences.

Finally, even when all stakeholders agree on the set of metrics and the methodology for determining those metrics, legitimate differences in how each of those metrics is valued will lead to different conclusions about the suitability of a given technology. These stakeholders make implicit judgments about how to weight the various metrics in their decision making processes, including non-linear weighting schemes that are a function of multiple metrics.

3 A Reference: the Once Through Fuel Cycle

The current nuclear fuel cycle in the United States is often referred to as the “Once Through Cycle” [OTC]. In this cycle, uranium is mined from the earth, converted to a form that can be used in enrichment facilities, enriched to increase the concentration of the more potent U-235 nuclide, formed into fuel assemblies and inserted into a reactor for a period of 36-72 months. When they are removed from the reactor, they are stored at the reactor site, first underwater and then possibly above ground. Under current policy, those fuel assemblies would next be transported directly to a mined repository for permanent underground disposal. A small modification to this would include shipping the used fuel assemblies to an interim storage site before sending them to the geologic repository.

The economic performance of this fuel cycle has improved dramatically over time thanks to the continuous improvement of operating procedures at nuclear facilities. Most attempts to predict costs of the OTC in the future rely on new reactors maintaining most of this benefit of improved operations costs and adding the cost of paying for new facilities including a substantial cost of capital.

Table 1. Resource requirements for a once-through cycle. Assumptions are shown in **bold-face**.

Burnup	**50**	**MWdth/kg**
Fuel Enrichment	**4.5**	**%**
Depleted uranium enrichment	**0.2**	**%**
Thermal Efficiency	**33**	**%**
Enriched uranium consumption	2.5	kg/GWh
Natural uranium consumption	21.1	kg/GWh
Depleted uranium production	18.6	kg/GWh
Required enrichment capacity	19.25	kgSWU/GWh
Water consumption [Sovacool2009a]	0.6	gal/kWh
Water withdrawals [Sovacool2009a]	0.8	gal/kWh

Other than assumed financial input parameters, one of the most important technical parameters is the burnup of the fuel when it is discharged from the reactor, measured as the amount of thermal energy released per units mass of the fuel. This parameter drives enrichment and, in turn, uranium resource utilization on the front end of the nuclear fuel cycle, as well as impacting the volume, mass and radiotoxicity of high-level waste (as used nuclear fuel). Based on current industry practice, the reference value of this parameter will be 50 $\mathrm{Mwd}_{\mathrm{th}}$/kg.

4 Comparison of Advanced Fuel Cycles

The AFCI Options Study was designed to collect and summarize results from previous fuel cycle systems analysis studies, and provide an assessment of their performance against a set of metrics based on the root causes of ongoing issues with commercial nuclear energy. Using the current once-through cycle [OTC] as a baseline, the “top-down” approach began with a qualitative analysis of three major “strategies” of fuel cycle technology, and in some cases provided additional comments on the impact of specific technology choices within those strategies. In the second phase of this study, some additional insights are provided, including some quantitative analyses.

Another important reference are the “Annual Comparison Reports” provided to Congress by the Department of Energy. Language in the Conference Report that accompanied the FY2003 Energy and Water Development Appropriations Act required the Department of Energy to submit an annual report to Congress that would provide sufficient information for the comparison of different advanced fuel cycle options. These reports, particularly the FY2003 and FY2006 reports, provide useful quantitative information on a number of metrics. In addition, these results will highlight some of the challenges in arriving at a consistent comparison of fuel cycle metrics.

In 2008, the Department of Energy issues a Draft Programmatic Environmental Impact Statement (PEIS) for the Global Nuclear Energy Partnership (GNEP). While the GNEP program has been replaced by other programs, the quantitative comparison of different fuel cycle scenarios offered in this document provides a valuable snapshot. This comparison is based on a variety of scenarios, each with a specific combination of technology options.

In this section, the Options Study Phase 1 report [Wigeland2009a] will provide a framework for discussion, with addition information provided by the other reports as appropriate.

4.1 Metrics of Comparison

4.1.1 Options Study Metrics

The Options Study identified six major categories of concern for nuclear energy and the Phase 1 report offered a set of metrics for assessing each:

1. Nuclear Waste Management
    - estimated peak dose rate – indicates hazard to population if repository is not disturbed
    - radiotoxicity of disposed materials – indicates hazard to population if repository is disturbed
    - mass (& volume) of used nuclear fuel (UNF), high-level waste (HLW) – indicates size of HLW repository
    - mass (& volume) of low-level waste (LLW) – indicates size of LLW disposal facility
    - interim storage – indicates impact of interim storage on waste characteristics
    - heat load – indicates constraints on geologic repository
2. Proliferation Risk
    - inventory of weapons-usable materials (SNM)
    - material attractiveness
    - need for uranium enrichment
    - safeguardability
3. Safety
    - difficulty in licensing
4. Security
    - inventory of radioactive materials
    - ability to provide physical security
5. Economics
    - similarity to existing infrastructure
    - capital at risk
    - technical maturity
    - technical risk
    - development time
    - life-cycle cost
6. Sustainability
    - fuel resources
    - disposal needs

4.1.2 Draft GNEP PEIS Metrics

The Draft GNEP Programmatic Environmental Impact Statement offers a slightly different set of metrics, focusing on a more robust analysis of waste streams and public health consequences.

1. Resource consumptions
    - natural uranium/thorium consumption

- water consumption

2. Radioactive waste management
    - spent nuclear fuel (SNF) mass/volume to repository
    - HLW volume to repository
    - GTCC LLW volume to disposal
    - Cs/Sr volumes to disposal
    - LLW volumes to disposal
3. Public health
    - cumulative dose to nuclear workforce
    - accident risk to population [latent cancer fatalities]
4. Transportation metrics
    - total number of radiological shipments
    - cumulative dose to transportation workforce
    - accident risk to population

4.2 Strategies for Comparisons

4.2.1 Options Study

The baseline for comparison was today's once-through cycle (OTC) in which natural uranium is enriched to a few percent, fabricated into nuclear fuel, irradiated in a reactor and sent directly to geologic disposal following some interim storage. Three other broad strategies were considered:

1. A defining feature of *Alternate Once-through strategies* is the lack of any chemical reprocessing of used nuclear fuel. Instead, these concepts involve higher enrichments leading to larger burnups, in-situ breeding of fissile material, and/or subcritical systems driven by external neutron sources. All used nuclear fuel is sent for geologic disposal.

2. *Limited Recycle strategies* are characterized by the direct geologic disposal of some used nuclear fuel, but also allow for some used nuclear fuel to be chemically reprocessed and some material returned for fabrication into new fuel. High-level waste (HLW) streams from the separations process will also be destined for geologic disposal.

3. *Continuous Recycle strategies* assume that used fuel at all stages of the fuel cycle will be reprocessed and only HLW streams from the separations process will be sent for geologic disposal.

Since the assessment of Safety, Security and Economics depend largely on specific design and operational details, these strategies are compared first against only the other three categories of metrics: Nuclear Waste Management, Proliferation Risk, and Sustainability. The comparison is largely qualitative in which changes in a given metric are described relative to the baseline, and only significant differences (an order of magnitude or more) are highlighted.

Following this top-level assessment, specific technology options are compared within each strategy, including choice of fuel, reactor or other irradiation environment, processing options, and disposal options. The impacts of the different technology choices within each strategy are also considered qualitatively.

4.2.2 Draft GNEP PEIS

For the Draft GNEP PEIS, a number of specific scenarios, each based on a specific set of technologies, were studied over a 50-60 year period. While different nuclear energy growth rates were considered, complete results are given for scenarios with a growth rate that leads to a doubling of nuclear generation by 2060-2070. As suggested in 1.3.1 above, each of these scenarios is based upon some set of assumptions. Although understanding these assumptions is important for placing the absolute quantitative results in context, since this study used a consistent set of assumptions where possible, a qualitative comparison of these results is possible without listing the complete set of assumptions for each case.

The results from this PEIS will be used to add quantitative details to the qualitative comparisons derived from the Options Study. Results are available for specific scenarios representing the traditional once-through strategy and continuous recycle strategies. While there are some alternative once-through strategies, only a strategy based on a complete transition to high-temperature gas reactors has the increased burnup that is characteristic of this strategy in the Options Study. There is only a single scenario that represents the limited recycle strategy based on using heavy water reactors.

4.3 Summary of Results

A table of high-level findings from the Options Study is available in Table 1 of that report [Wigeland2009a]. Quantitative results on material flows can be found in Figure 1 of the 2003 AFCI Comparison Report [AFCIComp2003a] and Table S.3-1 from the Draft GNEP PEIS [GNEPPEIS2008a].

4.3.1 Alternate Once-Through strategies

These strategies are characterized largely by higher burnups achieved by some combination of higher enrichment, in-situ breeding and/or external neutron sources. The degree to which burnup can be increased is limited by the ability of fuel and cladding materials to survive the higher burnups. Therefore, systems that result in nearly complete consumption of natural uranium in a once-through cycle, while theoretically possible, are considered unrealistic in the Options Study. Both uranium and thorium fuels are available for use in once-through cycles and a variety of different reactor/irradiation environments could be employed.

Used fuel contains a combination of fission products, uranium and transuranics (TRU). As burnup increases, the fission product inventory increases proportionally while the TRU inventory approaches an equilibrium level as some transuranics are involved in fission themselves. Therefore, there is a constant production of fission products per unit energy but a gradual reduction in the production of TRU per unit energy. Also, because more energy is released per unit of fuel, there are fewer units of fuel needed per unit energy. Together, these result in small improvements in many of the nuclear waste management metrics, proportional to the increase in burnup. The FY2006 AFCI Comparison Report indicates that doubling the burnup in the OTC will give a 38% reduction in long-term radiotoxicity and a 13% reduction in estimated peak dose [AFCIComp2006a, Table 1]. The waste management metrics for alternate once-through strategies are substantially the same as for a traditional OTC.

Without any reprocessing, most of the proliferation risk metrics are substantially the same for a traditional OTC, but some technology options may require additional enrichment capacity. Even systems that approach complete burnup and have very little special nuclear material (SNM) in their spent fuel do have substantial SNM inventories at intermediate burnups due to the in-situ breeding that takes place. All SNM that is generated is sent to the repository for disposal. At the time of disposal its attractiveness is low due to the radioactive barrier of short-lived fission products and TRU. Although the radioactive barrier is diminished over time, the attractiveness is still limited by the chemical form of the SNM mixed at low concentrations with large quantities of other nuclides.

There is also little impact on sustainability metrics (ie. substantially the same). While higher burnups mean less fuel is required at the reactor, the higher enrichments required in those fuels mean that nearly equivalent amounts of natural uranium are needed. There may be smaller inventories of material needed for disposal, but due to its heat load and radioactive inventory similar total sizes for disposal facilities will likely be required.

4.3.1.1 Technology Variations

Thorium fuels are also considered for once-through strategies, but found to offer little to no benefit for most metrics. Some configurations may results in modest reductions in the waste streams and plutonium production, but otherwise waste disposal and non-proliferation metrics are essentially the same as for uranium fuels. Larger uranium enrichments needed to drive these cycles will mitigate any savings in either enrichment capacity or natural uranium consumption.

Different reactor and irradiation technologies are also considered, including the option for both fast reactors and externally driven sub-critical facilities. Both systems offer the potential of very high consumption of natural uranium, limited primarily by the integrity of the fuel and cladding materials.

The high-temperature gas reactor scenario studied in the GNEP PEIS has approximately twice the burnup with a 16% larger consumption of natural uranium and a 2.7 to 15 times larger SNF volume (although a 65% lower SNF mass).

4.3.2 Limited Recycle Strategies

In the limited recycle strategies, some used nuclear fuel is reprocessed, typically extracting the plutonium for use in mixed oxide [MOX] fuel (U + Pu), and some used nuclear fuel is disposed directly. Burnup plays a similar role in limited recycle strategies as it does in once-through strategies.

There may be small reductions in the amount of high-level waste generated by limited recycle strategies, but they may generate substantially more low-level waste in the used fuel separations and fabrication process. In one estimate [AFCIComp2003a, Figure 1], the mass of LLW is approximately 50% of the mass of used nuclear fuel in the baseline once-through cycle, and twice as large as the mass of vitrified waste leaving the separations facility. The characteristics of used MOX fuel are similar to used uranium oxide [UOX] fuel, so other waste management metrics of limited recycle strategies are similar to once-through strategies. The waste management metrics are substantially the same as for a OTC with the exception of LLW which could see significant increases.

By recycling plutonium back into the fuel cycle, the total amount of special nuclear material that is sent to the repository is decreased, but the attractiveness of the SNM during processing is greatly increased. Although the Options Study fails to directly consider the potential for the accumulation of attractive SNM if the demand does not match the supply, it does conclude that it is possible to provide adequate safeguards for materials in such fuel cycles.

Limited recycle strategies make more efficient use of the natural uranium resource, and therefore require somewhat less natural uranium than (but substantially the same as) a baseline OTC. Due to the characteristics of the HLW generated in these cycles, the disposal requirements are expected to be similar to once-through cycles.

4.3.2.1 Technology Variations

The absence of naturally occurring fissile isotopes of thorium means that Th fuels are not practical for limited recycle strategies. The reactor technologies are similar to those available for once-through cycles, although the narrow mission of these strategies suggests that only thermal reactor systems are of interest. Similarly, most discussions of limited recycle strategies focus on a narrow range of reprocessing technologies that are effective in a MOX strategy (e.g. PUREX).

4.3.3 Continuous Recycle Strategies

The defining feature of these strategies is that all used nuclear fuel is reprocessed and none is sent directly to a repository. Once the spent fuel has been separated into different output streams, some are returned to the fuel cycle for fission and transmutation while other are converted into waste forms for ultimate disposal. A wide array of separations processes are possible, providing more control over which output stream contains which chemical elements, and therefore which radioactive nuclides. As a result, a wide variety of fuel, reactor and processing technologies are available and can be combined in many possible fuel cycle configurations. Their performance against the metrics can vary a great deal and it becomes a challenge to draw definitive conclusions. Moreover, a strategy can be designed to achieve substantial improvement in any one metric, but consistently assessing all the metrics is not always supported by the available studies and can lead to different outcomes.

The Options Study focuses on fuel cycles that recycle TRU into the fuel cycle in order to minimize the inventory of TRU in the repository and make that TRU available for fission in reactor/irradiation environments. Since TRU contributes significantly to peak dose, radiotoxicity and decay heat, removing TRU from disposal streams will improve all of these metrics. As there are no practical uses for separated fission products, selective separation of FPs is of limited value and usually employed to have more control over the waste forms and disposal pathway (e.g. technetium-99). Cesium and strontium have a high short-term heat load and can be managed separately until they become LLW. For many processing technologies, these systems have not been demonstrated on an industrial scale and there is little real experience with their performance. The magnitude of this improvement depends on which elements are being recycled to the fuel cycle and the recovery efficiency in the processing stages, and most studies assume such quantities or study them parametrically. These studies are able to make consistent estimates of high-level waste quantities based on this approach, but rarely make any complete or consistent estimate of low-level waste quantities. In summary, the Options Study concludes that some waste management metrics will be significantly improved while the LLW generation will be significantly increased.

A natural consequence of continuous recycle strategies is that less special nuclear material (SNM) is sent to the repository for disposal. This material accumulates in inventories of material being actively processed through the fuel cycle, in a variety of chemical and physical forms. The quantity of SNM in use by the fuel cycle is much larger in these strategies than in once-through strategies. The attractiveness of these materials varies widely depending on its form, and there is some debate about the role of different nuclides in reducing the attractiveness of separated materials. It is possible to design strategies that do not separate pure plutonium, but some strategies may include this. As with limited recycle strategies, the Options Study concludes that effective safeguards can be implemented for continuous recycle strategies. The need for additional enrichment capacity is unlikely for these fuel cycles, but also possible in some configurations. While the Options Study concludes that the proliferation metrics are substantially the same as for a OTC, there would be a significantly increased inventory of separated SNM in the fuel cycle.

Continuous recycle strategies can result in significant reductions in the demand for natural uranium, but will depend on the selection of fuel and reactor technologies. The required geologic disposal resources are expected to be significantly lower due to the removal of TRU from the disposal streams.

4.3.3.1 Technology Variations

Continuous recycle strategies are amenable to a wider array of fuel technologies, including both uranium and thorium systems, but also the possibility of liquid fueled systems. By removing any naturally occurring uranium from the fuel cycle, a true thorium fuel cycle can greatly reduce the production of TRU and therefore improve most waste management metrics. The proliferation metrics of such a fuel cycle, however, are similar to those of a uranium breeder cycle that includes separation of plutonium. In order to reduce these proliferation risks, natural uranium could be added to the thorium cycle with a commensurate reduction in performance on the waste management metrics. Liquid fueled systems allow continuous chemical separation during operation, allowing the fuel isotopics to be maintained at an optimum composition over time.

The FY2006 AFCI Comparison Report considers 3 continuous recycle scenarios based on aqueous UREX+ reprocessing[2] for continuous thermal recycle and both UREX+ & pyroprocessing[3] for strategies involving fast reactors. The thermal recycle option is estimated to have a 3x reduction in radiotoxicity and estimated peak dose, with a 10x reduction in repository space requirements. For both fast reactor based systems, there is estimated to be a 100x reduction in radiotoxicity and a 60x-100x reduction in estimated peak dose, with a 10x reduction in repository space requirements. All of these scenarios are anticipated to reduce the amount of weapons-usable material sent to the repository, but does not fully assess the inventory of these materials that are in the fuel cycle at any point in time. Finally, the uranium utilization is expected to improve under all scenarios, with an immediate improvement of up to 15% in the near-term, long-term improvements limited to 20% for the thermal recycle and up to 150x improvement for the fast reactor recycle scenarios.

The GNEP PEIS includes a variety of continuous recycle scenarios and provides lower bound and upper bound estimates of the waste volumes. The lower bound estimates of HLW is up to 39 times smaller than the SNF volume of a OTC, but only 5 times smaller if GTCC waste is included in this estimate. The upper bound estimate shows an 11% improvement in HLW, but a volume of GTCC waste volume that is 6.9 times larger than the SNF volume of a OTC. The continuous recycle scenarios are responsible for generating additional LLW volumes, with estimates between 20 lower and 34 times larger the SNF volumes of a OTC. Finally, these cycles result in small quantities of separated Cs and Sr that must be managed for centuries. The GNEP PEIS also includes a brief discussion of water consumption in which the consumption per reactor is similar for all strategies but estimates of consumption for each separation facility is 10-20 times lower than each reactor. Thus, consumption by reactors will dominate that aspect of the nuclear energy system’s environmental footprint.

---

[2] UREX+ is an aqueous reprocessing technique that extracts the uranium first and then selectively extracts different combinations of TRU and fission products, generally preventing the extraction of attractive special nuclear material.

[3] Pyroprocessing is a high temperature electrochemical batch process that can be configured to extract uranium first and then selectively extract combinations of TRU, leaving behind the fission products, and preventing the extraction of attractive SNM.

4.4 Spent Fuel Management Alternatives

The FY2003 report to Congress included a detailed comparison of different reprocessing technologies and the waste streams arising from those technologies [AFCIComp2003a]. A table of this comparison is reproduced as Table 2 [AFCIComp2003a, Figure 1]. In the context of the strategies used in the more recent Option Study, this tables includes a conventional OTC, represents the limited recycle strategy with the PUREX reprocessing[4] column, and includes an array of other continuous recycle strategies.

Although there is an accounting of of both low-level waste ("primarily comprises raffinates and other process materials ") and secondary waste ("Primarily used/broken equipment in the case of spent fuel treatment processes; contaminated resins from shipping cask decon for the once-through case"), is it not clear how comprehensive these estimates are. Only the PUREX column includes any LLW beyond recycled uranium and cladding hulls. It is unlikely that the other reprocessing technologies will result in no other LLW, particularly considering the annual consumption rate of reagents and other chemicals indicated in the second row. For secondary wastes, the OTC looks worse than all others, with the source being from decontamination of (shipping) casks. However, it is likely that an advanced fuel cycle with centralized reprocessing facilities is likely to require similar number of casks for transportation or storage and hence a similar quantity of secondary waste from this source. In addition, there is no indication of operational releases (liquids or gases) to the environment. While such releases would presumably be regulated to ensure protection public health, some stakeholders would consider these to be important parameters in evaluating the technology options.

At the time of this summary, a primary purpose was to contrast the HLW inventories being sent for disposal, and these fuel cycles indicate a reduction of 4x-9x on the basis of mass, but provides no estimate of how much reduction in disposal space this represents beyond the assumption that no repository beyond Yucca Mountain would be necessary. This table also makes an assessment of proliferation resistance, based primarily on the material attractiveness of separated actinides. There is no consideration for the quantity of separated material, and the comments suggest that the qualitative assessment is relative to the PUREX process rather than the baseline OTC.

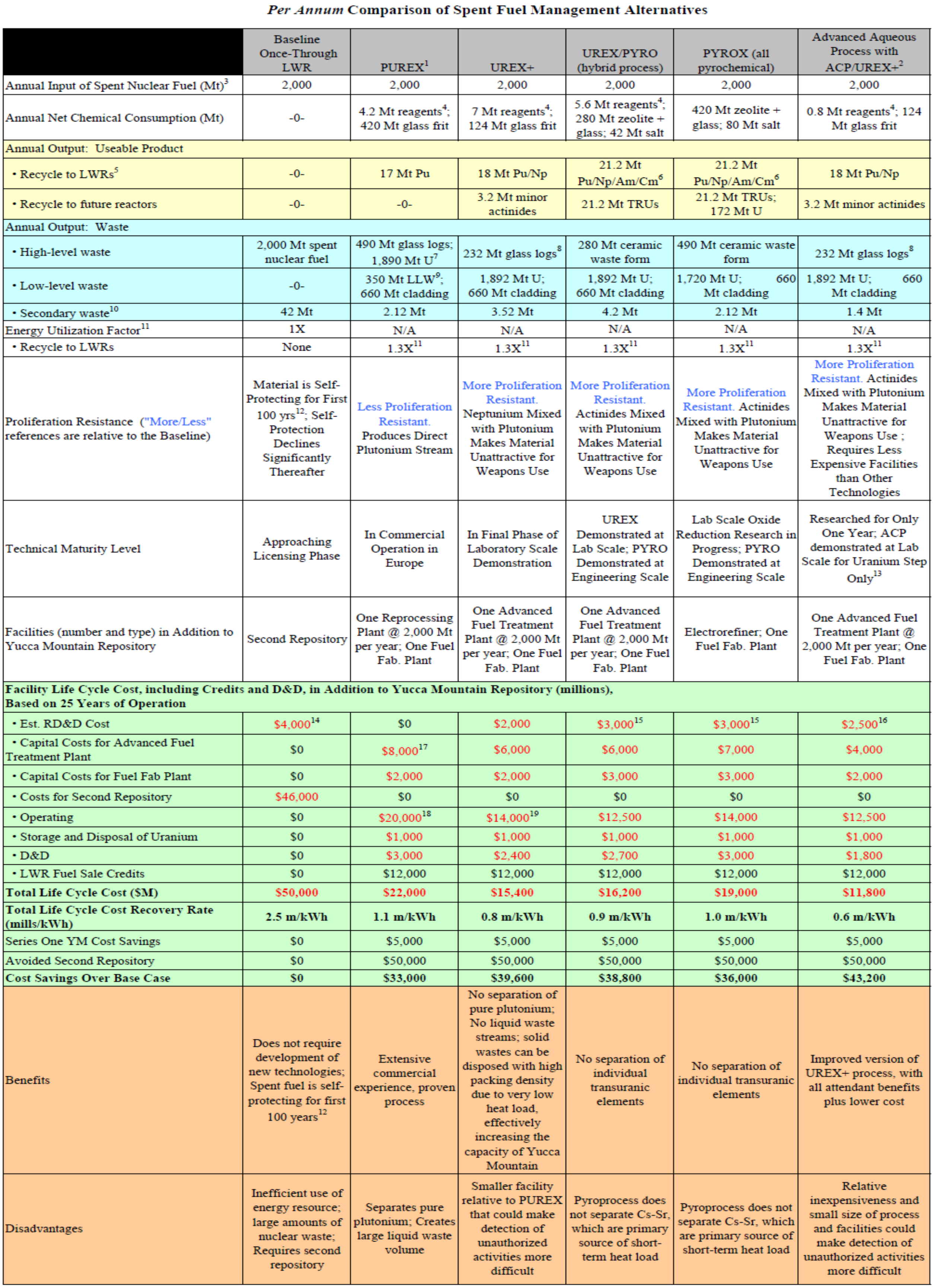
Finally, this table suggests some economic comparison. All of the reprocessing technologies assume that the choice to reprocess will avoid repository costs of $55B and that the actinides that are recycled as fuel will have a value of $12B over the life of the system.   Without these offsetting costs, the various advanced cycles are estimated to have fuel cycle costs between $24B-$34B over their system lifetimes. This does not include the costs of advanced reactor technologies – both RD&D costs and relatively larger capital/operational costs – to take advantage of the recycled actinides.

The FY2006 Comparison Report [AFCIComp2006a] offers ranges for the fuel cycle costs (based on 95% confidence bounds) of 4.3-6.2 $/Mwh for the OTC, 6.7-10.8 $/Mwh for the UREX+ based thermal recycle, and 4.4-7.7 $/Mwh for the fast-rector based thermal recycle. None of these estimates includes additional costs for advanced reactors.

The Options Study includes an analysis of the total cost of electricity that shows that two representative recycle strategies have a mean cost that is about 12% higher than the OTC baseline, and an uncertainty on those costs that is about 20% higher than the OTC baseline. This study produces probability distributions for the total cost of electricity by producing many thousand random samples of the unit costs that make up the total costs, based upon assumed uncertainties in those unit costs [Wigeland2010a, Figure 9]. This assessment of uncertainty is based on the full-width at half-maximum of those distributions.

---

[4] PUREX is an aqueous reprocessing technique that preferentially extracts plutonium.



Per Annum **Comparison of Spent Fuel Management Alternatives**

	Baseline Once-Through LWR	PUREX[1]	UREX+	UREX/PYRO (hybrid process)	PYROX (all pyrochemical)	Advanced Aqueous Process with ACP/UREX+[2]
Annual Input of Spent Nuclear Fuel (Mt)[3]	2,000	2,000	2,000	2,000	2,000	2,000
Annual Net Chemical Consumption (Mt)	-0-	4.2 Mt reagents[4]; 420 Mt glass frit	7 Mt reagents[4]; 124 Mt glass frit	5.6 Mt reagents[4]; 280 Mt zeolite + glass; 42 Mt salt	420 Mt zeolite + glass; 80 Mt salt	0.8 Mt reagents[4]; 124 Mt glass frit
Annual Output: Useable Product						
• Recycle to LWRs[5]	-0-	17 Mt Pu	18 Mt Pu/Np	21.2 Mt Pu/Np/Am/Cm[6]	21.2 Mt Pu/Np/Am/Cm[6]	18 Mt Pu/Np
• Recycle to future reactors	-0-	-0-	3.2 Mt minor actinides	21.2 Mt TRUs	21.2 Mt TRUs; 172 Mt U	3.2 Mt minor actinides
Annual Output: Waste						
• High-level waste	2,000 Mt spent nuclear fuel	490 Mt glass logs; 1,890 Mt U[7]	232 Mt glass logs[8]	280 Mt ceramic waste form	490 Mt ceramic waste form	232 Mt glass logs[8]
• Low-level waste	-0-	350 Mt LLW[9]; 660 Mt cladding	1,892 Mt U; 660 Mt cladding	1,892 Mt U; 660 Mt cladding	1,720 Mt U; 660 Mt cladding	1,892 Mt U; 660 Mt cladding
• Secondary waste[10]	42 Mt	2.12 Mt	3.52 Mt	4.2 Mt	2.12 Mt	1.4 Mt
Energy Utilization Factor[11]	1X	N/A	N/A	N/A	N/A	N/A
• Recycle to LWRs	None	1.3X[11]	1.3X[11]	1.3X[11]	1.3X[11]	1.3X[11]
Proliferation Resistance ("More/Less" references are relative to the Baseline)	Material is Self-Protecting for First 100 yrs[12]; Self-Protection Declines Significantly Thereafter	Less Proliferation Resistant. Produces Direct Plutonium Stream	More Proliferation Resistant. Neptunium Mixed with Plutonium Makes Material Unattractive for Weapons Use	More Proliferation Resistant. Actinides Mixed with Plutonium Makes Material Unattractive for Weapons Use	More Proliferation Resistant. Actinides Mixed with Plutonium Makes Material Unattractive for Weapons Use	More Proliferation Resistant. Actinides Mixed with Plutonium Makes Material Unattractive for Weapons Use ; Requires Less Expensive Facilities than Other Technologies
Technical Maturity Level	Approaching Licensing Phase	In Commercial Operation in Europe	In Final Phase of Laboratory Scale Demonstration	UREX Demonstrated at Lab Scale; PYRO Demonstrated at Engineering Scale	Lab Scale Oxide Reduction Research in Progress; PYRO Demonstrated at Engineering Scale	Researched for Only One Year; ACP demonstrated at Lab Scale for Uranium Step Only[13]
Facilities (number and type) in Addition to Yucca Mountain Repository	Second Repository	One Reprocessing Plant @ 2,000 Mt per year; One Fuel Fab. Plant	One Advanced Fuel Treatment Plant @ 2,000 Mt per year; One Fuel Fab. Plant	One Advanced Fuel Treatment Plant @ 2,000 Mt per year; One Fuel Fab. Plant	Electrorefiner; One Fuel Fab. Plant	One Advanced Fuel Treatment Plant @ 2,000 Mt per year; One Fuel Fab. Plant
Facility Life Cycle Cost, including Credits and D&D, in Addition to Yucca Mountain Repository (millions), Based on 25 Years of Operation						
• Est. RD&D Cost	$4,000[14]	$0	$2,000	$3,000[15]	$3,000[15]	$2,500[16]
• Capital Costs for Advanced Fuel Treatment Plant	$0	$8,000[17]	$6,000	$6,000	$7,000	$4,000
• Capital Costs for Fuel Fab Plant	$0	$2,000	$2,000	$3,000	$3,000	$2,000
• Costs for Second Repository	$46,000	$0	$0	$0	$0	$0
• Operating	$0	$20,000[18]	$14,000[19]	$12,500	$14,000	$12,500
• Storage and Disposal of Uranium	$0	$1,000	$1,000	$1,000	$1,000	$1,000
• D&D	$0	$3,000	$2,400	$2,700	$3,000	$1,800
• LWR Fuel Sale Credits	$0	$12,000	$12,000	$12,000	$12,000	$12,000
Total Life Cycle Cost ($M)	**$50,000**	**$22,000**	**$15,400**	**$16,200**	**$19,000**	**$11,800**
Total Life Cycle Cost Recovery Rate (mills/kWh)	**2.5 m/kWh**	**1.1 m/kWh**	**0.8 m/kWh**	**0.9 m/kWh**	**1.0 m/kWh**	**0.6 m/kWh**
Series One YM Cost Savings	$0	$5,000	$5,000	$5,000	$5,000	$5,000
Avoided Second Repository	$0	$50,000	$50,000	$50,000	$50,000	$50,000
Cost Savings Over Base Case	**$0**	**$33,000**	**$39,600**	**$38,800**	**$36,000**	**$43,200**
Benefits	Does not require development of new technologies; Spent fuel is self-protecting for first 100 years[12]	Extensive commercial experience, proven process	No separation of pure plutonium; No liquid waste streams; solid wastes can be disposed with high packing density due to very low heat load, effectively increasing the capacity of Yucca Mountain	No separation of individual transuranic elements	No separation of individual transuranic elements	Improved version of UREX+ process, with all attendant benefits plus lower cost
Disadvantages	Inefficient use of energy resource; large amounts of nuclear waste; Requires second repository	Separates pure plutonium; Creates large liquid waste volume	Smaller facility relative to PUREX that could make detection of unauthorized activities more difficult	Pyroprocess does not separate Cs-Sr, which are primary source of short-term heat load	Pyroprocess does not separate Cs-Sr, which are primary source of short-term heat load	Relative inexpensiveness and small size of process and facilities could make detection of unauthorized activities more difficult

Table 2 – Annual Comparison of Spent Fuel Management Alternatives (from AFCIComp2003a, Figure 1)

4.5 Public Health Metrics

The GNEP PEIS provides some insight into the cumulative public health impacts of different fuel cycle choices. With the exception of conventional traffic fatalities, these metrics are based entirely on radiological health impacts and use cumulative population exposures and the linear non-threshold theory to derive latent cancer fatalities. It is worth noting that the use of the linear non-threshold theory for this use is one area that is subject to legitimate disagreement among experts as discussed in section 2.6.

Tables S.4-1 offers a summary of the annual occupational health metrics. When comparing a continuous recycle strategy to the OTC baseline, the impact of increased radiation exposure for nuclear facility workers is estimated to result in 1 or 2 additional latent cancer fatalities per year (from a OTC baseline of 13 LCFs/yr) across the whole industry. The increased transportation of radioactive materials in continuous recycle strategies will cause increased radiation exposure to workers involved in those activities, with an impact of an additional 7 or 8 LCFs per year across the whole industry if using only trucks (from a OTC baseline of 2 LCFs/yr). This number is only 2-4 with a combination of rail and trucks (from a OTC baseline of 0 LCFs/yr).

The risk to the public from normal operation and accidents at nuclear facilities is also assessed in the GNEP PEIS. All alternatives are estimated to result in less than 1 additional LCF per year from normal operation, including the impact of routine radiological releases. All reactor technologies are judged to have a lower accident risk than existing reactors due primarily to reductions in the consequences of such accidents. Table S.4-4 indicates that even when the estimated frequency of the maximum consequence accident is 4 orders of magnitude higher, the overall risk is lower since the radiological consequences are much lower (from a OTC baseline of 1 LCF/500 yrs). The same is true for the highest risk accidents as shown in Table S.4-5. The risk for a nuclear fuel recycling center is estimated to be 2 times lower than the risk for a conventional light water reactor (~1 LCF/1000 yrs). Finally, the risk to the maximally exposed individual is also lower for all reactor technology options and for nuclear fuel recycling centers.

The increased transportation needs will also result in larger impacts for the public, but all scenarios have between 1 and 4 additional LCF per year for the 50 years span of the scenario. These all come from exposure during incident-free transportation. If traffic incidents are included, the radiological consequences are estimated to be less than 1 additional LCFs over 50 years, but up to 75 additional collision fatalities in 50 years.

5 Comparison of systems analysis tools

Due to the importance of studying the impacts of nuclear fuel cycle technologies on the entire nuclear energy system and the complexity of predicting these impacts, there are a number of efforts, both historical and contemporary, to develop software tools to aid in this systems analysis. The simplicity of the physical models necessary to capture the dominant effects of each individual technology facilitate this proliferation of tools, but the complexity in how the system models are assembled leads to the differences among them. While there are many subtle differences when comparing any two of these tools, they are a number of fundamental characteristics that can be used to group these tools into distinct categories.

In most cases, the systems model is based on continuous mass flows among fleets of facilities that all operate in an identical fashion. While this does still allow the study of system dynamics, it requires all facilities to operate with an average behavior and can cause particular difficulty when matching supplies of separated material with desired fuel compositions for advanced reactor systems. The alternative, a paradigm based on modeling discrete facilities and discrete transactions of material allows a more fine-grained analysis, but must deal with much larger quantities of information.

A range of computational platforms are used for these tools. The simplest models rely on spreadsheets for the bulk of their computation, often with some kind of macro programming to provide more complex behavior. The most heavily used models use proprietary systems dynamics software tools (e.g. iThink, PowerSim) that are designed specifically for studying the time evolution of systems of differential equations. In many cases, a complete model of an advanced nuclear fuel cycle is one of the biggest models every developed under these software systems. Finally, other tools are implemented using some general programming language, from high-level languages like Matlab© to traditional languages like Java and C++. In general, spreadsheet-based models are the most limited in their complexity and flexibility, and often incorporate more assumptions. At the other end of the spectrum, traditional programming languages offer the most complexity and flexibility in their models, allowing for fewer assumptions, but also requiring a different set of skills for development.

Few, if any, of the tools have robust models for the ultimate handling of waste streams, choosing instead to describe the accumulation of different waste stream masses and their compositions. Most of the metrics for nuclear waste management described above are dependent on these quantities alone, or in concert with information about the behavior of the waste form that is used for disposal.

5.1 Brief Descriptions

Most useful fuel cycle simulation tools have evolved over their life to become relatively sophisticated models that involve a complex network of material flows among a long list of facilities. A complete description of each would require more space than available here, but the following brief descriptions aim to provide some context for understanding the important features, limitations and scope of each.

5.1.1 VISION (INL)

The Verifiable Fuel Cycle Simulation (VISION) model [Jacobson2009a], developed primarily by Idaho National Laboratory, is the leading tool used by the Department of Energy to provide insight into mass flows, material distributions and economic assessments of advanced fuel cycles. VISION is implemented with continuous flows and fleets of facilities using the PowerSim systems dynamics software. These modeling environments are based on the concept of stocks and flows, requiring all systems to be modeled as some set of first-order differential equations. Feedbacks are available by making equation parameters depend on the current value of a stock, flow or other variable in the problem. Although it hasn't been used as extensively to provide analyses for the advanced fuel cycle R&D program, the newest version of VISION (v3.0), allows 10 different reactor types in a single simulation, tracks 81 different isotopes, permits annual changes to the fuel composition of each reactor fleet, and annual changes to the separation matrix of each of 10 separations facility types. VISION determines the quantity of separated material that is used to fabricate new fuel based on the user's selection of which isotopes should be most limiting. The user must specify the growth rate and/or deployment schedules of new facilities, with some algorithms available to automate these under certain assumptions. The outputs include the total capacity of any type of facility over the domain of analysis (typically 100 years) and the mass flows and material stocks during that same time frame. Economic assessment is carried out by a separate post-processing module that uses the mass flows and tabulated unit costs to calculate total system costs, with the provision for brute-force uncertainty propagation by generating thousands (typically 10,000) random realizations of the economic parameters.

5.1.2 DANESS (ANL)

The Dynamic Analysis of Nuclear Energy System Strategies (DANESS), developed primarily at Argonne National Laboratory, is very similar to VISION in most of its paradigms, and is implemented in the iThink/Stella systems dynamics software platform. Its design has evolved with improvements to its underlying modeling environment and now has a hierarchical design with physics models, systems models, assessment methods and policy analysis occurring at different layers of that hierarchy. One of the most important differences is that DANESS includes a variety of decision-making algorithms to govern facility deployment and material ordering. These algorithms attempt to model the financial decision making of institutions that would operate nuclear facilities, based on knowledge of the current market conditions and the evolution of those conditions over some future time frame. In addition, DANESS offers more flexibility in the time evolution of reactor-fuel combinations than VISION.

5.1.3 CAFCA (MIT)

The Code for Advanced Fuel Cycles Assessment (CAFCA) has been developed at MIT, initially to support their high-level assessments on nuclear energy and more recently, their report on the nuclear fuel cycle [CAFCA2006a]. Original versions were developed using Matlab© to track the flow of uranium and transuranics through a nuclear energy system that includes a combination of light water reactors and fast reactors. The newest version, CAFCA-SD, uses the VENSIM systems dynamic platform to model the nuclear fuel cycle as a continuous flow among fleets of homogenous facilities. CAFCA has been developed with a problem-based design, adding features and capabilities to address a series of specific simulations of interest to its developers. Rather than a general form of the input, many of the parameters are embedded in the software itself, making it difficult to adapt to a more general set of nuclear energy systems. It is limited to exponential growth of nuclear generation and includes a number of implicit assumptions to determine the deployment schedule of other facilities, especially recycling facilities. Users can also override the recycling facility deployment schedule, and the fast reactor deployment will respond accordingly to minimize the possibility of reactor shutdown due to lack of available fuel. CAFCA also includes some capability for multi-region analysis with trade of materials between pairs of regions. Economic assessment is performed for the whole fuel cycle using a range of specific economic models for each of the facility types.

5.1.4 NUWASTE (NWTRB)

The Nuclear Waste Technical Review Board (NWTRB) has recently developed the Nuclear Waste Assessment System for Technical Evaluation (NUWASTE), based on their long experience with analyzing the performance of spent fuel disposal systems [NUWASTE2010a]. NUWASTE is developed in the Microsoft® Access database environment, with additional functionality provided by Microsoft® Visual Basic functions. This software models individual reactor facilities throughout their operational life and the discrete shipments of fuel to/from those facilities. This software is focused on the repository impacts of a limited recycle scenario based only on Pu MOX fuel. It has a long list of parameters that govern each stage in the fuel cycle, but a smaller list of parameters that govern how the system itself is assembled.

The NWTRB makes two important assumptions in their model that only considers the use of thermal recycling based on mixed oxide (U and Pu) fuel. First, all back-end facilities draw spent nuclear fuel from storage in an attempt to maximize their utilization. That is, once a repository comes online with a fixed emplacement capacity, that repository will remove material from storage as quickly as possible to consume that capacity.

The same is true for reprocessing facilities. Second, reprocessing facilities have priority for access to spent nuclear fuel. The outcome is that a repository will reduce its utilization to allow a reprocessing facility to maximize its utilization.

5.2 *Benchmark exercises*

A number of benchmark exercises have begun to compare the results of different systems analysis tools, however they are challenged by many of the issues identified above. As such, these benchmarks cover a narrow range of scenarios and include a small set of metrics.

The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) has developed a benchmark in support of its goal of helping member nations study their possible fuel cycle transitions [NEA2011a]. This benchmark includes a depletion component and a transition component. The depletion phase provides a benchmark to isolate the impacts of individual nuclear fuel depletion calculations. Some systems analysis tools incorporate depletion calculations (describing the isotopic evolution of the nuclear fuel during irradiation in a reactor) within their frameworks and others consider them a separate calculation, the results of which are part of the input for the systems analysis. Therefore, this phase allows participants to isolate this important aspect of isotopic tracking that is part of all systems analysis. The transition phase describes specific combinations of reactor and separations technology, deployed with a specific timeline. A collection of different mass flows and isotopic compositions are used for comparison purposes. In addition to VISION, described above, there was participation from Japanese (FAMILY), Spanish (EVOLCODE), French (COSI) and Russian (DESAE) research organizations. The results of this exercise show that each software tool produced similar trends, with growing divergence in the numerical results as the fuel cycle complexity increased. An iterative process was necessary to arrive at a consistent set of input assumptions. Periods of equilibrium had larger agreement than transition periods.

MIT also conducted a benchmarking exercise that included participation by MIT (CAFCA-SD), INL (VISION), ANL (DANESS), and CEA (COSI) [MIT2009a]. All scenarios involved a transition to advanced fuel cycle strategies, with varying technologies and varying nuclear energy growth rates. As with the NEA study, the trends produced by each tool were similar and led to similar conclusions, but the quantitative results do show some discrepancies. Iteration to a set of input assumptions that would result in comparable results was only performed for a single scenario. Other scenarios were performed without such interaction and showed similar trends but expected differences in the details. This benchmark exercise concluded that different tools will generally lead to the same conclusion, even if the different assumptions (that might reflect different assumed industrial practices) lead to different detailed results.

6 Summary

Despite the challenges identified in section 1.3, most systematic analyses of advanced fuel cycles have similar conclusions. Increasing burnup in once through fuel cycles has a small impact on most metrics: it may have incremental improvements that are commercially attractive, but indicate a need for widespread policy changes. Thermal recycle in light water reactors is found repeatedly to offer only modest benefits in some waste management and resource consumption metrics, while negatively impacting other waste management metrics, posing at least an incremental reduction in proliferation resistance, and with a high likelihood of increased cost. The lack of commercial interest in unsubsidized thermal recycling in the United States is a further indication of these findings. Continuous recycling strategies, involving fast reactors, can be configured to reduce the amount of TRU that is sent to the repository, but have a small impact on the amount of TRU that exists in the fuel cycle. A substantial quantity of other waste streams would also arise from these fuel cycles and many of those waste streams do not yet have final disposal pathways. The economic uncertainty is higher for these fuel cycles, but they are likely to be more expensive. Similarly, the impact on proliferation metrics is varied, but implementing sufficient safeguards to accommodate the increased inventories of separated special nuclear material may have economic consequences. These findings do not support a near-term transition to advanced fuel cycles.

7 References

[Wigeland2009a] Wigeland, R, T. Taiwo, M. Todosow, W. Halsey, J. Gehin, "AFCI Options Study", INL/EXT-10-17639, Idaho National Laboratory, (September 2009).

[Wigeland2010a] Wigeland, R, T. Taiwo, M. Todosow, W. Halsey, J. Gehin, "Options Study – Phase II", FCRD-TIO-2010-000167, U.S. Department of Energy Report (September 2010).

[AFCIComp2003a] "U.S. Department of Energy, Office of Nuclear Energy, Science and Technology, Advanced Fuel Cycle Initiative (AFCI) Comparison Report, FY2003" (October 2003)

[AFCIComp2006a] "U.S. Department of Energy, Office of Nuclear Energy, Advanced Fuel Cycle Initiative (AFCI) Comparison Report, FY 2006 Update" (July 2006)

[GNEPPEIS2008a]"Draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement, Summary," DOE/EIS-0396, U.S,. Department of Energy (October 2008)

[Sovacool2009a] Sovacool, B.K. and K.E. Sovacool, "Preventing National Electricity-Water Crisis Areas in the United States," *Columbia Journal of Environmental Law*, 34 (2), pp 333-393 (2009)

[Jacobson2009a] Jacobson, J.J., R.F. Jeffers, G.E. Matthern, S.J. Piet, B.A. Baker, "VISION User Guide: VISION (Verifiable Fuel Cycle Simulation) Model," INL/EXT-09-16645, Idaho National Laboratory, (August 2009)

[CAFCA2006a] Aquien, A., "Fuel Cycle Options for Optimized Recycling of Nuclear Fuel," M.S. Thesis, Massachusetts Institute of Technology, Cambridge, MA (June 2006).

[NUWASTE2010a] U.S. Nuclear Waste Technical Review Board, "Nuclear Waste Assessment System for Technical Evaluation (NUWASTE) – System Overview," NUWASTE-005, (March 2010).

[NWTRB2010a] Personal communication with NWTRB staff (might want to seek reference on this).

[NEA2011a] Boucher, L., "NEA/NSC/WPFC Expert group on fuel cycle transitions scenarios benchmark on Scenario codes report," Nuclear Energy Agency, Paris, France (2009?)

[MIT2009a] Guérin, L., *et al*, "A Benchmark Study of Computer Codes for System Analysis of the Nuclear Fuel Cycle," MIT-NFC-TR-105, Massachusetts Institute of Technology, Cambridge, MA (April 2009)

[USNRC2011] "NRC: Special Nuclear Material" U.S. Nuclear Regulatory Commission [http://www.nrc.gov/materials/sp-nucmaterials.html] (accessed: February 27, 2011)