Dynamic Systems Analysis Report for Nuclear Fuel Recycle

Advanced Fuel Cycle Initiative

Prepared for
U.S. Department of Energy

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EXECUTIVE SUMMARY

This report examines the time-dependent dynamics of transitioning from the current United States (U.S.) nuclear fuel cycle where used nuclear fuel is disposed in a repository to a closed fuel cycle where the used fuel is recycled and only fission products and waste are disposed. The report is intended to help inform policy developers, decision makers, and program managers of system-level options and constraints as they guide the formulation and implementation of advanced fuel cycle development and demonstration efforts and move toward deployment of nuclear fuel recycling infrastructure.

The analyses in this report have highlighted a number of key findings associated with nuclear energy growth and fuel cycle transitioning. These findings are discussed in this summary and may be found in a bulleted list in Section 6.1 of the main report.

The report opens with a summary of advanced fuel cycle objectives and goals from the Global Nuclear Energy Partnership (GNEP) and its predecessor programs. These objectives and goals provide the basis for assessing fuel cycle system performance in the analyses that follow.

To understand the magnitude of potential nuclear energy growth, energy demand and nuclear competitiveness are assessed. Long-range global energy models based on the U.S. Climate Change Science Program Reference Scenario project a five-fold increase in world electricity consumption by the end of the century. The Reference Scenario indicates nuclear energy is competitive with other energy sources and shows an increasing reliance on nuclear energy later in the century, with the world's nuclear share of the electricity market rising from the current 16% to 20% and the United States' share rising from 20% to 25%.

Actions to reduce carbon dioxide emissions to address climate change significantly increase projected growth of nuclear energy and other low-carbon energy sources. Figure ES-1 shows the change in sources of electricity generation when a CO_2 emissions constraint is applied globally and carbon capture and storage (CCS) technologies are successfully developed for use with fossil fuels. The Reference Scenario shown in Figure ES-1 is based on the *Scenario of Greenhouse Gas Emissions and Atmospheric Concentrations* from the U.S. Climate Change Science Program [Clarke2007], which incorporates the most up-to-date historical information and assumptions regarding future demographics, socioeconomic parameters, and energy use, and thus, employs an important reference baseline for long-term global energy and economic analysis. With CCS, nuclear energy market share increases to 33% of electricity generation globally and 41% domestically. Without CCS technologies, nuclear energy market share increases to 50% globally and 58% domestically. These analyses do not consider non-electric

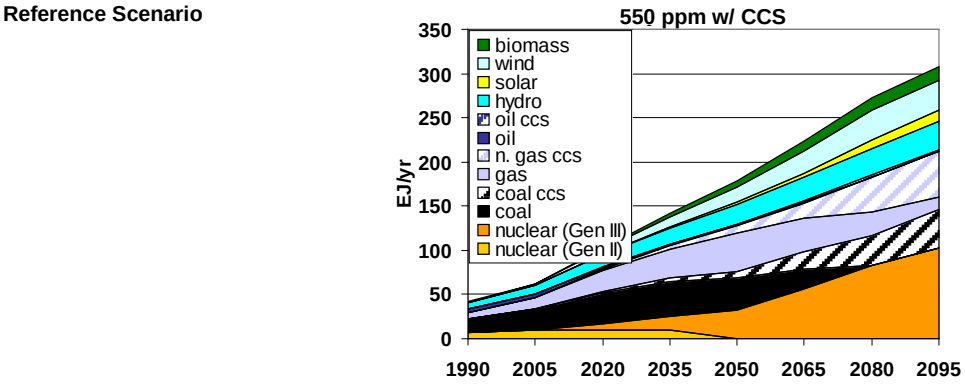

Figure ES-1. Global electricity generation without carbon constraints and with a CO_2 emissions constraint designed to stabilize atmospheric CO_2 at 550 ppm.

applications of nuclear energy that may generate additional growth, such as transportation, water desalination, chemical industry, direct steam used for district heating, or resource extraction (tar sands).

While these analyses using the once-through fuel cycle and a global energy simulation indicate the significant value of nuclear energy as one of the key tools for reducing CO_2 emissions to address climate change, they also show huge increases in uranium demand and used fuel inventories. The impact of deploying a GNEP advanced fuel cycle to address these system demands is assessed in the report based on transitioning to recycling in the U.S. (global transition studies are planned as a future Systems Analysis activity). The domestic analyses address the system design and deployment challenges for a closed fuel cycle to be economically deployed in the U.S. to meet energy demands while minimizing the impact on natural resources and the environment. Analyses consider key issues such as timing, constraints, and costs.

U.S. energy growth is projected by extending the 25-year growth rates generated by the Energy Information Agency's Annual Energy Outlook reports, while nuclear growth is nominally assumed to be 1.75%/year (starting in 2015), which is sufficient to achieve 28% electricity market share by the end of the century (this U.S. market share is similar to that projected by the global model Reference Scenario, which calculates growth rates dynamically based on demand curves and competing energy technologies. Sensitivity studies also assess higher and lower growth rates and associated market shares). With projected nuclear energy growth in the U.S., a once-through fuel cycle will require ~4,200,000 tonnes of additional uranium by the end of the century and generate an additional ~410,000 tonnes of used fuel, including 5,300 tonnes of transuranics (or TRU – elements heavier than uranium), needing geologic disposal.

The impact of advanced fuel cycle technologies on these numbers is highly dependent on the rate of deployment of separations facilities and fast reactors. (Fast refers to the energy spectrum; current commercial light water reactors, or LWRs, are thermal energy spectrum reactors). The size and timing of uranium oxide (UOX) used fuel separations facilities is the primary driver behind the rate of deployment of TRU-burning fast reactors. The fast reactor deployment rate in turn impacts the amount of TRU both generated and consumed.

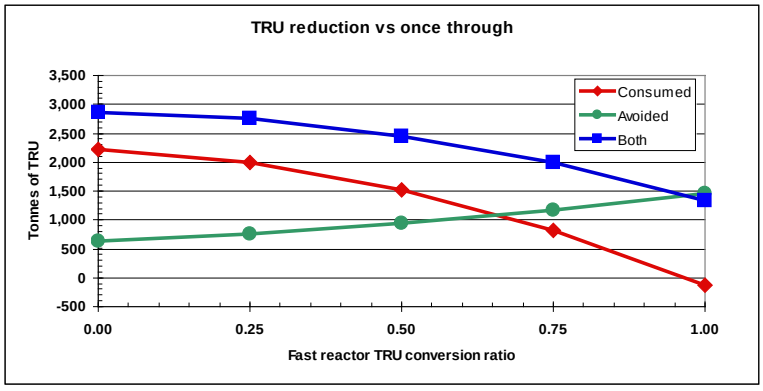

Figure ES-2. Transuranics reduction between 2000 and 2100 with a 1-tier fuel cycle as a function of conversion ratio.

Fast reactor deployment rates will be much lower than the levels predicted by simple "equilibrium" calculations due to multiple system constraints that impact the amount of TRU available for fueling new reactors at startup. Sensitivity studies have identified the most important constraints (in order) to be separations capacity and timing, nuclear growth rate, fast reactor TRU conversion ratio (the ratio of the mass of transuranic isotopes created over those destroyed during fuel irradiation; fast reactors can operate with TRU conversion ratios both below and above 1.0.), used fuel cooling time, and fast reactor introduction timing. In a 1-tier system (where recycling takes place in fast reactors only) with fast reactors at a TRU conversion ratio of 0.5, over 75% of the reactor fleet will still be LWRs in 2100. A 2-tier system (where recycling takes place first in thermal reactors, then in fast reactors) with a mixed oxide uranium/plutonium fuel (MOX-Pu) recycle stage in LWRs imposes additional constraints that result in

over 90% LWRs in 2100. These additional constraints are related to the time required for the MOX-Pu cycle, including both fuel irradiation and cooling.

Transuranics are important for two reasons: they can substitute for uranium in fuel, and they are the primary contributors to long-term waste management impacts. TRU management needs to account for both the TRU consumed in fast reactors and the additional TRU generation avoided due to fast reactors replacing some LWRs. Each factor reduces TRU quantities by over 1,000 tonnes during the century (versus once-through). The more TRU "at work" in fast reactors, the more total TRU is reduced. Figure ES-2 shows the impact on TRU management as a function of fast reactor transuranic conversion ratio.

The early phases of transitioning from once-through to a closed fuel cycle require extra flexibility to address uncertainty in initial facility sizes and timing that can drive material supply/demand mismatches. For example, a later date for initial fast reactor deployment in a 1-tier system can result in large inventories of separated TRU requiring secure storage, unless MOX-Pu is used in LWRs (an interim 2-tier system) or separations deployment is also later (which moves the system back toward the status quo of excess used fuel in storage).

The location of used fast reactor fuel recycling facilities (onsite versus centralized) also has a significant impact on the rate of fast reactor deployment, impacting the amount of TRU tied up in used fuel due to the added cooling time required for efficient transportation (transportation of used fuel is often decay heat limited, with minimum cooling times required to ship full casks).

The costs associated with facility construction and operations for the once-through, 1-tier, and 2-tier fuel cycles were analyzed to determine both total costs and the relative share for each system coming from the fuel cycle front end and back end and the reactors. A closed fuel cycle employing advanced technologies is projected to increase the total system cost of nuclear-generated electricity by only 5 to 6 $/MWh (~10%), but the cost uncertainties are large. The primary contributor to the increased cost is the projected capital cost of fast reactors, with fuel recycling costs contributing between 20 to 40% of the total cost difference.

Costs were also compared to competing base-load electricity generation systems. With either an open or closed fuel cycle, nuclear costs are projected to be competitive with fossil fuels with or without a carbon tax, and the total cost uncertainties for nuclear (although large) are less than the cost uncertainties of fossil fuel energy systems.

The once-through fuel cycle consumes less than 1% of mined uranium, with the rest left in enrichment tails and used fuel. Recycling of used fuel allows for slightly more of the uranium to be consumed, but 100% of the depleted uranium from enrichment and 99% of the uranium recovered from used fuel remains unused at a fast reactor conversion ratio of 0.50.

Dynamic analyses show that transitioning to a closed fuel cycle only reduces uranium needs in this century by ~750,000 tonnes (~18%), assuming fast reactors with a TRU conversion ratio of 0.5.

Sensitivity analyses were performed to determine the most significant parameters associated with uranium usage. Figure 3 shows the combined impact of growth rate and conversion ratio on uranium consumption by the end of the century. Uranium usage is improved when higher conversion ratio fast reactors are deployed, but large savings will not occur until the next century unless fast reactor conversion ratios are substantially greater than 1. This figure also shows the large difference in results obtained when dynamic analysis is used versus static analysis. Dynamic analysis includes facility life, startup material requirements, and other factors that constrain the rate of transition of systems. These constraints are not considered in static analysis, often resulting in larger overestimates of the near-term impact of closed fuel cycle systems.

The impact of transitioning to a closed fuel cycle on waste management is large. Sensitivity analyses on the efficiency of recycling facilities show both the long-term radiotoxicity and long-term decay heat of waste from recycled fuel needing geologic disposal reduced by more than a factor of 100 versus once-through if uranium and TRU losses to waste could be held below 0.5% (see Figure ES-4). These improvements reduce the time the waste is more radiotoxic than uranium ore from ~300,000 years to ~300 years, while making space-efficient geologic disposal much easier.

Figure ES-3. Static and dynamic analysis of uranium usage improvement factors relative to once-through as a function of both growth rate and conversion ratio.

The analyses presented in this report provide answers to a number of questions concerning the transition to an advanced fuel cycle. Dynamic analyses can be used to evaluate the constraints that inhibit the rate of transition to a recycling system.

The report also indicates where additional analyses would be beneficial. Areas of future analysis and tradeoff studies include:

- Assessing the impact of advanced fuel cycle cost differentials on domestic and global projections of nuclear energy growth
- Assessing phased fuel cycle transition options, including the initial fielding of mature technologies followed by a later phase-in of advanced technologies
- Supporting major technology decisions and requirements development through integrated analyses

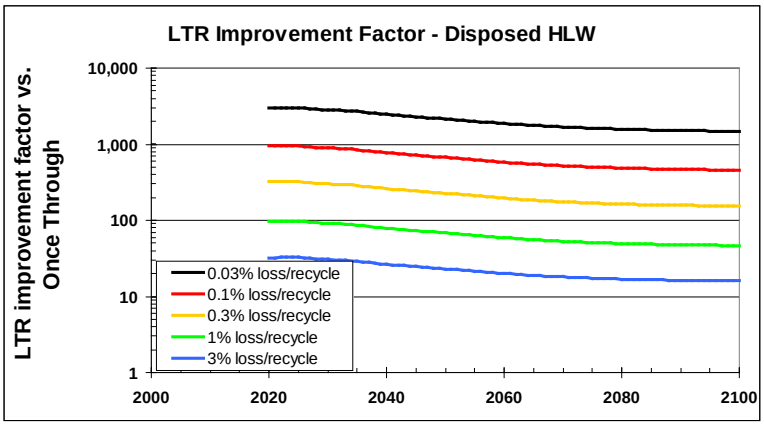

Figure ES-4. LTR improvement factors for 1-tier versus once-through at different recycle efficiencies.

- Extending the types of analyses provided while expanding the scope to include the impacts of expansion of nuclear energy beyond electricity generation, and assessment of global transitions including fuel take-back systems and grid appropriate reactors.

CONTENTS

FIGURES

TABLES

ACRONYMS AND UNITS

AAA	Advanced Accelerator Applications
AFCI	Advanced Fuel Cycle Initiative
Ag	Silver
ANL	Argonne National Laboratory
Am	Americium
ARR	Advanced Recycling Reactors
ATW	Advanced Transmutation of Waste
BTC	Billion Tonnes Carbon
^{14}C	Carbon-14
CCS	Carbon Capture and Storage
CCSP	U.S. Climate Change Science Program
CFR	Code of Federal Regulations
Cf	Californium
CR	Fast reactor transuranic conversion ratio
CO_2	Carbon dioxide
COL	Combined License for reactor construction and conditional operation
Cm	Curium
CR	Conversion Ratio
Cs	Cesium
CY	Calendar Year
D&D	
DOE	Department of Energy
DPL	Decision Programming Language
DSARR	Dynamic Systems Analysis Report for Nuclear Fuel Recycle
DU	Depleted uranium
EAWG	Economic Analysis Working Group
Echem	Electrochemical separation, also known as pyroprocessing
EIA	Energy Information Agency
EJ	Exajoule (10^{18} joules), equivalent to ~280 million MWh or ~32 GWe-year
EPACT	Energy Policy Act
DU	depleted uranium
FCCG	Gen IV Fuel Cycle Crosscut Group
FOAK	first-of-a-kind
FP	Fission Products
FPY	Full Power Year
FR	fast reactor
GBZ	Glass Bonded Zeolite waste form
GDP	Gross Domestic Product
GHG	greenhouse gas
GNEP	Global Nuclear Energy Partnership
GTCC	greater-than-class-C waste, a classification of low level waste
GWd	Gigawatt day
GWe	Gigawatt electric, a unit of power, e.g., nuclear power plant capacity
GWe-year	Gigawatt electric year, equivalent to 8,766,000 MWh
GWth	Gigawatt thermal
GWth-day/ tonne-HM	Gigawatt thermal day per tonne heavy metal (equivalent to MWth-day/kg-HM)
GWd/MTiHM	Gigawatt day per tonne initial heavy metal
G4-ECONS	Generation IV Excel Calculations of Nuclear Systems

^{3}H, H-3	Tritium
HLW	high-level waste
HM	Heavy metal, includes uranium and transuranic elements
I	Iodine
IAEA	International Atomic Energy Agency
iHM	Initial heavy metal, the mass of heavy metal prior to irradiation
INL	Idaho National Laboratory
Kr	Krypton
kWe	Kilowatt electric
LLW	low-level waste
Ln, La	Lanthanide
LTH	long-term decay heat, a metric describing the heat committed to waste disposal from time of repository closure to ~1500 years
LTR	long-term radiotoxicity, a metric describing the radiotoxicity of isotopes at a specific time after repository emplacement
LWR	Light-Water Reactor
MA	Minor Actinides, actinides other than Pu
Mtn	Mountain
MOX	mixed oxide fuel, a mixture of uranium oxide and one or more transuranic element oxides (e.g., MOX-Pu or MOX-TRU)
MT	metric ton (tonne) (1000 kg)
MTiHM	metric ton initial heavy metal (see initial heavy metal above)
MTU	Million tonnes uranium
MWth-day/ kg-HM	Megawatt thermal day per kilogram heavy metal, a unit of burnup, i.e., energy per mass of fuel. Equivalent to GWth-day/tonne-HM
MWh	Megawatt-hour
NOAK	n^{th}-of-a-kind
NRC	Nuclear Regulatory Commission
NU	Natural uranium, 0.7% U-235
O^{bj}ECTS	Object-oriented Energy, Climate, and Technology Systems
OECD	Organisation for Economic Cooperation and Development
O&M	Operation and Maintenance
Pa	Protactinium
ppm	Parts per million
Pu	Plutonium
Ra	Radium
RU	Recovered uranium, uranium separated as a product from used nuclear fuel
SF	Spent Fuel, also called used fuel
SNF	spent nuclear fuel, also called used fuel
Sr	Strontium
SS	Stainless Steel
t	Tonne (metric ton), 1000 kg
TA	Transmutation Analysis
Tc	Technetium
TCOE	total cost of electricity
Th	Thorium
THORP	Thermal Oxide Reprocessing Plant (located at Sellafield, England)
TIO	Technical Integration Office
TR	Thermal Reactor
TRU	transuranic elements (neptunium, plutonium and higher on periodic table)
U	Uranium

UDS	Undissolved Solids, remaining solid material after fuel dissolution step of aqueous separation processes
UNFCCC	United Nations Framework Convention on Climate Change
U_3O_8	Tri-Uranium octa-Oxide
UOX	uranium oxide fuel
UREX	Uranium Extraction
UREX+1	UREX producing U, and all-TRU as product streams and several sets of fission products as individual waste streams
UREX+3	UREX producing U, NpPu, and AmCm as product streams and several sets of fission products as individual waste streams
UREX+4	UREX producing U, NpPu, Am, and Cm as product streams and several sets of fission products as individual waste streams
U.S.	United States
USD	United States Dollars
VISION	**V**er**i**fiable Fuel Cycle **Si**mulati**on**, a dynamic simulation of the nuclear fuel cycle
VISION.ECON	Economics submodel of Verifiable Fuel Cycle Simulation
Xe	Xeon
Zr	Zirconium

System Analysis Campaign
Dynamic Systems Analysis Report For
Nuclear Fuel Recycle (DSARR)

1. INTRODUCTION

The U.S. Department of Energy (DOE) has been researching technology to evolve the commercial nuclear fuel cycle to better meet the needs of energy and economic security and environmental sustainability. This report examines the time-dependent dynamics of the evolutionary pathways for three possible fuel cycles:

- Once-through fuel cycle: Continue to use nuclear fuel once in Light-Water Reactors (LWRs) and then dispose of it
- 1-tier closed fuel cycle: Recycle LWR used nuclear fuel in fast spectrum reactors systems that also continuously recycle the fast reactor used fuel
- 2-tier closed fuel cycle: Recycle LWR used nuclear fuel once in LWRs followed by continuous recycling in fast reactors.

Analyses address the role of U.S. nuclear energy in the broader electricity context, how the transition to the three different fuel cycles would work, and the impacts of those fuel cycles on economics, uranium supply, and waste management. Proliferation resistance and physical protection of material, details of technologies, and designs of potential facilities are addressed by other GNEP campaigns and projects.

1.1 Purpose of DSARR

The purpose of this report is to provide the reader with an improved understanding of the important system-level concepts, parameters, and ramifications associated with potential future evolution of the U.S. civilian nuclear energy infrastructure. The report provides the results of systems assessments associated with the expansion of nuclear energy and the transition from the current once-through nuclear fuel cycle to a closed fuel cycle based on advanced fuels, separations, and reactor technologies. The analyses reveal the dynamic interactions of nuclear facilities and associated material flows and economics and demonstrate how the system is constrained by these interactions as it grows and transitions.

The report is intended to help inform policy developers, decision makers, and program managers of system-level options and constraints as they guide the formulation and implementation of advanced fuel cycle development and demonstration efforts and move toward deployment of a nuclear fuel recycling infrastructure.

The report provides information on how projected global nuclear growth rates will drive increased demands for uranium and nuclear waste management, and then examines the impact of transitioning to nuclear fuel recycling as a means of reducing both. Transition analyses include assessment of the physical and economic constraints on new technology deployment and how these constraints impact the rate of deployment and the accrual of recycling benefits.

The approach and analyses in this report are consistent with and complimentary to other reports addressing fuel cycle technology development (the Global Nuclear Energy Partnership [GNEP] Technology Roadmap [GNEP 2007]) and waste management (the GNEP Integrated Waste Management Strategy [Gombert 2008]). Together these reports provide a breadth of information on the feasibility and impact of implementing an advanced closed nuclear fuel cycle.

1.2 Systems Analysis Description

Systems analysis is used to assess integrated performance of complex systems, such as advanced nuclear fuel cycle systems, from an analytical perspective, following a phased approach for identifying, defining, evaluating, and refining the goals, technical options, requirements, architecture, and workscope of a project or program.

During the discovery phase, systems analysis provides the set of tools needed to define program goals, to analyze credible technical options, and to ensure that the options are compatible and meet the program objectives.

During the definition phase, these technical options must be optimized. This is achieved through deployment studies to show where and when facilities can be built and identifying infrastructure requirements; economics studies that integrate all the phases of the program, including costs, uncertainties and benefits (including externalities, if possible) in an economically justifiable manner; and a process to down-select between alternative technologies.

During the deployment phase, classical systems engineering is employed to integrate the program in a hierarchical manner, including formal requirements management, project scheduling, risk management, and benefits analysis all focused on achieving program objectives.

The DOE nuclear fuel cycle systems analysis activity is now moving from the discovery phase to the definition phase, in parallel with the program moving from a primarily research-focused effort to an effort focused on moving forward toward demonstration facilities. Appendix A includes a more complete description of current systems analysis activities, including the approach, methods, and tools used. Appendix B contains a bibliography of selected systems analysis reports.

1.2.1 Review of Prior Systems Analysis Activities

The Department's ongoing systems analysis effort directed at nuclear fuel cycle analysis began in 2001 as part of the Generation IV road-mapping activity (DOE 2003), which assessed advanced reactors and their associated fuel cycle systems, and the Advanced Accelerator Applications (AAA) program (DOE 2001), which assessed methods to transmute transuranic elements.

In 2003, the AAA program was expanded into the Advanced Fuel Cycle Initiative (AFCI) to address a range of advanced fuel cycles. As directed by Congress, "[t]his program subsumes the Advanced Accelerator Applications program and its activities and will focus on the development of advanced fuel cycles, including recycle or reprocessing of spent[a] fuel, and transmutation technologies" (Senate 2003). The systems analysis activity within the AFCI program has produced several reports provided to Congress on advanced fuel cycle systems. These include:

- A report issued in January 2003 describing the Department's spent fuel recycling research program (*Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research* [DOE 2003a]).
- A report issued in May 2005 providing quantitative goals and performance objectives for advanced fuel cycle development *(Report to Congress – Advanced Fuel Cycle Initiative: Objectives, Approach and Technology Summary* [DOE 2005]).

a. This report generally uses the term used fuel instead of spent fuel, except when referencing previous reports.

- Annual reports issued since 2003 providing comparisons of fuel cycle technology options. (See *Advanced Fuel Cycle Initiative Comparison Report*, FY 2003, FY 2004 Update, FY 2005 Update, FY 2006 Update [DOE 2003b, DOE 2004, DOE 2005a, DOE 2006a].)
- A report issued in May 2006 documenting fuel cycle technology development activities to accelerate efforts to develop enhanced technologies to recycle commercial spent nuclear fuel (*Report to Congress – Spent Nuclear Fuel Recycling Program Plan* [DOE 2006]).

Another systems analysis report to Congress supporting the DOE Generation IV Nuclear Energy Systems Initiative identified the sodium-cooled fast reactor as the preferred technology for management of transuranics in a closed fuel cycle (*The U.S. Generation IV Fast Reactor Strategy* [DOE 2006b]).

Taken together, these reports describe the waste management, proliferation resistance, and energy sustainability objectives for advanced fuel cycles, a wide range of potential fuel cycle technologies, how these technologies can work together to achieve the objectives, and the status of bench-scale research to develop these technologies.

These previous discovery-phase systems analyses have clarified the required characteristics of an advanced fuel cycle that balances waste management, proliferation risk management, and energy sustainability. Considerable detailed analysis has been performed and integrated and used to guide program development (a large number of technical references are provided in Appendix B).

The GNEP technologies and infrastructure presently being considered reflect these discovery phase systems analysis results, including separation and recovery of transuranics for recycle, use of fast spectrum reactors for transuranics management, and approaches directed towards optimizing disposition of all wastes.

1.3 Technical Objectives and Approach

The 2005 AFCI report to Congress established technical objectives for advanced fuel cycle research and a deployment approach which both remain applicable within GNEP (DOE 2005). The AFCI strategic goals reported to Congress consisted of the following:

- Develop and make available for industry the separations technology[b] needed to deploy by 2025 a commercial-scale spent fuel treatment facility capable of separating transuranics in a proliferation-resistant manner for their recycle and destruction through transmutation
- Develop and make available the fuel cycle technology needed for commercial deployment by 2040 of fast spectrum reactors operating either exclusively as transuranics transmuters or as combined fuel breeders and transmuters.[c]

The 2005 report also described a staged recycle implementation strategy that supports an evolutionary approach to management of spent nuclear fuel (see Figure 1). The rate of evolution was based on assumptions that the geologic repository would be opened soon and nuclear energy growth would be limited. Since the preparation of that report, two important changes have occurred. First, the repository has again been delayed, with the opening date now projected to be after 2017 (Sproat 2008). Second, the Energy Policy Act of 2005 (EPACT 2005) was passed, providing significant assistance for initial new nuclear plant construction. The nuclear industry has responded by announcing plans for multiple new

b. Since this time, the program has learned that an overall proliferation-resistant system (and not just the separate technologies) is important for reducing proliferation risk.

c. The DOE GNEP program has focused on potential uses of fast reactors as transuranic transmuters and not as fuel breeders.

plants. Combined license (COL) applications for construction and operation of 15 new reactors have been filed with the Nuclear Regulatory Commission (NRC) between September 2007 and April 2008, and many more are expected (NRC 2008a). The heavy interest in new construction coupled with additional repository delays has resulted in a reassessment of the implementation strategy for managing spent nuclear fuel. In the current GNEP approach, limited recycle is bypassed in favor of rapid development of continuous recycle capabilities with initial recycle facilities completed as early as 2020. Continuous recycle eliminates the direct disposal of used fuel.[d] Both the 1-tier and 2-tier closed fuel cycles analyzed in this report achieve continuous recycle.

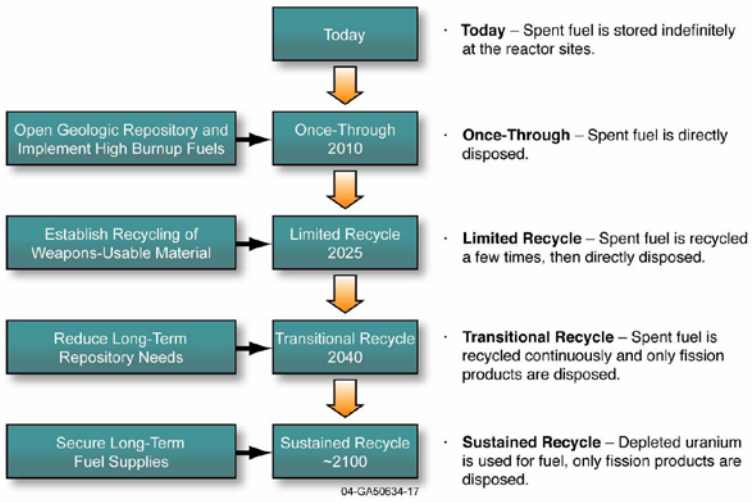

Figure 1. Fuel cycle implementation strategy in the 2005 AFCI report to Congress.

The Spent Nuclear Fuel Recycling Program Plan report to Congress (DOE 2006) specified three recycle system goals:

- Reduce the current and future burden related to geologic disposal of spent nuclear fuel in terms of waste volume, heat load, radiotoxicity, and number of repositories needed
- Recover the energy value contained in spent nuclear fuel for future energy production needs
- Reduce the proliferation risk associated with the use of nuclear energy globally.

Based on technical requirements derived from the general goals of the GNEP initiative and other considerations, such as U.S. non-proliferation policy, U.S. environmental laws, and good engineering and business practices, the 2006 report also provided a set of technical requirements for a system to recycle used fuel:

- The system should be protective of public health, safety and the environment
- The system should maximize the amount of material recovered from spent fuel for use in producing additional energy and minimize the amount that needs disposal in a geological repository
- The system should make available the energy value of separated materials for future use
- The system should reduce proliferation risk

d. In the domestic scenarios analyzed in this report, once-through is assumed to continue in parallel with continuous recycle for a time as infrastructure is established, with direct disposal of used fuel ending when the statutory first repository limit of 63,000 MTiHM is reached.

- The system should be deployable within the GNEP Technology Demonstration Program timeframe (20–25 years)
- The system should remain as economical as possible.

The 2005 report also established high level objectives and quantified goals (see Figure 2). The objectives, goals, and requirements from both reports are consistent and provide the basis for much of the current systems analysis. They are also consistent with the Global Nuclear Energy Partnership Statement of Principles (DOE 2007), first issued in September 2007, and now agreed to by 21 countries (DOE 2008). Specific portions of the Principles applicable for systems analysis include:

- Expand nuclear power to help meet growing energy demand in a sustainable manner and in a way that provides for safe operations of nuclear power plants and management of wastes.
- Develop, demonstrate, and in due course deploy advanced fast reactors that consume transuranic elements from recycled spent fuel.
- Develop and demonstrate, inter alia, advanced technologies for recycling spent nuclear fuel for deployment in facilities that do not separate pure plutonium. Such advanced fuel cycle technologies, when available, would help substantially reduce nuclear waste, simplify its disposition and draw down inventories of civilian spent fuel in a safe, secure, and proliferation-resistant manner.
- Take advantage of the best available fuel cycle approaches for the efficient and responsible use of energy and natural resources.

These high level objectives and goals have been applied in the analyses contained in this report. They provide the basis for the general approaches used in nominal analysis scenarios, performance metrics, and sensitivity studies. Throughout the report, reference is made back to the objectives and goals as a means of measuring fuel cycle system performance.

1.4 Organization of Report

The previous material provided an overview of the systems analysis activity and the objectives to which advanced fuel cycle systems are analyzed. The remainder of this report describes the projected expansion of nuclear energy in the context of global energy demand and climate change, identifies key facility deployment and material management features of expanding the domestic nuclear infrastructure while transitioning to a closed fuel cycle, and describes the related impacts in terms of nuclear energy costs, uranium use, and waste management.

Section 2 provides information on projected global demand for nuclear energy. The analysis uses a base scenario developed by the U.S. Climate Change Science Program (CCSP) to project the global level of nuclear energy through the end of the century assuming current conditions, and then assesses changes in the energy mix if carbon mitigation policies are implemented. The results provide an indication of the future potential for nuclear energy, as well as the associated impacts on uranium needed and used fuel generated, assuming a once-through fuel cycle. The balance of the report then assesses the difference between the once-through fuel cycle and the GNEP closed fuel cycle.

Section 3 uses the results of dynamic simulations and sensitivity studies to assess a domestic transition from the status quo to a closed fuel cycle. Key assumptions and parameters are identified that impact the rate of transition, the number and types of reactors and fuel cycle facilities, and management of transuranics in the system. Operational impacts assessed include management of total used fuel inventories and transuranic inventories. Specific considerations for initial advanced fuel cycle facilities are also discussed.

Advanced Fuel Cycle Initiative Objectives and Quantified Goals

Objective 1. Reduce the long-term environmental burden of nuclear energy through more efficient disposal of waste materials.

- In the short-term, develop and demonstrate fuel cycle technologies and facilities that remove more than 99.5 percent of transuranics from waste destined for geologic disposal and initiate their recycle in existing reactors.
- In the short-term, improve management of the primary heat producing fission products in spent fuel (cesium and strontium) to reduce geologic repository impacts.
- In the intermediate- and long-terms, enable repeated recycling to reduce disposed transuranics by a factor of 100, delaying the need for additional geologic repositories for a century or more, even with growing energy production.
- In the intermediate- and long-terms, reduce the long-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of a waste isolation system.

Objective 2. Enhance overall nuclear fuel cycle proliferation resistance via improved technologies for spent fuel management.

- In the short-term, develop fuel cycle technologies that enhance the use of intrinsic proliferation barriers.
- In the short-term, demonstrate the capability to eliminate more than 99.5 percent of transuranic weapons-usable materials from waste streams destined for direct disposal by destroying these materials through recycling
- In the long-term, stabilize the inventory of weapons-usable material in storage by consuming it for sustained energy production.

Objective 3. Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting resource for nuclear power.

- In the short-term, develop the technologies needed to extend nuclear fuel supplies by up to 15 percent by recycling the fissile material in spent nuclear fuel.
- In the long-term, extend nuclear fuel resources more than 50-fold by recycling uranium in spent fuel and depleted uranium, thereby converting current wastes into energy assets.

Objective 4. Improve fuel cycle management, while continuing competitive fuel cycle economics and excellent safety performance of the entire nuclear fuel cycle system.

- At all times, ensure that advanced fuel cycle technologies cause no significant decrease in the economic competitiveness of nuclear electricity.
- At all times, maintain excellent safety performance of nuclear fuel cycle facilities and operations.
- For the longer term, improve spent fuel management to reduce on-site storage at nuclear power plants

Figure 2. Objectives and quantified goals from the 2005 AFCI report to Congress.

Section 4 focuses on the economics of transitioning to a closed fuel cycle. Static and dynamic cost models, probability analyses, and sensitivity studies assess the costs and cost uncertainties associated with both reactors and the front and back ends of the fuel cycle. This includes discussion on which cost drivers contribute most to variations in system costs and where improved design information and technologies may contribute most to reducing overall costs and cost uncertainties.

Section 5 examines the outcome-based impacts of transitioning to a GNEP closed fuel cycle based on a number of metrics developed from the objectives presented earlier in this section. These metrics assess the impacts of closed fuel cycles from the perspectives of used fuel inventories, uranium utilization and waste disposal. The waste discussion includes expected waste streams with masses and volumes, along with metrics on long-term radiotoxicity (LTR) and long-term decay heat (LTH).

Section 6 provides a summary of report findings, where additional analyses would be beneficial, and future plnned systems analysis activities.

Appendix A provides additional information on the types of questions addressed by systems analysis and a description of the methods and tools that are used in systems studies.

Appendix B provides a bibliography of selected systems analysis reports and papers.

Appendix C provides the assumptions used for modeling the domestic once-through and nominal 1-tier and 2-tier scenarios used throughout the report.

2. Global Nuclear Energy Perspective

The first objective in the GNEP Statement of Principles (DOE 2007) is to expand nuclear power to help meet growing energy demand in a sustainable manner. A number of studies have examined global population growth, growth in Gross Domestic Product (GDP), and the energy growth needed in support. This section looks at the specific area of sustaining energy growth while stabilizing greenhouse gas concentrations (based on [Kim 2008]).

The scale of change necessary for the stabilization of greenhouse gas concentrations holds profound implications for the shape of the global energy system because global CO_2 emissions must peak and then decline indefinitely thereafter.

Long-term scenarios of the future global energy system with nuclear energy technologies were developed to identify and understand key issues. The focus is on the long term, because lead times in technology development, the long lifetime of nuclear technologies, and the nature of the climate issue require that perspective. The analysis in this section used the Pacific Northwest National Laboratory's O^{bj}ECTS (Object-oriented Energy, Climate, and Technology Systems) implementation of the MiniCAM integrated assessment model (Kim 2006). The O^{bj}ECTS-MiniCAM is a long-term, global integrated assessment model of energy-economy interactions and greenhouse gas (GHG) emissions.

The models include both a Reference Scenario from the U.S. CCSP and alternate scenarios where CO_2 emissions are reduced. To determine the value of nuclear energy versus other alternatives, a version of the scenarios was also developed where nuclear power is phased out as a means of comparison.

The Reference Scenario includes no limitations on CO_2 emissions, and market share is based on economic competition between energy sources. In the alternate scenarios with CO_2 limitations, energy sources with low carbon footprints have a relative cost advantage. Nuclear, renewables, and biomass all have low carbon footprints, while the deployment of CCS technologies could, in principle, facilitate the continued use of fossil fuels with substantially reduced emissions, and one might expect that CCS technologies would be competitive in a world with a significant value of carbon (Freund 1997, Herzog 1997, Edmonds 2002, Dooley 2004). Under carbon mitigation policies, however, technologies that emit CO_2 would include the additional burden of the carbon value as part of their costs. The degree to which nuclear energy captures market share depends both on its own, absolute performance, and on the performance and character of competing technologies as well as the implementation of future climate change policies.

2.1 Reference Energy Future

The Reference Scenario used in the analysis in this section is based on the *Scenario of Greenhouse Gas Emissions and Atmospheric Concentrations* from the CCSP (Clarke 2007), which incorporates the most up-to-date historical information and assumptions regarding future demographics, socioeconomic parameters, and energy use, and thus employs an important reference baseline for long-term global energy and economic analysis.

A scenario is built up from a set of externally specified inputs. Some of the most important are population and technology performance; specifically, the global population peaks at approximately 9 billion in 2065 and declines to 8.7 billion by 2100. The scale of global economic activity increases by an order of magnitude over the course of the century.

Both fossil fuel resources and uranium are modeled as depletable graded resources. While the abundance of conventional oil and gas is limited, unconventional forms of these resources are extremely abundant and it is assumed that technological change enables the gradual transformation of oil and gas

resources from unconventional to conventional categories. The abundance of coal resources is so great that resources and resource grades provide no meaningful limit on coal use.

Assumptions on the availability of natural uranium vary widely (Schneider 2008). The model uses a supply curve for natural uranium based on a generalized crustal model of the relationship between uranium abundance and concentration fitted to the resource estimates and costs from the International Atomic Energy Agency (IAEA) Redbook (OECD 2003). The uranium supply curve provides the global availability of uranium as a function of price. The natural uranium supply curve is assumed to be continuous such that significant amounts of natural uranium are available beyond those estimates in the Redbook data in lesser concentrations but at higher costs. The supply curve used in this analysis falls within the range of estimates derived by the Gen IV Fuel Cycle Crosscut Group (FCCG) (DOE 2002) and Deffeyes and MacGregor (Deffeyes 1980).

The Reference Scenario assumes that nuclear fuel and power technology development is limited to that which is presently available. As such, it does not explicitly model the impact of deploying GNEP technologies. This is done to provide a benchmark for understanding the impact of current generation nuclear technologies. (Analyses that do model the impact of deploying GNEP are in Sections 3, 4, and 5.)

Two groups of nuclear power technologies were included in this analysis: currently operational conventional light-water reactors (in the U.S. and elsewhere) and advanced thermal spectrum reactors (which have been built outside the U.S. and are planned for U.S. construction). These reactors are, in general, referred to as Gen II and Gen III reactors, respectively. A generic Gen III technology is assumed for the purpose of modeling (EIA 2007a, U of C 2004). Cost assumptions for Gen III technologies are based on the Advanced Fuel Cycle Cost Basis Report by Idaho National Laboratory (INL) and DOE Energy Information Agency's (EIA) representative cost of evolutionary LWRs (Shropshire 2007, EIA 2007a). Legacy Gen II reactors do not compete for new capacity and no new investments in Gen II reactors can occur. Existing Gen II reactors are assumed to have life expectancy of 60 years with all Gen II reactors retired by midcentury.

Although current nuclear fuel cycle and waste management practices vary across countries, this study characterizes the fuel cycle as a once-through system for all modeling regions. Direct disposal of used fuel is assumed and the capacity for nuclear waste disposal is not limited. These assumptions are intended to provide a baseline for understanding the issues of uranium resource use and nuclear waste accumulation. Fixed costs for interim storage and permanent waste disposal are included. Assumed nuclear fuel and reactor characteristics, such as burnup and enrichment factors and costs, are typical for central values available in the literature (Deutch 2003, Bunn 2003, Shropshire 2007).

In the Reference Scenario, the growth in the scale of global economic activity over the course of the century leads to almost a three-fold increase in the consumption of primary energy from 500 EJ/yr in 2005 to 1440 EJ/yr in 2095 (Figure 3)). Fossil fuel use remains central to the global energy system. Oil, natural gas, and coal continue to provide the bulk of primary energy and together comprise 63% of total energy by the end of the century. Unconventional oil, which is composed of shale oil, natural bitumen and heavy crude oil, become the dominant source of liquid fuels by the end of the century.

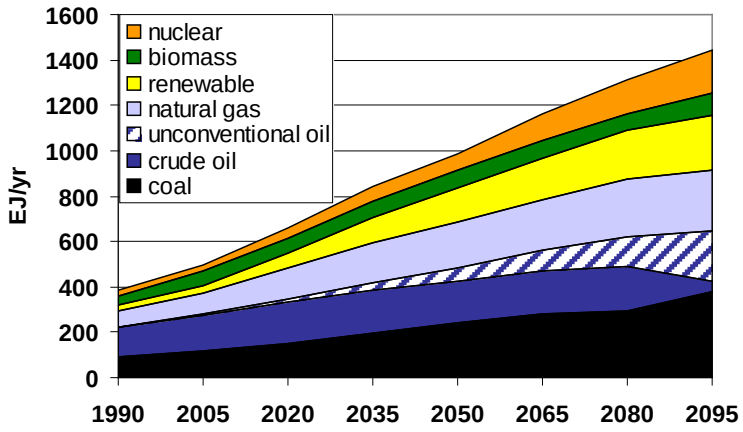

Figure 3. Global primary energy consumption by fuel (Reference Scenario).

Economic growth around the world increases the demand for energy services based on electric power. The Reference Scenario global electricity consumption grows five-fold from 62 EJ/yr[e] in 2005 to 313 EJ/yr by 2095 (Figure 4). Without a climate policy, electricity from fossil fuels is the major source of electricity throughout the century. Fossil fuel power's contribution to total electricity generation, however, declines from 66% in 2005 to 52% in 2095 as generation from wind, solar, biomass, hydro, and nuclear grows with time. Nuclear power transitions from Gen II to Gen III technology and expands as fuel and capital costs remain competitive. By 2050, 24 EJ/yr, or 13%, of the power market is generated by nuclear energy. The nuclear power output corresponds to the global deployment of more than 900 reactors in the middle of the century.[f] The global share of nuclear electricity falls below the current share of 16% by midcentury due to the retirement of legacy reactors before rising again in the second half of the century. Nuclear's global power market share grows to 20% and 64 EJ/yr of nuclear electricity is generated annually with the deployment of nearly 2,400 reactors worldwide by the end of the century.

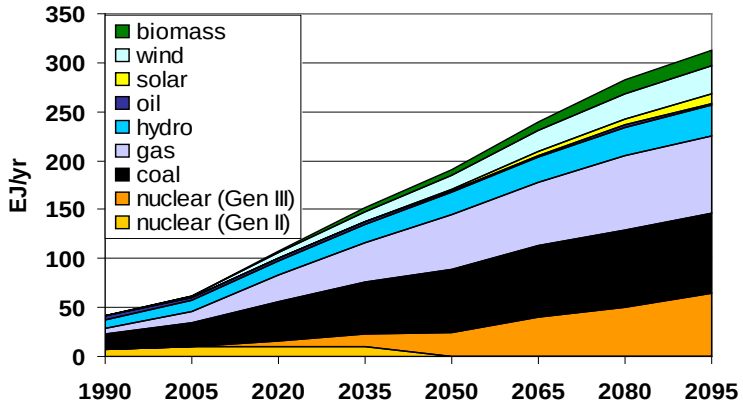

Figure 4. Global electricity generation by type (Reference Scenario).

e. An EJ is equal to 278 TWhr of electricity.

f. Each reactor is assumed to be 1,000 MWe in size with an annual capacity factor of 0.85 and lifetime of 60 years.

CO_2 emissions continue to grow over time as fossil fuels remain the primary components of the global energy system (Figure). Global emission of CO_2 grows three-fold from 7.5 billion tonnes carbon per year (BTC/y) in 2005 to 21 BTC/y by 2095. The bulk of direct CO_2 emissions is produced from the industrial, electric power, and transportation sectors with each contributing to approximately one-third of total emissions. The three-fold increase in global CO_2 emissions raises the atmospheric concentration of CO_2 to 731 ppm by 2095, a factor of 2.6 times the pre-industrial concentration of 280 ppm.

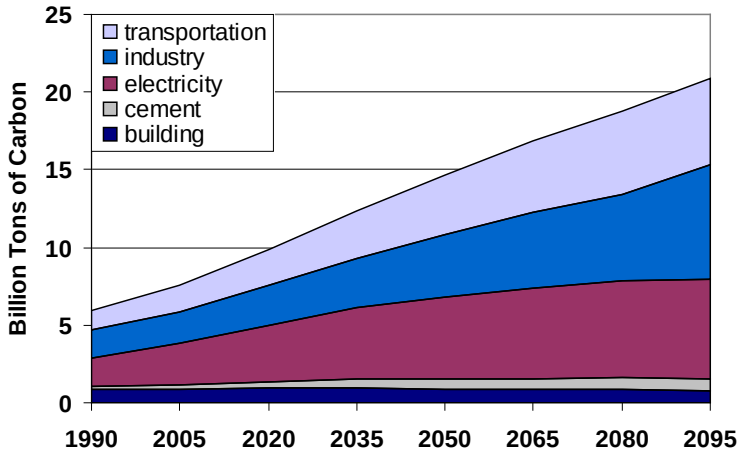

Figure 5. Global annual carbon emissions by sector (Reference Scenario).

2.2 Nuclear Energy and Climate Change

Four alternative concentrations—450 ppm, 550 ppm, 650 ppm, and 750 ppm—are examined for the stabilization of CO_2 concentrations in the atmosphere because there is no scientific consensus at which concentration level stabilization should occur.[g] Stabilization of CO_2 concentrations in the atmosphere is achieved by limiting global CO_2 emissions to paths that peak and decline over the course of the century as shown on the left side of Figure 3.

The emissions limitation is achieved by imposing a global carbon tax across all of the world's economies. All regions participate in imposing an economy-wide carbon tax beginning at the same time, and all sources of emissions are included. The corresponding price of carbon follows along the Hotelling-Peck-Wan price path that is economically efficient over time resulting in minimum global discounted costs for the stabilization of CO_2 concentrations (Peck 1996, Hotelling 1931). How large the tax becomes depends on how great the emissions mitigation must be at the end of the century and the set of technology options for emissions mitigation available to society. The assumption of a global carbon tax, charged uniformly around the world, is unrealistic, but its principal virtue is that it implies a minimum cost for achieving the stabilization goal. Resulting carbon taxes for all CO_2 concentration targets are also shown in Figure 3. The magnitude of these taxes includes the contribution from nuclear and CCS technologies for power generation.

g. The preindustrial concentration of CO_2 is estimated to have been 280 ppm and the concentration of CO_2 in 2005 is estimated to be approximately 380 ppm (NOAA 2008, UN 1999, Keeling 2004).

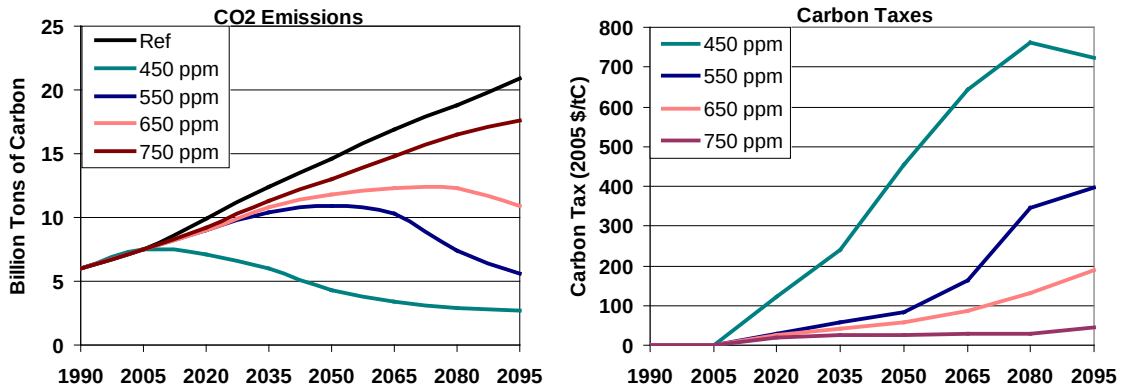

Figure 3. Sensitivity results for global CO_2 emissions paths and resulting carbon taxes for the stabilization of atmospheric CO_2 concentrations.

Stabilization of CO_2 concentrations dramatically affects the deployment of nuclear technologies in power generation. The 550 ppm scenario is used in the remainder of this subsection to explore the energy response of nuclear technologies in addressing CO_2 concentrations. The contribution of all power technologies to total global electric generation for the 550 ppm scenario, with and without CCS, is displayed in Figure 4. All non-emitting or low-emitting technologies are more competitive in the presence of the CO_2 constraint. With CCS, nuclear power grows dramatically and fossil fuel CCS technologies become competitive and share the market for power. Globally, nuclear is the largest source of power (see Table 1). Most of the growth in nuclear deployment occurs in the second half of the century with nuclear power output 60% greater than in the Reference Scenario. Fossil CCS technologies combined contribute nearly as much as nuclear and enable the continued use of fossil fuels in the production of electricity. Wind and solar technologies gain market share as well. Coal use without CO_2 capture is completely phased out, while natural gas use without CCS continues to play a role.

Without CCS technologies, nuclear power becomes one of the few remaining competitive options under CO_2 constraints that can meet the tremendous need for global power without the concurrent production of CO_2 emissions. Nuclear power becomes the largest single source of global electricity with a power market share of 50% by 2095. The next largest contribution comes from wind, followed by natural gas with free venting of CO_2 emissions, hydro, biomass, and solar.

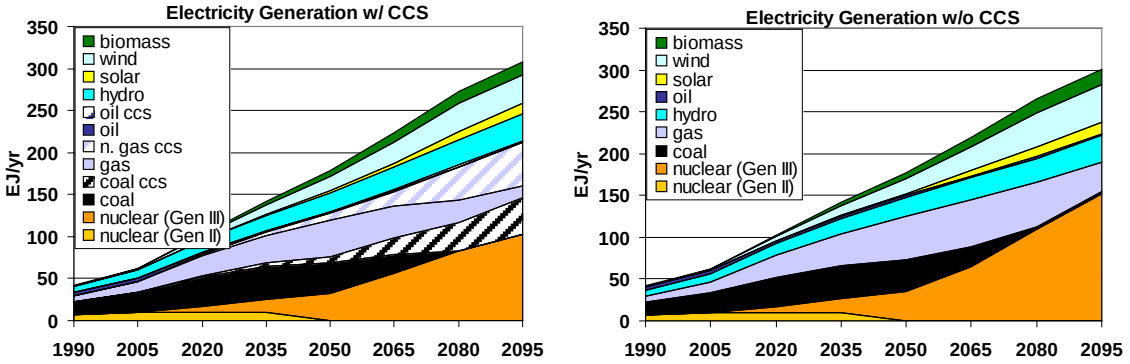

Figure 4. Global electricity generation with and without CCS (550 ppm Scenario).

Table 1. Electricity market share in 2095 in three climate strategy scenarios.

	Fraction of world electricity in 2095					
Climate Scenario	Nuclear	Fossil	Wind	Solar	Hydro	Biomass
Reference	20% 64 EJ/year	52%	9%	3%	10%	6%
550 ppm stabilization with CCS	33% 103 EJ/year	36%	11%	4%	11%	4%
550 ppm stabilization without CCS	50% 152 EJ/year	13%	15%	5%	11%	6%

The rising value of carbon in the stabilization scenarios results in an economic cost to society. This cost has been computed for the cases in which nuclear power is available to the economy. To estimate the value of nuclear technology to the economy, an alternative nuclear moratorium case is assessed. The difference in costs between the presence and absence of nuclear technology is the inferred value to society of the nuclear technology in stabilizing CO_2 concentrations. This case is assessed with and without CCS technologies to measure the impact of technology competition on nuclear's value.

The calculated global economic cost of CO_2 stabilization is the lowest when both nuclear and CCS technologies are available to contribute to emissions mitigation and greatest when neither technology is available.[h] In the 550 ppm scenario, the inferred global economic value of nuclear is 0.9 trillion U.S. dollars (USD) with CCS and 1.3 trillion USD without CCS. When the CCS option is not available, the value of nuclear technology increases by an additional 50% in the 550 ppm scenario. Limited options for low carbon or carbon-free power generation imply that the cost for achieving any stabilization regime is higher. The marginal value of adding a nuclear option is therefore increased when CCS is not available.

The cost of CO_2 stabilization and the value of nuclear technology are not only affected by the competition but closely tied to the concentration target. The lower the CO_2 concentration target is, the higher the cost, and similarly, the lower the CO_2 concentration is, the higher the value of nuclear technology. Although the value of nuclear is progressively greater at more restrictive concentration levels, it is disproportionately greater at low CO_2 concentrations and without the option for CCS. In the 450 ppm scenario a threshold level is crossed; the global value of nuclear is 9.8 trillion USD without CCS, nearly a factor of four greater than nuclear's value with CCS at 2.6 trillion USD (Figure 5).

2.3 Nuclear Energy Challenges

The response to climate change implies a sustained and significantly increased nuclear plant construction schedule throughout the 21st century. There are currently 440 reactors installed in 31 countries, with an additional 338 reactors currently being built, planned, or under consideration around the world.[i] The response to climate change would require a much greater effort to increase the global nuclear capacity, both human and capital, to achieve the numbers of nuclear reactor deployment in the above scenarios.

h. Costs are calculated by discounting annual costs at 5% per year and summing over the period 2005 to 2095.

i. http://www.world-nuclear.org/info/reactors.html. Of the 338 new reactors, 34 reactors are under construction in 11 countries, 81 reactors are planned and approved in 17 countries, and 223 reactors are proposed in 27 countries, but do not have firm commitments [WNA2008].

In addition, these scenarios show that nuclear power becomes an increasingly global energy technology. The distribution of nuclear power plants around the world shifts from the current Annex I nations (Organisation for Economic Cooperation and Development [OECD] plus Former Soviet Union and Eastern Europe)[j] to Non-Annex I nations. Before the middle of the century, more than half of the global nuclear electricity is generated in Non-Annex I nations. That share rises to nearly 75% by the end of the century. In the 550 ppm scenario, of the 3,800 GWe of total installed global nuclear capacity, 2,800 GWe is installed in Non-Annex I regions by the end of the century. The significantly increased deployment of nuclear plants in Annex I and Non-Annex I regions in these scenarios highlights the potential proliferation concerns from the global trade and transfer of nuclear technologies and materials.

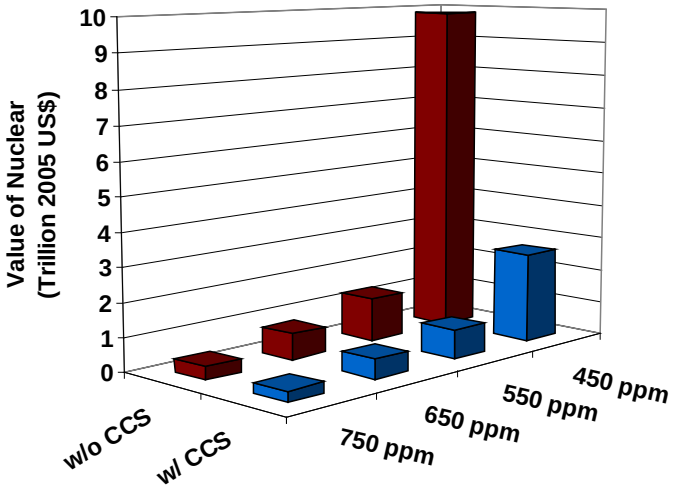

Figure 5. Sensitivity results for global economic value of nuclear deployment with and without CCS.

The growth in the deployment of nuclear reactors worldwide steadily raises the demands for natural uranium. In the Reference Scenario, cumulative global uranium production reaches 24 million tonnes by the end of the century, while the cost of uranium has risen to $130/kg. Under the climate constraint, greater use of nuclear energy with reliance on the once-through fuel cycle requires an ever increasing supply of natural uranium. The left side of

Figure 6 shows the comparison of the global cumulative uranium production for the 550 ppm scenarios with and without CCS and the Reference Scenario. By 2095, cumulative uranium extraction reaches 33 million tonnes of uranium (MTU) with CCS and 40 MTU without CCS in the 550 ppm scenario. The corresponding prices of uranium ore at the end of the century are $150/kg and $165/kg with and without CCS technologies, respectively.

It is worth noting that although uranium prices, and thus nuclear fuel costs, move higher with time; the increasing price of uranium provides no meaningful obstacle to the deployment of nuclear power. Nuclear power remains competitive because capital, and not fuel costs, accounts for the bulk of electricity cost from nuclear power. Also, the competition faces the additional burden of carbon prices under climate policies, thus reducing the impact of rising fuel costs on nuclear power. The carbon price

j. Annex I refers to a list of nations in the UNFCCC that includes members of the OECD plus the former Soviet Union and Eastern Europe.

approaches $400/tC in the 550 ppm scenario and raises the cost of electricity from coal without CCS by 170% and natural gas without CCS by 50%.

While the long-term uranium ore price may not in itself be an obstacle to nuclear expansion, market availability and access to uranium could pose significant challenges. For all scenarios, known conventional resources (4.6 MTU) of the Redbook estimate are exhausted by 2020, and total Redbook estimates (14.4 MTU) including speculative resources are exhausted soon after the middle of the century. Discovery of uranium resources beyond those in the Redbook estimates are required by the middle of the century to support the growing use of nuclear energy projected in these scenarios. Long lead-times, in the order of decades, with sufficient infrastructure development including energy and water resources, are required to ensure continuous supply of uranium. Inability to bring alternative sources of uranium into production in a timely manner could lead to supply shortages and volatile short-term prices.

Nuclear waste is an inevitable by-product of nuclear energy production, and the expansion of nuclear energy for addressing climate change results in a growing worldwide accumulation. The global inventory of once-through used fuel waste generated in the Reference and 550 ppm scenarios is displayed on the right side of

Figure 6. By 2095, nearly 2.2 million tons of used fuel is produced from all reactors worldwide in the Reference Scenario. That amount exceeds 3 million tons in the 550 ppm scenario. In the U.S., used fuel accumulation reaches 326 thousand tons in the Reference Scenario and exceeds 440 thousand tons in the 550 ppm scenario.

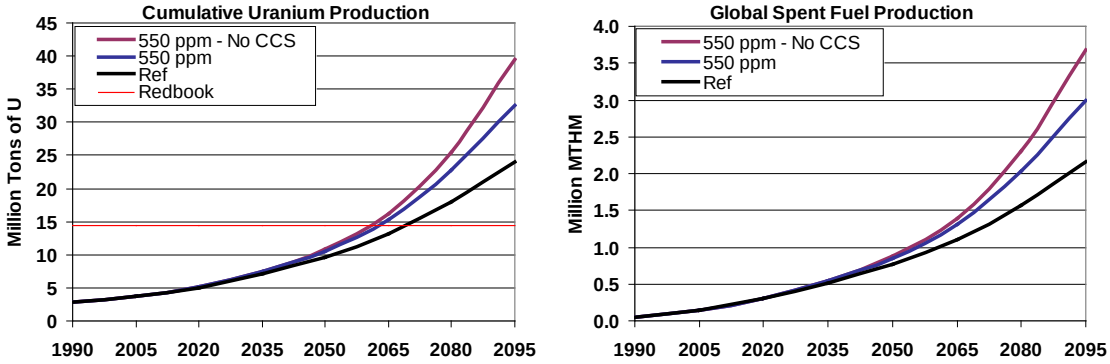

Figure 6. Cumulative global uranium production and used fuel waste production.

2.4 Impact of Closing the Fuel Cycle

The expectation of increasing global energy demand is driven by a growing global economy, including major improvements in GDP in Africa and Asia. The base scenario results in large generating capacity increases for all sources of energy, including nuclear-generated electricity. This results in increased demand for uranium resources and used fuel disposal.

The environmental impact of climate change associated with increased energy production can be reduced through additional growth of non-greenhouse gas emitting energy sources, including nuclear energy. Scenarios with meaningful reductions in projected atmospheric GHG levels demonstrate a large economic value in significantly increasing the market share of energy from nuclear sources. These scenarios compound the already large demands for uranium and used fuel management.

While these analyses show the potential for large increases in nuclear electricity, they do not consider non-electric applications of nuclear energy that may generate additional growth. These include direct

heat applications such as water desalination, hydrogen production for transportation (synthetic fuels and fuel cells), chemical industry applications, and direct steam used for district heating or resource extraction (tar sands).

The remainder of this report examines the impacts of the U.S. transitioning from a once-through fuel cycle to a closed fuel cycle, including the costs and impacts. A closed fuel cycle allows the expansion of nuclear energy as described in this section, while improving uranium use and reducing the radiotoxicity and decay heat of waste that must be disposed. While the focus is domestic, the technologies involved and how they impact uranium utilization, waste generation, and economics are applicable to the global system.

3. GNEP DEPLOYMENT CONSIDERATIONS

The preceding Section 2 describes world nuclear futures with and without CO_2 emission constraints. The U.S. CCSP Reference Case without carbon constraints projects nuclear energy supplying 20% of world electricity by the end of the century, while cases with carbon constraints included up to a 50% electricity market share for nuclear energy. These cases all require more uranium than identified in OECD/IAEA conventional resources estimates and generate orders of magnitude more used nuclear fuel than is currently in storage.

The analyses in Sections 3, 4, and 5 explain how GNEP deployment could mitigate these consequences domestically, thereby facilitating the required growth in nuclear power with lower demand for uranium and used nuclear fuel disposal. All analyses in these sections were performed with the Verifiable Fuel Cycle Simulation Model (VISION) model (Jacobson 2008). VISION models the entire integrated fuel cycle in a dynamic, time-dependent fashion, tracking mass flows at the isotopic level and constraining infrastructure development (new reactors, etc.) based on material availability (for fuel, etc.). VISION generates time-dependent information on infrastructure, material inventories, and system performance metrics such as uranium usage and waste parameters. The VISION economic submodel uses the AFC Economic Cost Data Base (Shropshire 2008) and generates time-dependent information on system infrastructure and operational costs.

This section discusses dynamic analyses of the transition from the current fuel cycle to either a 1-tier or 2-tier recycle options, as well as continuation of the once-through fuel cycle for comparison. The analyses include a set of nominal[k] scenarios and a number of sensitivity analyses based on the nominal scenarios. In the sensitivity analyses, one or two parameters are varied at a time to identify the impact of each parameter and how the system reacts.

These analyses demonstrate how system components interact to produce overall system behavior, providing insights into how changes in the deployment approach may result in different outcomes.

The primary value of the analyses is the improved understanding of system behavior they provide. This behavior is illustrated through changes in trends of key parameters, often depicted in histograms and other graphs. The specific values shown on the graphs are only approximate projections. Thus, the reader should focus on the trends and not any specific values.

3.1 Nominal Scenario Descriptions

3.1.1 Assumptions

Analyses of future fuel cycle systems require a number of assumptions. These include growth rates[l] for nuclear energy, general architecture of fuel cycle facilities, time frames for availability of new technologies and facilities, information on how those technologies and facilities will perform, and assumptions about what policies will be followed concerning used fuel inventories, etc. Since these assumptions have a significant impact on the analyses, they are carefully developed based on best available information, including technology performance, policy, regulations, and historic trends. Still,

k. The term “nominal” is used to refer to a scenario chosen as the basis around which sensitivity studies are performed. The nominal scenario is not necessarily the preferred or the most likely scenario.

l. The analyses in Section 2 calculated nuclear growth rate based on overall energy growth and competition with other energy sources. The models used for the analyses in this section provide much more detail on nuclear facilities and technologies, but do not include other energy sources, and therefore assume a growth rate instead of calculating one.

they are only assumptions; sensitivity analyses help to understand the impact if the assumptions prove to be inaccurate.

All scenarios discussed in the remainder of this report are based on the same basic assumptions. A short summary of these assumptions is provided here, while a full listing is provided in Appendix C.

Assumptions for all scenarios:

- Analysis of domestic systems.
- Nuclear energy resumes growth in 2015 at an annual rate of 1.75%, resulting in 200 GWe-year of electricity generated in 2060 and 400 GWe-year in 2100. (Current output is ~90 GWe-year.)
- The federal geologic repository accepts LWR used fuel for direct disposal starting in 2017 and ending in 2039 for a total of 63,000 MTiHM. For the once-through case, additional used fuel is disposed in generic additional repository capacity when sufficiently cooled (20 years). For the closed fuel cycle cases, additional used fuel is recycled.

Assumptions for closed fuel cycle scenarios only:

- Separation of LWR used fuel begins in 2020, initially with a small plant (800 MTiHM/year capacity) with additional plants added as needed to work off any excess stores of used fuel by 2100. LWR used fuel is cooled 10 years before shipment for recycling. The TRU from separations is used to make recycled fuel (either MOX-Pu for LWRs or TRU fuel for fast reactors).
- A small fast reactor starts up in 2022 to prove the reactor and transmutation fuel technologies. Follow-on commercial fast reactors use a TRU conversion ratio (CR) of 0.5, metal fuel, and onsite recycling. (Sensitivity studies examine other options.)
  - For the 1-tier scenario, commercial fast reactors follow 10 years later (2032), with construction rates limited for the first decade to allow for learning ("learning" is discussed in Section 3.4.3).
  - For the 2-tier scenario, the MOX cycle takes at least 15 years (5 years in the reactor, 10 years cooling) before the used fuel is available for recycle into fast reactor fuel, so commercial fast reactors are delayed 15 years (to 2047).
- All TRU elements are recovered whenever used fuel is separated. Cesium and strontium (CsSr) together is a separate waste product. All separations occur with 0.1% processing loss.

3.1.2 Once-Through Scenario

The once-through scenario provides the basis for comparison with the closed fuel cycle scenarios. All electricity generation is based on LWRs using standard UOX fuel. The growth curve is depicted in Figure 7 and shows the current growth "pause," with no new reactors until 2015. After 2015, growth is modeled with simple compounding at 1.75%. This is a lower rate than previous analyses, reflecting a lower overall energy growth rate projected by the EIA (EIA 2008). However, it is faster than the current EIA predictions for nuclear growth, which have consistently been revised upward by EIA over the last decade.[m] The growth is comparable to those predicted by climate change models (Kim 2008). (The growth does not include the potential additional demand for nuclear energy in non-electric applications.)

m. The 2008 edition of Annual Energy Outlook includes a 33% increase in new reactor builds versus the 2007 edition (EIA 2007b, EIA 2008).

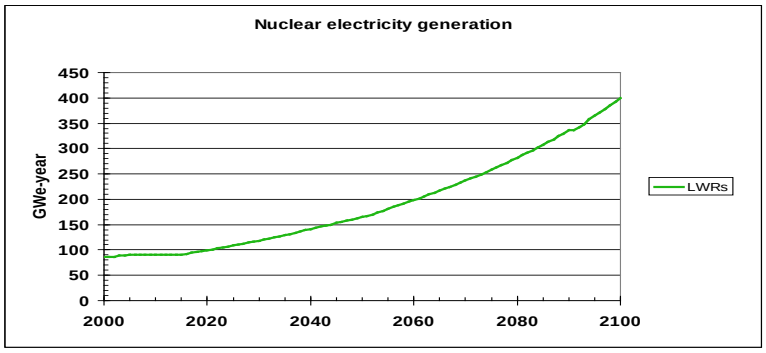

Figure 7. Nuclear electricity generation for the once-through scenario.

The general shape of Figure 7 with the increasing upward slope is the dominant feature of most of the time history graphs in this report. The compounded growth of nuclear electricity is repeated in compounded growth of reactors and fuel cycle facilities, uranium utilization, used fuel production, and waste generation.

The location of used fuel for the once-through scenario is shown in Figure 8. The used fuel graph shows some used fuel in wet storage and some in dry storage. This is not reflective of actual practice, which will vary at each reactor; it instead reflects the assumption of 10 years of wet storage for cooling before used fuel is moved followed by a minimum 10 years of additional cooling storage before it is emplaced in the repository.[n] The total cooling time from reactor discharge to repository disposal is assumed to be a minimum of 20 years, based on current burnup and thermal limits for Yucca Mountain. The "additional repository inventory" reflects how much more used fuel would be available for direct disposal (cooled more than 20 years), without any assumption about where the additional repository capacity would be located. Note the decrease in dry storage between ~2020 and 2040; this reflects excess fuel in storage today which is transferred to geologic disposal once the initial repository becomes available.

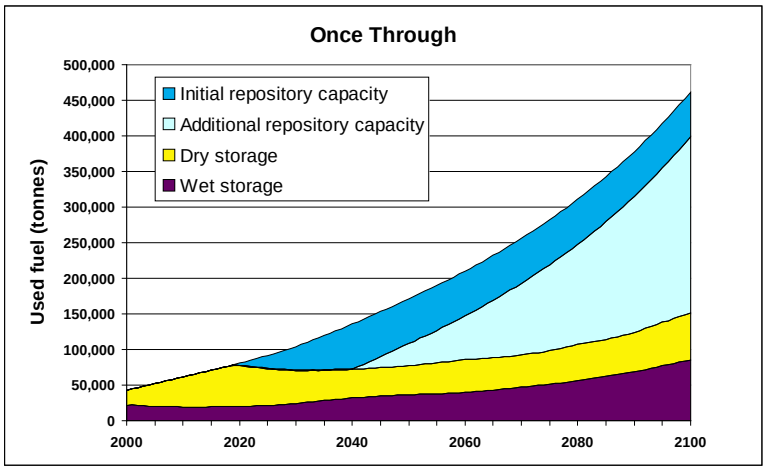

Figure 8. Used fuel quantities and location in the once-through scenario.

n. These analyses assume characteristics for heat management consistent with a Yucca Mountain-type repository.

3.1.3 One-Tier and Two-Tier Closed Fuel Cycle Scenarios

The closed fuel cycle scenarios follow the same growth curve as shown in Figure 7, except the reactor fleet is a combination of LWRs and fast reactors. Figure 9 shows electricity generation based on fuel type, with the yellow area representing the fast reactor generation and the other areas representing LWR generation using both standard UOX and MOX (in the 2-tier scenario).

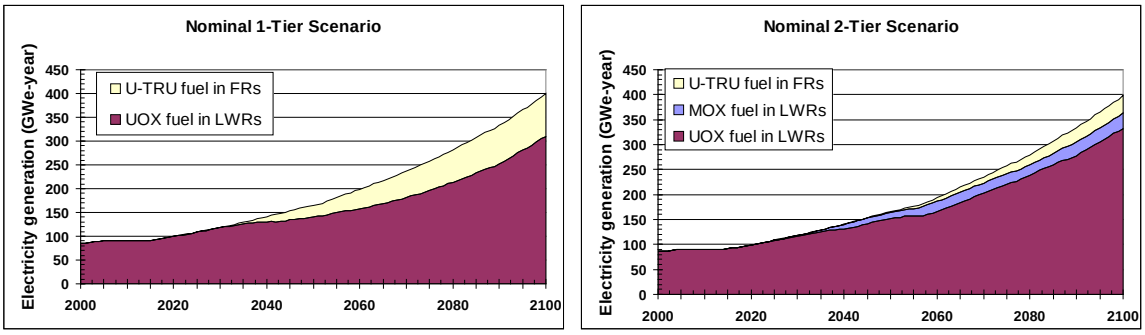

Figure 9. Electricity generation for 1-tier and 2-tier scenarios as a function of fuel and reactor type.

Figure 10 shows the new LWR electricity generation projected (and actual through 2007) for once-through and both closed fuel cycle scenarios. Once-through involves more new LWRs, but not by major amounts. The small bump between 2000 and 2006 reflects the impact of uprates (NRC 2008b). The large peaks in the 2030–2045 range are replacements for retiring reactors; all current and new LWRs are assumed to operate for 60 years. The peak after 2090 reflects the start of a second round of retirements. Note that if current reactor licenses were extended an additional 20 years, these peaks would shift to the right by that amount. The graph is in units of GWe of capacity, so the actual number of new reactors depends on their size. The current average for the 15 reactors in the COLs filed with NRC through April is around 1.25 GWe (NRC 2008c). For perspective on the overall build rate, 15 reactors were completed (received full power operating licenses) in both 1974 and 1975 (EIA 2006). This is reflected by the retirement peak around 2035.

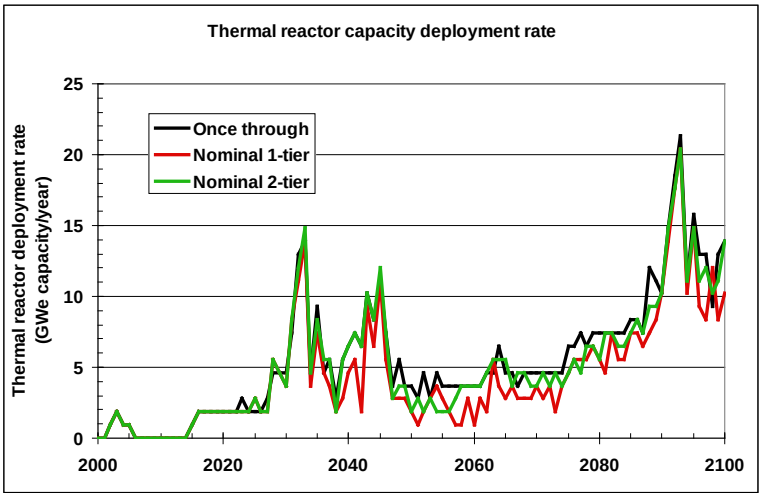

Figure 10. LWR new construction for once-through and the nominal scenarios.

Figure 11 shows the new fast reactor electricity generation projected for the closed fuel cycle scenarios, as well as the portion of total nuclear-generated electricity coming from the fast reactor fraction of the fleet. The 2-tier scenario includes fewer fast reactors and the reactors start up later due to the impact of the MOX pass in the thermal reactors. The MOX pass delays the availability of TRU for the fast reactors. The MOX pass also reduces the TRU available to the fast reactors through two mechanisms. First, some TRU is consumed in the MOX reactors—approximately two-thirds of a tonne per GWe-year.[o] Second, the electricity produced from MOX offsets electricity from UOX, avoiding the generation of an additional quarter tonne of TRU. When these two mechanisms are combined, the amount of TRU eventually supplied to the fast reactors is reduced by almost a tonne per MOX-fueled GWe-year.

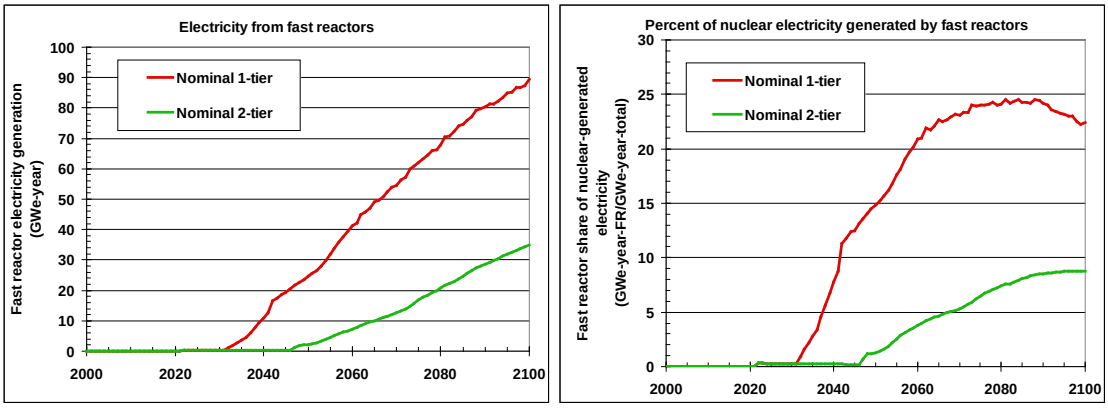

Figure 11. Fast reactor electricity generation in absolute and percentage terms for 1-tier and 2-tier scenarios.

The portion of fast reactors for the 1-tier case levels out near 25% (and may be decreasing) as excess LWR used fuel is worked off and the fast reactors reach a dynamic equilibrium with the LWRs. This number is much lower than what is calculated by a simple static material balance (36%). This is an important finding from the transitional analysis, as it substantially reduces the number of fast reactors required for a "balanced" system.

The difference is due to several factors:

- The amount of TRU needed to start up a fast reactor is much greater than what is needed to keep it going. This includes the first core, as well as 100% of the initial refueling needs (until used fast reactor fuel can be recycled). The static analysis assumes the fast reactors already have their initial cores and most of their refueling needs are met by recycling of their own used fuel, with only ~20%[p] coming as new makeup fuel from the LWRs.
- The fast reactors are using TRU generated at least 10 years earlier by the LWRs. While the LWR used fuel cools, more LWRs are added, so even without the startup effect the fast reactors would always be "behind."
- Some amount of TRU is caught up in buffer storage as a hedge against temporary shutdown of the separations or fabrication facilities or the transportation links.

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o. Based on MOX-Pu fuel run to 50 GWd/MTiHM burnup using 9.8% plutonium and 90.2% uranium, both recovered from UOX separations.

p. This assumes a TRU conversion ratio of 0.5. At higher ratios, even less makeup fuel from LWRs is needed.

The location of used fuel is also very different with the closed fuel cycle. Figure 12 shows the used fuel for the 1-tier scenario. The 2-tier scenario is very similar. When compared to Figure 8, there are large differences, with the fuel previously in "additional repository inventory" now recycled.

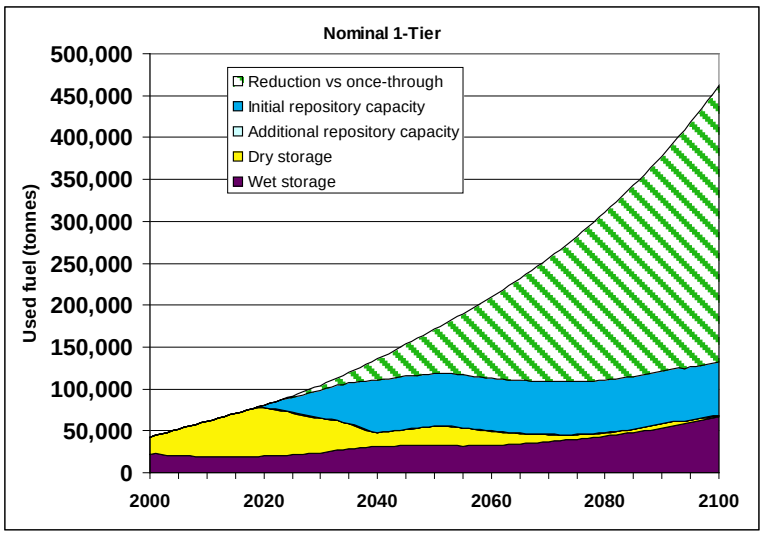


Figure 12. Used fuel quantities and location in the 1-tier scenario.

The amount of used fuel that is recycled is dependent on reprocessing capacity. For the nominal cases, sufficient capacity is assumed to reprocess all used fuel that is sufficiently cooled for efficient shipping, represented by the yellow area in Figure 12 (compare to Figure 8). The excess of cooled fuel that builds up prior to the start of reprocessing is assumed to be worked off gradually over the course of the century. (This approach was developed after early analyses indicated an accelerated program to work off excess inventories often resulted in excess separations capacity after midcentury.)

Figure 13 shows the reprocessing capacity needed for LWR used fuels (both UOX and MOX) for the 1-tier and 2-tier cases, as well as the inventory of cooled UOX as a function of time. The UOX capacity for the 1-tier case is lower late in the century because there are more fast reactors and therefore fewer LWRs and less LWR used fuel. The used fuel available graph clearly shows the impact of opening Yucca Mountain, where all inventories decline between ~2020 and 2040, reflecting direct disposal of 63,000 metric tons of heavy metal (MTiHM). This graph also shows the fuel for the once-through case, assuming no additional disposal beyond the 63,000 MTiHM; the inventory "takes off" after 2040 when the repository has reached statutory capacity. In contrast, the inventories for the nominal 1-tier and 2-tier cases are steadily reduced until the annual separations capacity is in balance with annual discharges and excess inventories are near zero. With nuclear growth the LWR capacity and associated used fuel discharge rate will both continue to increase well into the next century, requiring continued separations capacity additions to maintain this balance.

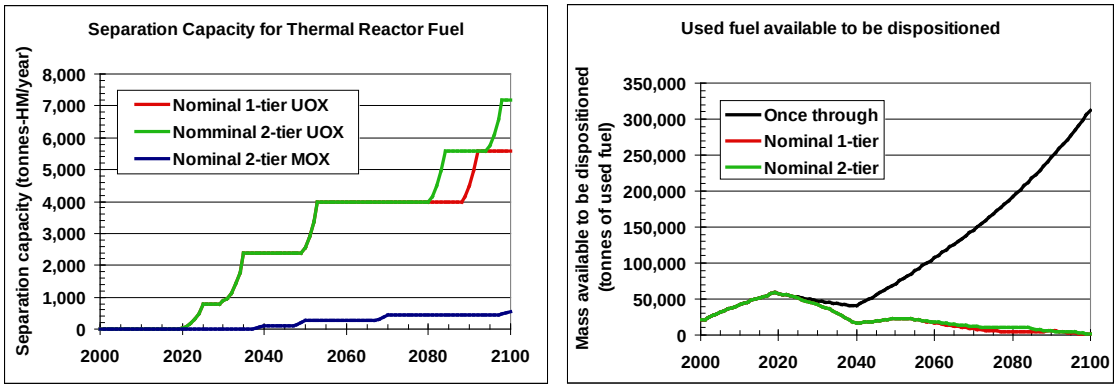


Figure 13. LWR used fuel separations capacity and feedstock for nominal cases showing the separations capacity increases needed to eliminate excess used fuel inventories.

3.2 Factors Constraining Fast Reactor Numbers

Several factors impact the number of fast reactors added during transition. This section uses the results of sensitivity analyses to show the relative impact of some of the more important factors. The 1-tier nominal scenario is used as the basis of analysis.

For all sensitivity runs, the same assumptions are used as for the nominal case except for the factor being examined and some associated parameters which need to be modified in tandem to keep the model in balance. For example, if a sensitivity analysis involves different values for the total nuclear growth rate, then startup dates for technologies, etc., are kept the same but the total amount of separations will be modified such that excess initial stocks of used fuel are still worked off, but there is no excess separations capacity sitting idle due to a lack of feedstock.

3.2.1 Feedstock Availability

The fast burner reactors assumed for the GNEP scenarios require TRU, including large amounts for initial startup and smaller continuing amounts as makeup for refueling. The initial core material for enough fast reactor capacity to produce 1 GWe-year of electricity[q] includes ~7 tonnes of TRU, and additional TRU would be needed for the initial refueling cycles when 100% of the fuel would still come from used UOX. After a few years, the fast reactor fuel could be recycled and the amount of "makeup" fuel from used UOX would drop by ~80%. The annual makeup TRU needed for refueling the same capacity of established fast reactors would be slightly less than half a tonne (Hoffman 2007).

The source for the TRU feedstock is the LWR used fuel, which must be reprocessed. Assuming all available TRU is used for fast reactors, the reprocessing capacity is the single largest factor impacting fast reactor availability. (The analyses assumed that fuel fabrication was not a constraint.) In the VISION model, if there is not sufficient TRU to start a fast reactor when a new reactor is needed, an LWR is built instead. Figure 14 shows the results of a sensitivity study on used UOX separations capacity; with lower total capacity, there are fewer fast reactors.

q. 3,210 MWt or 1,220 MWe of reactor capacity, assuming thermal efficiency of 38% and a capacity factor of 0.82.

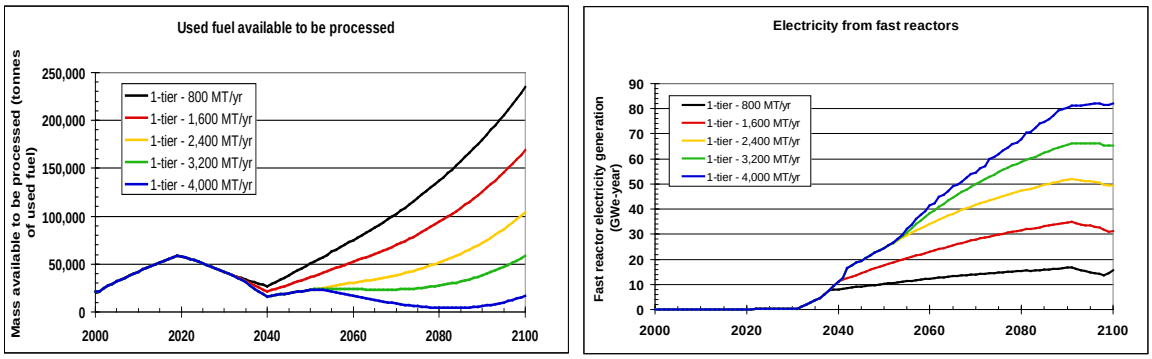


Figure 14. Impact of varying UOX separations capacity on the amount of fast reactors.

The separations capacity analysis is based on UOX at current burnup. Another feedstock consideration is the burnup of the used UOX. If burnup were significantly increased, many fewer tonnes of used fuel would be generated for the same level of electricity generation. However, the amount of TRU per tonne of used fuel would increase. At current burnup, the TRU content in used fuel is ~1.3%. If burnup could be doubled to ~100 GWd/MTiHM, of the tonnes of used fuel discharged would be cut in half, while the TRU content per tonne would increase to ~2%. Thus, the total amount of TRU would decrease, but the amount made available per tonne of separations capacity would increase. The isotopic makeup of the TRU also changes as burnup increases, with less fissile and more non-fissile content. This would equate to somewhat higher TRU content in the fast reactor fuel, so for the same fast reactor capacity slightly more TRU would be needed. (For the 2-tier scenario the impact of isotopic changes on Pu enrichment in MOX fuel would be greater because LWRs are more sensitive to fissile content.)

3.2.2 Growth Rate

Another major impact on the number of fast reactors is the overall growth rate of nuclear electricity. Higher growth equates to more used fuel, and assuming all available used UOX fuel is reprocessed, to higher numbers of fast reactors. Figure 15 shows the impact of growth rate on both the total electricity output from fast reactors and the percent output.[r]

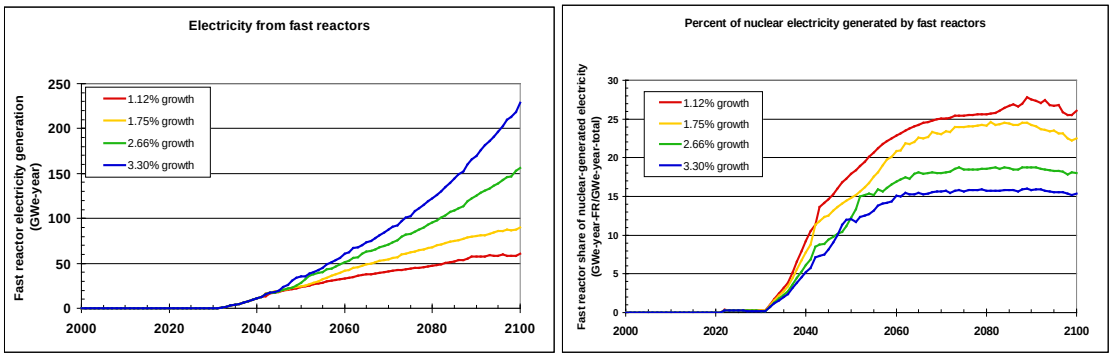


Figure 15. Fast reactors as a function of growth rate.

r. The growth rates used in the sensitivity analysis are based on achieving 150, 200, 300, and 400 GWe-year of nuclear electricity generation in 2060.

One important finding from dynamic analysis is 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 lags increase with increasing growth rate (e.g., more LWRs are added while fuel is cooling). This finding has implications on system economics, since the cost of fast reactors is currently projected to be higher than LWRs. At low growth rates, this cost difference will have a greater impact on the overall cost competitiveness of nuclear energy versus other energy sources, but as the growth rate increases, the cost difference due to closing the fuel cycle becomes smaller. Reactor and fuel cycle costs are discussed in more detail in Section 3.5.

3.2.3 Conversion Ratio Impacts

The TRU conversion ratio (CR) is calculated as the ratio of TRU produced to TRU consumed during fuel irradiation. Fast burner reactors are defined as having a CR <1.0. The CR has a large impact on the level of fast reactors for two reasons:

- In the initial core, changes in conversion ratio require virtually no change in TRU content. However, in refueling there is a very large difference. At a CR of 1.0, no additional TRU would be needed, whereas in an equilibrium core[s] at a CR of 0.0, roughly 1 tonne of makeup TRU would be required per GWe-year of generation.
- Since at higher conversion ratios less makeup TRU is needed, more fast reactors can be built from the TRU provided by the LWRs. However, at a constant growth rate, more fast reactors means fewer LWRs and less TRU generated. Thus, at higher CR, while less TRU is consumed, more TRU generation is avoided (by generating electricity using recycle fuels instead of UOX).

Figure 16 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 levels of fast reactor generation increases. The reason for this is as the conversion ratio increases—the total amount of TRU consumed plus avoided declines—so more net TRU is available for more fast reactors.

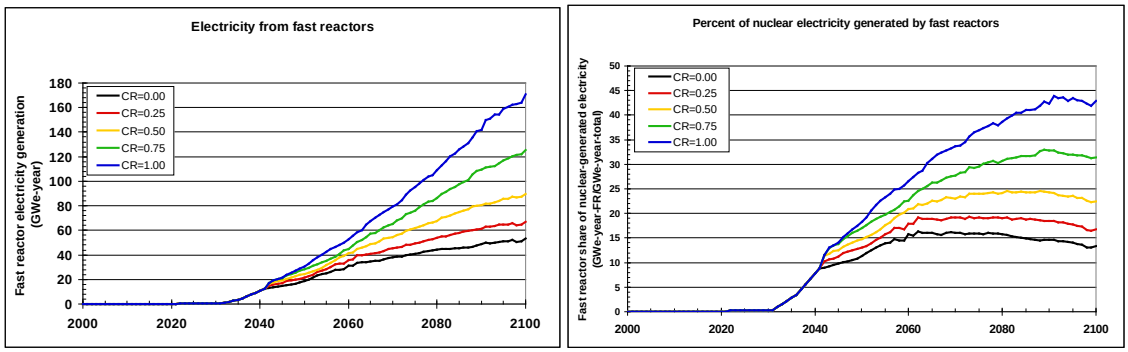


Figure 16. Fast reactors as a function of conversion ratio.

Figure 17 shows the impact of conversion ratio on both the amount of TRU consumed in the fast reactors and the amount of generation avoided in the LWRs. At low conversion ratios, consumption dominates as there are fewer fast reactors displacing LWRs, but each fast reactor has higher net TRU

s. The startup core of a fast reactor has an isotopic content based on the source of TRU, but as the fast reactor's fuel is recycled the content shifts and after several cycles an equilibrium content is reached. The equilibrium content is dependent on both makeup fuel content and the TRU conversion ratio.

consumption. At high conversion ratios, avoidance dominates because more LWRs are displaced by fast reactors, but each fast reactor consumes less TRU.

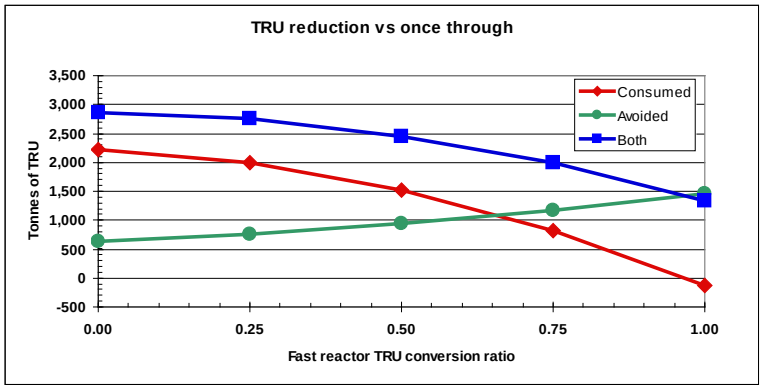


Figure 17. TRU reduction as a function of conversion ratio.

Figure 17 is based on the nominal growth rate of 1.75%. At higher growth rates, the blue line in the figure moves closer to level, indicating less sensitivity to conversion ratio.

3.2.4 Used Fuel Cooling Time

Used fuel cooling time is another parameter affecting feedstock availability, and therefore fast reactor capacity. The nominal cases are based on a system that is efficiently functioning by the end of the century, meaning no excess stocks of fuel at intermediate stages in the system, such as the excess fuel currently stored at reactor sites. The used fuel cooling time is assumed to be 10 years for LWR fuel (both UOX and MOX). This is based on the decay heat wattage limits of current shipping cask designs, which can accept full loads of used fuel at current burnup approximately 6 or more years after discharge. The value was rounded up, both to account for potential higher burnup and for MOX fuel. However, an "efficiently functioning" system could also be defined with longer cooling times. This would mean more TRU would be tied up in used fuel not yet available for reprocessing, and therefore fewer fast reactors.

3.2.4.1 Onsite versus Centralized Fast Reactor Used Fuel Recycling

Cooling time for fast reactor used fuel is a much larger factor than cooling time for LWR used fuel in determining the number of fast reactors deployed. The nominal case assumes onsite recycling of fast reactor fuel, which means it does not need to cool sufficiently for efficient shipping. For this reason, the assumed cooling time is only 1 year. (An additional year is assumed for separations and recycled fuel fabrication resulting in 2 years total recycle time.) One alternative is regional or centralized reprocessing of fast reactor fuel. A number of factors may lead to centralized facilities, including economies of scale and fuel type. However, significant transportation considerations must also be considered.[t]

Centralized reprocessing is more likely if an aqueous technology is used, because this technology has significant economies of scale. The overall plant complexity stays fairly constant with size, while the lines, tanks, and other equipment scale up. If an electrochemical (Echem) process is used, there is not as significant a gain in scale economies. Echem is essentially a batch process with limits on equipment size, so a larger plant would involve more processing stations, and therefore more equipment and complexity. Aqueous processing is usually equated with oxide fuels and Echem with metal fuels; both fuels have been

t. Transportation technical issues are a current area of systems studies.

used successfully in fast test reactors. A decision on fuel type for the initial GNEP fast reactor has not yet been made, as more information is needed.

Fast reactor fuel produces higher levels of decay heat per MTiHM than LWR UOX fuel. The fresh fuel has a high percentage of TRU, including plutonium-238 (Pu-238), americium-241 (Am-241) and curium-244 (Cm-244). Used fuel has large percentages of both TRU and fission products (due to much higher burnup than UOX). The fuel also contains heavy isotopes with high energy decay products, requiring substantial shielding. These properties of fast reactor fuel make shipping more difficult, and longer cooling times or less fuel per shipment may be required.

Figure 18 shows the impact of fast reactor fuel cooling time on the fraction of fast reactors at the end of the century. The impact of fuel type is also shown. Oxide fuel has a softer spectrum, allowing for longer fuel cycles but also requiring more TRU to support those cycles, and therefore more initial TRU for startup. However, overall impact of fuel type is minimal when compared to the impact of cooling time.

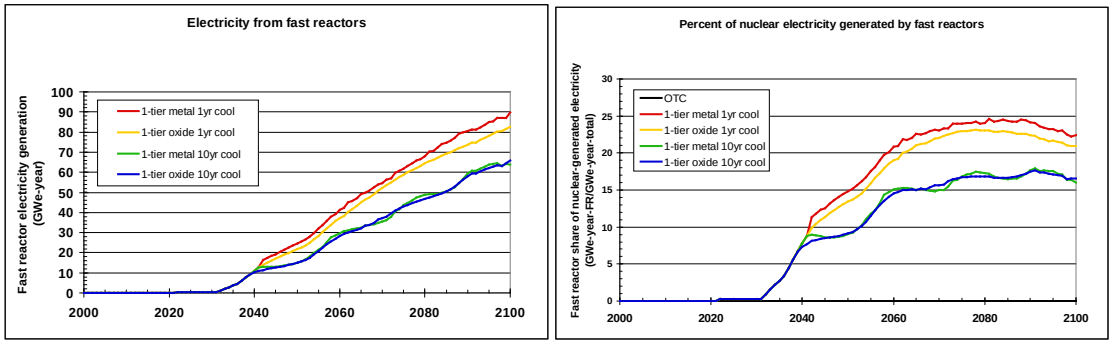


Figure 18. Impact of cooling time and fuel type on fast reactor level.

3.2.5 Impact of Fast Reactor Deployment Timing

The final factor considered in determining the level of fast reactors is the time of introduction of the technology. The nominal 2-tier case has the effect of pushing back fast reactor introduction by ~15 years (versus 1-tier) while the TRU is tied up moving through the MOX cycle. But the timing of fast reactor introduction could also be later for the 1-tier case. Figure 19 shows the impact of pushing back fast 1-tier fast reactor introduction by 5, 10, and 15 years, while including the nominal 2-tier case for comparison.

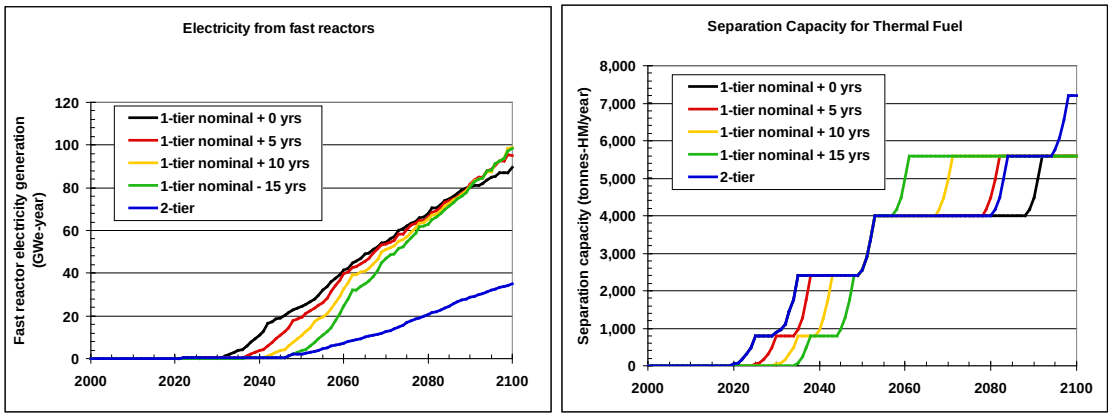


Figure 19. Impact of varying fast reactor introduction timing.

Later fast reactor introduction has little long-term impact on the numbers of fast reactors. In fact, there are more fast reactors toward the end of the century than in the nominal scenario. This is due to more TRU being generated by LWRs in the middle of the century (less TRU avoided), providing more feedstock. While initial separations is delayed (because there are no fast reactors to take the separated TRU), separations capacity additions must be brought on line sooner to achieve the elimination of excess used fuel by 2100. Stores of cooled fuel are two to three times as high throughout much of the century due to both the larger numbers of LWRs generating it and the delay in separations capacity deployment.

3.3 Factors Impacting TRU Management

The management of TRU is a major emphasis behind closing the fuel cycle. The waste management benefits of TRU management are discussed in Section 5.2, which emphasizes the importance of keeping transuranics out of the waste streams. This section looks at the factors that impact the amount of TRU in the fuel cycle.

3.3.1 Nominal TRU Inventories

The nominal cases all assume TRU is either disposed (once-through), "working" in reactor cores (1-tier and 2-tier), or in cooling used fuel (all scenarios). Figure 20 shows the general locations of TRU in all three scenarios.

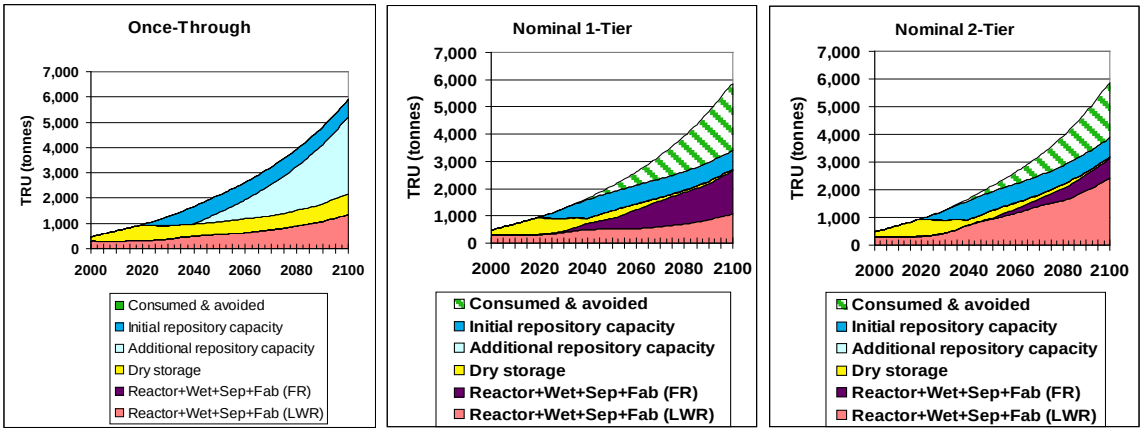


Figure 20. TRU location in the fuel cycle for once-through, 1-tier, and 2-tier scenarios.

The location of TRU for the once-through scenario is identical to the location of used fuel in Figure 8. However, for the 1-tier and 2-tier scenarios, the relative amount of TRU consumed and avoided is less than the amount of used fuel reduction in Figure 12. This is due to the higher concentrations of TRU in MOX and fast reactor fuel. The amount of TRU in used fuel increases considerably in moving from UOX to MOX and FR fuel. Used UOX has a relatively low TRU content (~1.3% at current burnup). In used MOX fuel the TRU content is roughly five times higher, while in used fast reactor fuel (at CR = 0.5) it is around twenty times higher. Due to the large differences in TRU content of the used fuels, the assumed cooling times for fast reactor and MOX fuels have a large impact on TRU inventories.

The 1-tier scenario has a larger amount of TRU consumed and avoided (~2,500 tonnes), primarily because there are more fast reactors at work. The 2-tier case has less TRU available for fast reactors and it is available later, but the MOX cycle does avoid some TRU generation. Much of the TRU in the system in the 2-tier case is either in the LWRs or cooling after LWR discharge (the salmon-colored band) and the total TRU consumed or avoided is about 25% less (~2,000 tonnes).

All cases show more TRU at the end of the century, due to the overall growth in the amount of electricity generated by nuclear energy, and the closed fuel cycle cases have more TRU "in the system" versus the once-through scenario (assuming the extra used fuel has been disposed rather than sitting in storage). This is an important finding—to permanently consume/avoid TRU, more TRU must be "at work."

3.3.2 Consumption and Avoidance

The largest factors in TRU inventories for the closed fuel cycle scenarios are the amount of TRU consumed in recycle fuel and the amount of new TRU generation avoided by generating electricity using recycle fuels instead of UOX. Focusing on 1-tier recycle, the consumption rate is driven by the CR, while the number of fast reactors is driven by a number of factors just discussed. Static analysis significantly overestimates the total fast reactor level. Figure 21 shows the average share of total nuclear electricity coming from fast reactors in the final decade of the century as a function of both conversion ratio and growth rate. The values calculated for static equilibrium (growth independent) are shown for reference. The graph extends to a CR of 1.07 to better show the static and dynamic trends around the "break even" point of CR = 1.0.

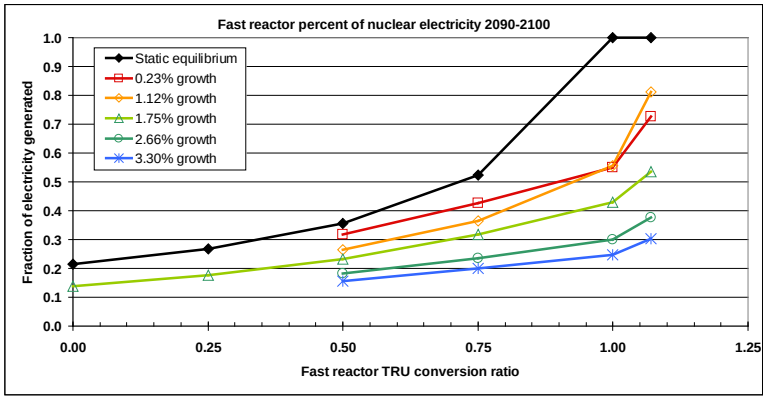


Figure 21. Fraction of fast reactors as a function of both CR and growth rate.

The trends are all consistent except for the lowest growth rate at the highest conversion ratios, when additional constraints apply. At very low growth, most new reactors are replacements for retiring reactors, so the percent of fast reactors depends not only on how much TRU is available, but when. At high conversion ratios and low growth rates, no new LWRs are built after midcentury, but due to growth rate constraints not enough fast reactors are built to use all the TRU available.

The impact of avoidance is an important insight gained from the systems analyses. LWRs operating on UOX are fairly efficient TRU breeders, producing ~270 kg of TRU per GWe-year. A fast reactor operating at a CR = 1.07 produces less than half this amount. Thus, for an equal amount of electricity generation, less TRU is created by operating a fast reactor with a low TRU breeding rate than operating an LWR with UOX. The impact on total TRU generation is muted by the fast reactor deployment rate but is still significant. Figure 22 shows the cumulative impact of deploying fast reactors at a CR = 1.07 at different growth rates, with the solid lines showing the amount of TRU generation avoided (positive values) and the dashed lines showing the amount "consumed" (negative values because TRU is actually being generated). At the nominal growth rate of 1.75%, the difference is a net decrease of 900 tonnes of TRU versus once-through (850 tonnes generated versus 1,750 tonnes avoided).

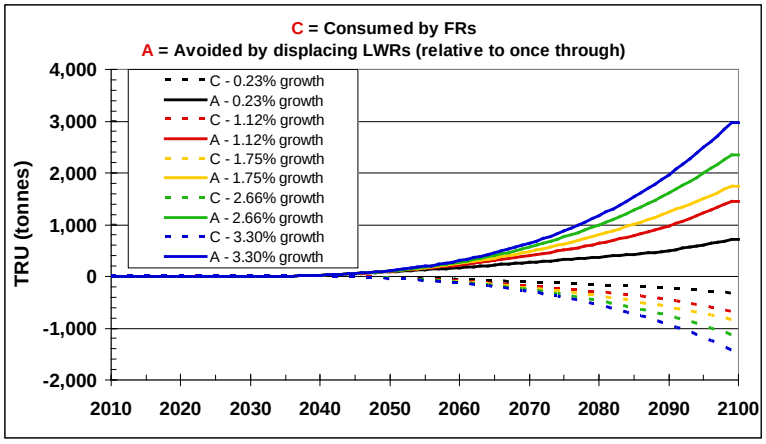


Figure 22. TRU avoided versus created when deploying fast reactors at CR = 1.07 as a function of growth rate.

If the entire fleet of reactors was composed of fast reactors of CR slightly above 1, not only would less total TRU be generated, but no uranium enrichment would be required. The small extra TRU generated would support new reactors to maintain a low growth rate. The relationship of conversion ratio to growth rate can be expressed as

$$CR = e^{m(t_F + t_R)}$$

where

m = desired nuclear power growth rate

t_R = time that TRU is in fast reactors

t_F = time between fast reactor discharge and re-insertion (and isotope decay is ignored).

For the nominal assumptions, including collocation of efficient recycling facilities, the nominal growth rate of 1.75% can be achieved with a CR = 1.11.

The impact of cooling time is significant. If centralized recycling of the fast reactor fuel is assumed, the used fuel cycle time from discharge to re-insertion increases from 2 to 11 years and the associated CR needed to support 1.75% growth increases to 1.30.

3.3.3 Startup and Buffer Impacts

The management of TRU during the initial deployment of GNEP facilities is a special problem. LWR separations are assumed to be brought on line in large steps, with an 800 MT/yr initial plant starting as early as 2020. This plant will separate 10+ tonnes of TRU per year when at full operation. However, commercial fast reactor deployment using TRU-based fuels is not expected until 2032 or later, based on the time needed to complete development and qualification of the TRU fuels. This results in a period of time in the 1-tier scenario when separations are occurring but the separated material is stored rather than immediately used. In the 2-tier scenario, the impact is reduced because the plutonium can be fabricated into MOX without delays and only the minor actinides require storage.

Figure 23 shows the amount of excess stored TRU for the 1-tier scenario based on a sensitivity study where deployment of the commercial fast reactors occurs up to 15 years later than the nominal case. The

nominal case shows the impact of ramping up the initial 800 MT/yr separations plant before there are fast reactors to use the separated product. The inventory builds to a peak of ~35 tonnes in 2028 then declines as fast reactor fuel begins fabrication while the reactors are under construction (so initial cores are available for startup). The later deployment cases show how much additional TRU accumulates if the fast reactors are not available in the quantities and schedule assumed. The TRU accumulation rate increases in the mid-2030s as 1,600 MT/yr of additional separations capacity ramps up. The graph shows only the mass of TRU, but the material may also contain uranium, increasing the total inventories. The material (with or without uranium) will require shielded, cooled secure storage.

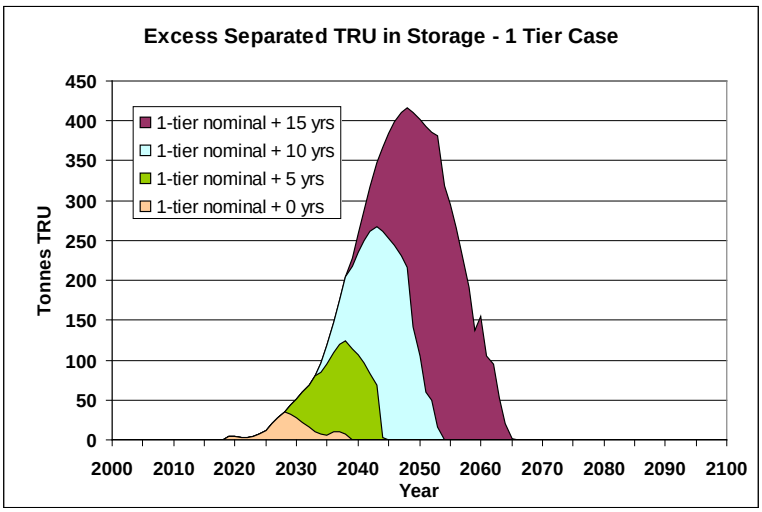


Figure 23. Excess separated TRU in the 1-tier scenario as a function of fast reactor deployment timing.

A second operational issue is the amount of TRU that needs to be in buffer storage throughout the system. These buffers need to protect the system against temporary shutdowns of processing facilities or associated transportation links. Each buffer needs to be of sufficient size to ensure continued operation of downstream facilities, factoring in maintenance (planned shutdowns), reliability (unplanned shutdowns), and alternate material sources or other forms of system flexibility. The material in the buffers is considered to be "in process" rather than "idle" because it is required for smooth system operation. The eventual sizes of the various buffers will depend on detailed design and reliability data, number of parallel facilities, etc. Currently buffers are modeled via minimum time steps to move through a facility (for example, 6 months in separations), with the exception of a separate "TRU bank," which is explicitly modeled. The TRU bank size is a function of a combination of the largest single UOX separations plant capacity, representing the largest unit of supply which could have an unplanned shutdown, and the total TRU needs of the fast reactor fleet, representing the amount of demand that needs to be supported. As currently modeled, the TRU bank tops out at ~62 tonnes.

3.4 First Facility Constraints

The previous discussion has considered overall transition from a once-through to a closed fuel cycle. This section focuses on issues associated with the initial facilities that would begin that transition by examining some of the system-level considerations involved with their startup.

3.4.1 Technology Readiness and Uncertainty

The advanced fuel cycle includes a number of facilities and other capabilities which require new technologies. The current development level of many of these technologies is insufficient to support

design and construction of full-featured, advanced industrial-scale facilities. Two generic pathways have been assessed for moving forward:

- Measured scale-up of advanced technologies as they mature, passing from bench scale to laboratory scale and engineering scale before deployment at full industrial scale.
- Near-term industrial scale deployment of mature but less advanced technologies, with a phase-in of more advanced technologies as they mature. Phase in would be accomplished via retrofits or as part of the design of follow-on facilities.

The current GNEP approach is a combination of these pathways.

3.4.2 Managing Uncertainty

The technology fielding approach for each initial component of the closed fuel cycle is highly dependent on other components. Any integrated deployment plan will likely require several changes during execution due to technology and regulatory uncertainties.

Technology uncertainties include both uncertainties in the rate of development progress and in the predicted full-scale performance. If development progress proceeds slower than planned, other facilities may also be delayed due to interdependencies.

New technologies often also require new or modified regulations to properly ensure their safe and secure application while also removing unintended roadblocks. Current regulations designed for management of intact used fuel may not adequately address facilities for separating used fuel into recyclables and wastes with different contents and forms. The potential for regulatory changes increases the already large uncertainty of the time required to license a new fuel cycle facility or certify a new waste form.

A good tool for managing uncertainty is flexibility. A closed fuel cycle involves a number of interdependent components. Since the timing, features, and performance of all initial facilities is subject to change, a flexible implementation strategy involves reducing interdependencies. Examples of this approach include:

- The UOX separations plant is dependent on fast reactors to use its product, but initially the product could be stored or used in MOX in LWRs. The initial separations plant could use proven technologies which do not capture minor actinides for recycle (resulting in reduced waste benefit in the near-term).
- The fast reactor is dependent on separations for fuel, but could be fueled initially using either excess highly enriched uranium or excess plutonium from other government programs. Fabrication of fuel from these materials would not require fully remote operations, so initial fabrication facilities could be constructed more quickly and at lower costs.
- A fuel cycle research facility could provide engineering scale demonstration of advanced technologies which would serve to prove out technologies before committing to industrial scale construction projects while providing the smaller quantities of materials and smaller scale fully remote fuel fabrication and separations initially needed.
- Advanced transmutation fuels development is dependent on fast reactors for irradiation of lead test assemblies, but smaller international test reactors could be used for initial development (up to rodlets) and proven fuels without minor actinides could be used on an interim basis. If the initial separations plant does not capture minor actinides, a fuel cycle research facility could provide the needed materials for fuels development.

- After transmutation fuels are proven, the core of the fast reactor would be converted to a transmutation fuel core. Transition of the fast reactor to a full core of transmutation fuel would require additional feedstock and fabrication capacity. If experiments have been completed in the fuel cycle research facility, the separations and fabrication capabilities could be converted to full-time operation to support this need, but only if the relative sizes of the reactor and laboratory are compatible. Otherwise, the commercial-scale separations facility would need to be able to supply feedstock and fuel fabrication sufficient for core conversion.

The systems studies needed to address initial facility material flows and capacities will be performed iteratively as the planning and designs for these facilities mature, such that the systems studies inform the next level of planning, and the resulting design work informs a new level of system studies. This is part of the transition from the definition phase of systems analysis to the deployment phase, where the systems studies move into classical systems engineering.

3.4.3 Learning

First facilities may be demonstrations or full scale. In either case, there is a significant opportunity for operational improvements and cost reductions during the period from when the first-of-a-kind (FOAK) facilities are built, proceeding to the second through the nth-of-a-kind (NOAK) facilities. This is particularly applicable to fast reactors, since the initial learning gained from the advanced burner reactor and the first few commercial fast reactors can drive down construction costs, lead to technology refinements, and improve the operational efficiencies that allow reactors to be operated at high capacity factors.

To determine the effects of learning, a study was conducted (EAWG 2007) to develop a general economic model to forecast the costs of a FOAK and NOAK fast reactor. The model was based on previous cost engineering and econometric studies and assumed a modular reactor design. The study assumed that future learning rates in the U.S. nuclear construction industry would be between 3 and 10% (U of C 2004). The cost relationships between FOAK to NOAK were developed from industry cost estimates for NOAK system costs. The study identified five key assumptions for fast reactor deployment, where deployment is assumed to consist of at least 8 GWe of capacity with a commercial fleet size of 32 GWe:

1. The deployment of advanced recycle reactors would involve more or less continuous construction of two reactors per power block with 8 power blocks (i.e., 16 to 24 modular reactors, with an equilibrium production of two reactors per year from 8 to 12 years), thus capturing “economies of series” in production.
2. Reactor modules would be built at one national (or international) location and shipped in pieces for assembly at the site, thus allowing the internalization of factory learning (because of the smaller reactor vessel, it is assumed that there are competitive manufacturers of these reactor vessels; if there are few reactor vessel manufacturers, much of the cost savings that would be attributable to learning could be captured by monopolistic equipment manufacturers). Construction crews could work nationally or internationally on modular, sequential sites, thus capturing “learning by doing.”
3. An internationally certified standardized design would support capturing “economies of standardization.”
4. The construction industry is assumed to bid these jobs aggressively. However, to help align the incentives of all participants, equity positions in the plant could be held by a construction manager, the architect-engineer, the nuclear energy system supplier, the fuel supplier, and the plant owner and operator. This incentive structure maximizes the discovery of cost and risk reduction opportunities, thus helping to capture “economies of diversification and risk management.”

5. Fast reactor deployment is well orchestrated with all regulatory bodies and most stakeholders on board, as well as assured continuous government and corporate funding of research, development, demonstration, deployment, and commercialization.

The study used a range of learning rates (3% to 10%) to evaluate the decline in cost from FOAK to NOAK with each doubling of capacity to 8 GWe. At the highest learning rate of 10%, the FOAK costs would be 53% higher than the NOAK unit. For more likely learning rates between 3 and 6% (per doubling), FOAK capital costs range from 12% to 23% higher than NOAK costs. This range of cost difference is well within the range of uncertainty of the fast reactor costs used in this study. These results are shown in Figure 24. The impact of learning on NOAK costs is significant and supports the value of planning for a learning period during fast reactor deployment as a way to reduce the relative cost differential between LWRs and fast reactors. (This differential is discussed in Section 4.)

Figure 24. Fast reactor learning rates for a range of learning curves.

3.5 Fuel Cycle Transition Objectives

Section 1.3 discussed timing objectives for deploying advanced fuel cycle technologies. The general objectives from 2005 included fielding of advanced separations technologies by 2025 and burner fast reactor technologies by 2040, but recent events associated with a greater potential for new reactors and another delay in the repository availability date are driving acceleration of these dates.

Assuming the technologies are available, the systems analyses presented in this section have shown that fielding of separations by 2020 is feasible from a material flow perspective, and fielding of fast reactors in limited numbers could occur within the following ten years. The rate for initial fast reactor deployment would be highly dependent on the size of the initial separations facility and less dependent on growth rate and conversion ratio. After a learning period and the construction of additional separations capacity, fast reactor deployment could proceed in earnest. The next section will assess the economics of deploying a closed fuel cycle system.

4. SYSTEM COSTS

This section presents a summary of system cost comparisons between closed fuel cycles and the once-through fuel cycle contained in the GNEP Economic Analysis report (EAWG 2008). The analysis combines fuel cycle costs with reactor costs (with associated uncertainties) to produce a total cost of electricity representing the levelized cost of a system consisting of all reactors and the supporting fuel cycle services. Reactor costs consist of capital, operating, and decontamination and decommissioning (D&D) costs. Fuel cycle costs include front-end and back-end costs, as well as costs associated with fuel recycling. System cost comparisons are presented in terms of cost distributions and/or ranges rather than single point values. Reactor and fuel cycle technology research, development, and demonstration costs are not addressed.

The analysis provides a baseline system cost comparison between the once-through fuel cycle and closed fuel cycle systems to improve understanding of overall cost trends, cost sensitivities, and trade-offs. The analysis also improves understanding of the cost drivers that will determine nuclear competitiveness. This cost analysis builds on the AFCI program cost collection, economic methodology and algorithm development, and economics studies.

One of the primary resources developed by the AFCI/GNEP Economic Analysis Working Group (EAWG) is the "2008 Advanced Fuel Cycle Cost Basis" (AFC Cost Basis) report (Shropshire 2008), which contains approximately 400 reference citations. The "GNEP Economic Tools, Algorithms, and Methodology" report (EAWG 2007) includes the cost models and methodologies for use in the economic analysis activity. The primary elements of the analysis methodology include:

- The economics submodel of Verifiable Fuel Cycle Simulation (VISION.ECON) and Generation IV Excel Calculations of Nuclear Systems (G4-ECONS) modeling and analysis
- Definition of front-end costs (uranium and secondary supply analysis, enrichment and fuel fabrication market structure economics)
- Evaluation of reactor construction learning (GNEP facility deployment analysis)
- Insights to current fuel separation costs in the U.S.

The cost analysis was performed using G4-ECONS to provide static (snapshot-in-time) cost under equilibrium system conditions. The spreadsheet data were evaluated for their cost uncertainty using a software program called Decision Programming Language (DPL). The analysis also considers dynamic conditions such as start-up, ramp-down, end-of-life conditions, intermittent or long-term storage strategies, and fuel cycle facility and reactor deployment scenarios. VISION.ECON was used to provide the dynamic cost analysis consistent with the scenarios presented in Section 3. The software was also used to perform sensitivity analyses and evaluate uncertainties in the cost due to system performance effects. For verification purposes, the static spreadsheet model was used as a check on the accuracy of the dynamic results.

The system costs were developed from a foundation of referenced cost information. In Table 2, the cost ranges are provided for the fuel cycle front-end and back-end, recycling processes, and LWR and fast reactors. The associated low, nominal, and high costs and units of measure are primarily based on the March 2008 AFC Cost Basis report (Shropshire 2008). Some subsequent analysis was performed to further define costs in specific areas of the analysis (e.g., waste conditioning, storage, and disposition). All cost estimates are in current year dollars (2008) and are intended to support comparative assessments of scenarios including growth.

Table 2. Cost ranges for fuel cycle and reactor cost modules.

Variable	Low	Nominal	High	Units
A - Natural Uranium Mining and Milling	25	60	240	$/Kg U
B - Conversion Processes	5	10	15	$/Kg U
C1 - Enrichment	80	105	130	$/SWU
D1-1 - LWR UO2 Fuel Fab	200	240	300	$/Kg U
D1-2 - LWR MF Fuel Fab	1,000	1,950	4,000	$/Kg HM
K1 - Depleted Uranium Disposition	5	10	50	$/KgU
E2 - Dry Storage ($ normally included with reactor costs)	100	120	300	$/Kg HM
I - Monitored Retrievable Storage	94	96	116	$/Kg HM
L1 - Geologic Repository (SNF)	400	1,000	1,600	$/Kg HM
L2-1 - Geologic Repository (HLW FPs+Ln+Tc)	2,500	10,000	12,500	$/Kg FP
L2-2 - Geologic Repository (activated hulls)	387	1,000	1,550	$/Kg metal
M1 GTCC Intermediate Depth Disposal (GTCC Iodine+hulls)	70,000	100,000	440,000	$/m3 GTCC
F1-1 UREX+1A Aqueous Separation	500	1,000	1,500	$/Kg HM
F1+ (HYBRID) UREX+3, Product Conditioning, 15 years storage (2-Tier)	700	1,320	2,080	$/Kg HM
F2/D2 - Reprocessing - Electrochemical & Remote Fuel Fab	2,500	5,000	7,500	$/Kg HM
E3-1 - Recycled U/TRU Product Storage	7,000	10,000	13,000	$/Kg TRU
E3-2 - Recycled U/Pu Product Storage	3,500	5,000	6,500	$/Kg Pu
G3-1 - LLW Conditioning, Storage, Packaging (solids)	400	500	1,000	$/m3 solids
G3-2 - LLW Conditioning, Storage, Packaging (liquids)	3,300	11,000	22,000	$/m3 liquids
G3-3 - LLW Conditioning, Storage, Packaging (resins)	81,000	90,000	99,000	$/m3 resins
J - Near Surface Disposal	450	1,250	2,500	$/m3 LLW
G4-1A - Aqueous LLW-GTCC Offgas absorber (H3, Kr, Xe)	8,000	11,200	15,000	$/m3 gas
G4-2A - Aqueous GTCC Ceramic Conditioning (Cs/Sr)	5,700	7,800	12,000	$/Kg Cs/Sr
G4-1E - EChem LLW-GTCC Offgas absorber (H3, Kr, Xe)	8,000	11,200	15,000	$/m3 gas
G4-3E - Echem GTCC GBZ Conditioning (Cs/Sr+I)	5,700	7,800	12,000	$/Kg Cs/Sr+I
E4 - Managed Decay Storage (Cs/Sr)	10,000	22,500	35,000	$/Kg Cs/Sr
G4-4A - Aqueous LLW-GTCC Ag Zeolite (Iodine)	50,000	67,000	80,000	$/m3 Iodine
G4-5A - Aqueous GTCC Metal Alloy Conditioning (ZrSS)	200	540	1,800	$/Kg metal
G1-1A - Aqueous HLW Conditioning, Storage, Packaging (FP+Ln)	1,800	2,000	2,700	$/Kg FP
G1-2A - Aqueous Metal Alloy (Tc)	18,000	25,000	30,000	$/Kg Tc
G1-2E - EChem HLW Metal Alloy Conditioning (ZrSS+Tc)	200	540	1,800	$/Kg metal
G2 - UOX or (UOX/MOX) Conditioning & Packaging	50	100	130	$/Kg HM
G5 - CH-TRU Conditioning, Storage, and Packaging	69,000	70,000	90,000	$/m3 TRU
K2 - RU Disposition from Aqueous Reprocessing	6	12	30	$/Kg RU
K3 - RU Conditioning for Electrochemical Reprocessing	75	93	150	$/Kg RU
R1 - Thermal LWR Reactor (Overnight Capital)	1,800	2,300	3,500	$/kW(e)
R2 - Advanced Recycling Reactor (Overnight Capital)	1,800	2,900	5,000	$/kW(e)
r - Real Discount Rate	5.0	7.5	10.0	%
c - Construction Time	3.5	4.0	5.0	years
R1 - Thermal LWR Reactor (O&M Fixed)	55	64	75	$/kWe-yr
R2 - Advanced Recycling Reactor (O&M Fixed)	60	68	80	$/kWe-yr
R1 - Thermal LWR Reactor (O&M Variable)	0.8	1.8	2.5	mills/kWh
R2 - Advanced Recycling Reactor (O&M Variable)	1.0	2.0	2.7	mills/kWh

4.1 Total System Costs

The majority of the costs for the open and closed systems are in the reactor capital and operations and maintenance (O&M). These costs make up 82 to 85% of the total cost of electricity (TCOE) of the systems. The non-reactor (fuel cycle) cost for the once-through system is less expensive at 15% of the TCOE, as compared to 18% for the 1-tier and 2-tier systems. A breakdown of the cost composition of the once-through and the two closed fuel cycle systems is provided in Figure 25. In the once-through system, the largest cost components are the LWR capital and O&M which comprise 85% of the total costs. The front-end and back-end costs cover the remaining 15%, and there are no recycling costs. For the 1-tier system, the largest cost components are LWR and fast reactor (FR) capital and O&M, which encompasses 82% of the total costs. The front-end and back-end costs are a lower percentage than for the once-through, and the recycle costs comprise 10% of the remaining costs. For the 2-tier system, the largest cost components are the LWR and FR capital and O&M consisting of 82% of the total costs, including LWRs and FRs. The front-end and back-end costs are a lower percentage than for the once-through, and the recycle costs comprise 10% of the remaining costs.

Figure 25. Cost break-down of the once-through, 1-tier, and 2-tier systems.

Analysis of fuel cycle system costs involve large uncertainties due to variation of reactor capital costs, uranium prices, recycle facility costs, variations in waste forms, repository costs, etc. These uncertainties are reflected in the probability distributions for total fuel cycle costs. Figure 26 shows the large cost uncertainties with all the fuel cycle strategies, with equilibrium total costs of electricity ranging from ~$30 to $80/MWh,[u] with a most-likely range of $40 to $60/MWh. The associated fuel cycle costs range from $5/MWh to $13/MWh.

While the distributions overlap, the expected values for both closed fuel cycle cases are $5 to $6/MWh higher than the expected value for once-through (or about 10% higher cost). The primary contributor to this cost "gap" is fast reactor capital costs averaging higher than LWR capital costs. Fuel cycle cost differences also contribute up to 40% of the gap. Note that the results shown are for a static balanced system of LWRs and fast reactors in equilibrium. As discussed in Section 3, the percent share of fast reactors during deployment is considerably lower, so the portion of the cost gap due to higher fast reactor capital costs would be reduced. This dynamic impact is sensitive to the growth rate, with higher growth resulting in a smaller relative share of fast reactor and a smaller corresponding cost gap.

u. Note: "$/MWh" is the same as "mills/kWh." Divide above numbers by 10 to get cents/kwh.

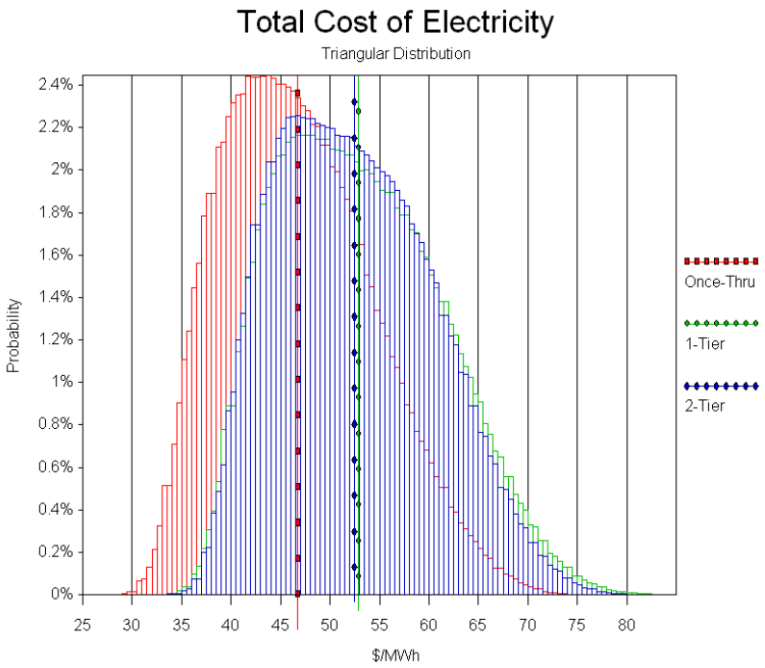


Figure 26. Total cost of electricity including uncertainty for the once-through, 1-tier, and 2-tier systems.

The economics team has identified reactor cost, performance improvements, and fuel cycle cost reductions that can (when combined) effectively close the cost gap between closed and open cycles. The reactor cost distributions and uncertainties shown in Figure 27 include the capital, O&M, and financing interest rate variables. Color-coded, double-headed arrows show the primary cost uncertainties (ranges) with respect to the nominal costs (vertical dotted lines) from Table 2 for each of the distributions. The lengths and positions of the arrows show the range of cost uncertainty due to varying each factor from its low value to its high value. The uncertainties include:

Construction Finance Interest. A large and important source of cost variability with potential to affect all nuclear reactor deployments. The interest rates, which could range from 5% to 10%, are related to the perceived risk of the nuclear capital investment. The newer, less proven FRs would be considered to have higher risks than the proven LWR designs. General market conditions (e.g., conservatism in borrowing) could also drive the market toward higher (or lower) rates for LWRs and FRs.

1. Construction Finance Interest. A large and important source of cost variability with potential to affect all nuclear reactor deployments. The interest rates, which could range from 5% to 10%, are related to the perceived risk of the nuclear capital investment. The newer, less proven FRs would be considered to have higher risks than the proven LWR designs. General market conditions (e.g., conservatism in borrowing) could also drive the market toward higher (or lower) rates for LWRs and FRs.
2. FR overnight capital. A source for significantly increasing the costs of the closed fuel cycle. These costs are affected by their wide potential range of costs ($1,800 to $5,000/kWe) and the percentage of FRs in the system. The capital costs for 1-tier systems have a higher cost range than 2-tier systems due to the larger percentage of FRs in the 1-tier system.
3. LWR overnight capital. A large source of potential cost uncertainty ($1,800 to $3,500/kWe) for the once-through cycle as well as closed systems that include LWRs. There are also common construction cost factors (construction materials, escalation, etc.) that could drive up the costs of all power plants (i.e., nuclear, fossil, renewable).

4. Reactor O&M. A relatively low cost uncertainty as compared to the other variables shown. It includes a fixed component not dependent on power generated and a variable component that varies with power generated.

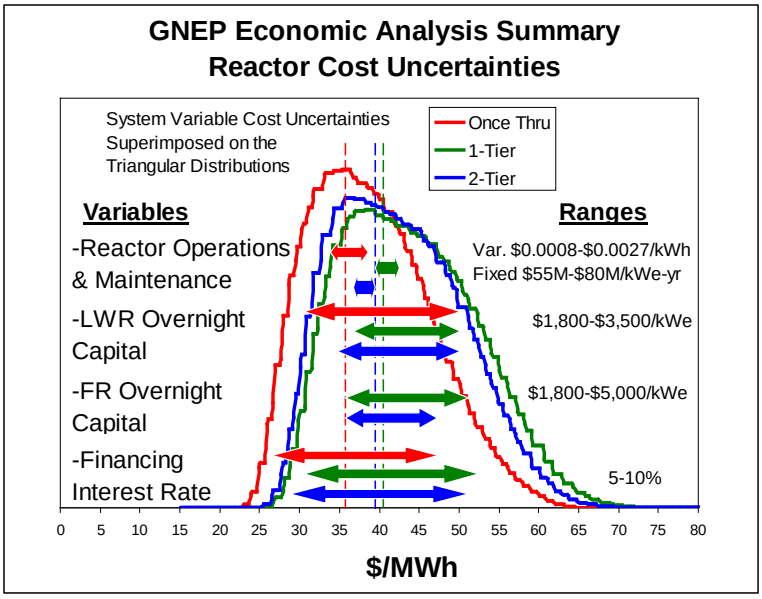


Figure 27. Reactor cost uncertainties showing interrelationships of uncertainty contributors.

4.1.1 Learning

As discussed earlier in Section 3.4.3, there are significant opportunities for operational improvements and cost reductions during the period from when the FOAK facilities are built, proceeding to the second through the NOAK facilities. This is particularly applicable to fast reactors, since the initial learning gained from the advanced burner reactor and the first few commercial fast reactors can drive down construction and start-up costs, lead to technology refinements, and improve the operational efficiencies that allow reactors to be operated at high capacity factors.

The analysis presented here uses reactor and fuel cycle facilities that represent NOAK costs. Due to the relatively rapid deployment of the new systems, the costs are expected to be driven down from the FOAK to NOAK systems within the first decade of deployment. For the purposes of consistency and comparability, any further evaluation of the FOAK to NOAK is left to a future cost sensitivity analysis.

4.1.2 Nuclear Energy Costs in Perspective

Nuclear energy generation costs were compared to the generation costs projected for other future base-load electricity producing technologies, including a review of the domestic market competitiveness of nuclear energy as compared to fossil fuel-derived electrical energy (particularly if carbon is taxed or carbon capture/storage is required). The overall assessment shows that the busbar electricity cost from nuclear and conventional pulverized coal power are similar (with a slight advantage to coal) if no cost of carbon (tax, carbon capture/storage, or “cap and trade” program) is imposed. Natural gas, a relatively clean energy source that until recently has been the preferred source for new baseload electricity, now suffers from high fuel costs and continued volatility. A carbon tax greater than a few dollars per tonne of carbon dioxide would shift the fossil fuel energy cost edge toward nuclear, even for closed fuel cycle systems. These domestic results are similar to the global results presented in Section 2.

Figure 28 shows the costs for the fossil fuel technologies, both with and without the cost of carbon, along with the three nuclear systems. The cost ranges for each system were developed by setting individual cost parameters at the low, nominal, or high values. The uncertainty in the cost of carbon is the largest uncertainty driver for the fossil fuel technologies. For natural gas, the volatility in fuel pricing is also a highly significant contributor to the wide distribution.

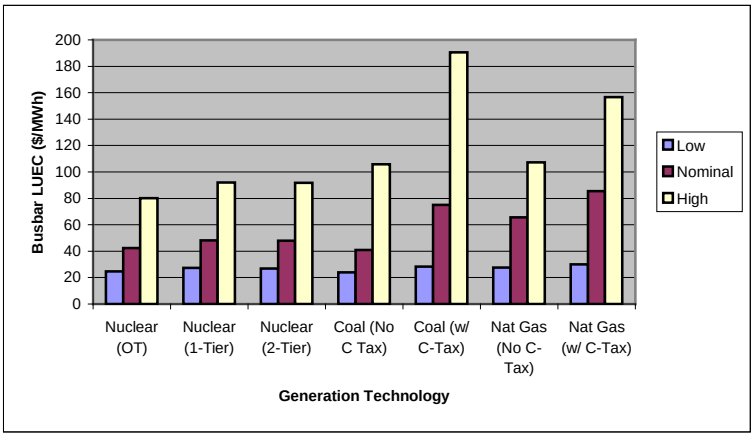


Figure 28. Comparisons of busbar costs of baseload energy systems.

The following conclusions can be drawn from these studies:

- Closing the nuclear fuel cycle would result in a much smaller cost increase to the cost of electricity than the addition of a "cost of carbon" (tax or CCS) to fossil fuel-based energy sources.
- The potential cost of carbon is a major cost driver for the fossil technologies.
- The fossil energy costs are largely driven by the cost of the fuels themselves, which tend to move with the cost of crude oil. The oil-linkage effect is greatest for natural gas.
- The cost of carbon is assumed to cover the social and environmental costs of greenhouse gas emission or the costs of mitigation/adaptation. Nuclear costs include all costs for safety, emissions control, regulation, and accident prevention measures. The inclusion of these "externalities" for this study gives a more realistic comparison of generation technologies.

Figure 29 shows the results of an uncertainty analysis for the three generation technologies. The uncertainty in the cost of carbon is the largest uncertainty driver for all the fossil fuel technologies. Coal-based energy costs nearly double with the cost of carbon. For natural gas, fuel price volatility is a significant contributor to cost uncertainty, in addition to the increased costs (~50%) resulting from the cost of carbon.

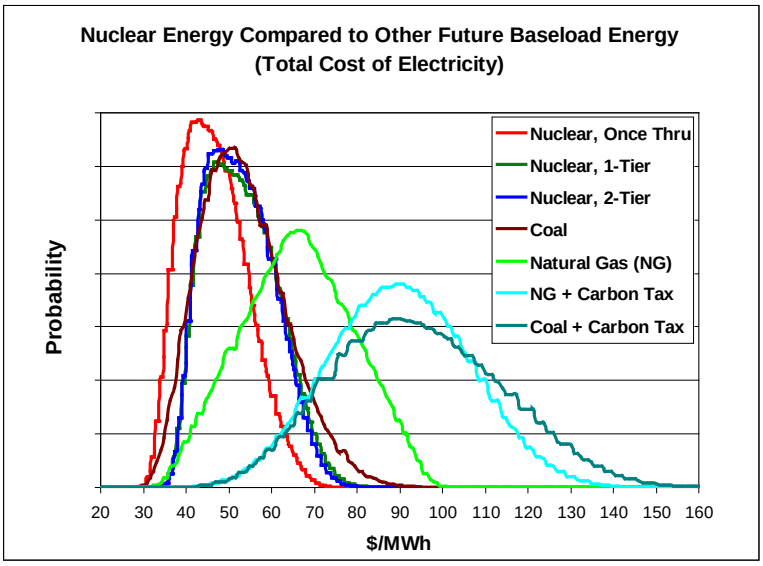


Figure 29. Uncertainty cost distributions for baseload energy technologies.

4.2 Fuel Cycle Costs

4.2.1 Primary Fuel Cycle Cost Drivers

According to this analysis, the main fuel cycle cost discriminator/driver for the open cycle is the unit cost for uranium mining and milling, which can vary the fuel cycle component of generation costs by up to $5/MWh. The primary areas of cost uncertainty from the closed fuel cycle are aqueous and electrochemical separation and fuel fabrication, mixed oxide fuel fabrication, and separated waste conditioning and final disposition. Additional fuel cycle cost uncertainties due to system effects were also evaluated, such as LWR and FR capacity factors and thermal efficiency, fuel burn-up, construction time, and impacts due to varying the fast reactor conversion ratio. Figure 30 represents the fuel cycle cost uncertainties including the LWR front-end (uranium, conversion, enrichment, depleted uranium disposition, and UOX fuel fabrication), mixed-oxide fuel recycle (LWR fuel separation, MOX fabrication, U-Pu product storage, and waste disposition), and FR recycle, which includes the LWR fuel separation, TRU product storage, metal fuel fabrication, and recycling and waste disposition.

The arrows superimposed on the distribution show the range of costs attributed to each of the variables for the three fuel cycles. The uncertainties include:

- LWR Front-End. A large source of uncertainty due to uranium (natural U_3O_8 or tri-uranium octa-oxide) mining and milling costs ($25–$240 kgU). The closed fuel cycles are less dependent on uranium and therefore show a smaller range of cost uncertainty.
- Disposal. A large uncertainty ($400–$1600 kgHM) for the once-through cycle since all fuel is disposed of rather than recycled. The primary cost uncertainty driver for the closed fuel cycle is due to the HLW loading of the waste form (ranging from 2 to 10× relative to used fuel) that is sent to the geologic repository.
- MOX Thermal Recycle. Used only in the 2-tier cycle, MOX has a significant associated range of cost uncertainty ($2,400–$7,400 kgHM) due to the large potential variation in the fuel separation and fabrication unit costs. Another contributing factor on the costs is the assumption that no actinides are disposed. A key assumption on the 2-tier cycle is that no actinides are disposed in the geologic

repository. This assumption increases the recycling costs for the 2-tier fuel cycle by 30 to 50% over the costs of separation and fabrication of only U-Pu.

- Fast Reactor Recycle. A high cost uncertainty ($4,000–$12,600 kgIHM) on the 1-tier cycle, the fuel cycle cost uncertainty is associated with the many unknowns concerning the ultimate process design and commercial costs of the less mature Echem separation/fabrication process.

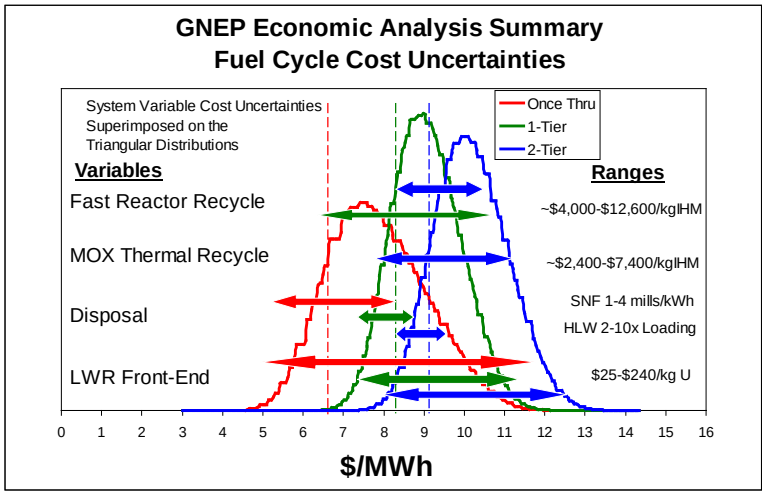


Figure 30. Fuel cycle cost uncertainties.

4.2.2 Evaluation of the Cost Gap between Open and Closed Systems

The overall electricity generation cost increase due to closing the fuel cycle versus direct disposal was found to be minimal (~10% effect). These cost differences were analyzed to identify measures, taken singly or in combination, that could close this gap, including potential impacts of advanced technologies. Figure 31 shows the impact of different cost reduction measures for bringing the 2-tier closed fuel cycle system closer in cost to the once-through fuel cycle system. The cost measures to reduce the cost gap are divided between reactor measures (blue arrows on the left) and fuel cycle measures (green arrows on the right).

The cost gap can be reduced the most by decreasing fast reactor capital costs (through improved designs, etc.). The blue arrows on the upper left show the impact of reducing FR capital costs by 10% and 20%. The reduction of the FR O&M costs to match LWR O&M costs has an impact of about $0.8/MWh. Improvements in FR capacity factor from 82% to 90% (through longer fuel cycles, etc.) directly translate to higher energy production and lower electricity costs. (Higher FR conversion ratios provide longer fuel cycles, but also more total fast reactors. This relationship will be analyzed in future systems analyses.) Thermal efficiency (through higher outlet temperatures or more efficient energy conversion technologies) has a small impact ($0.2/MWh) on overall costs.

Fuel cycle measures also have a large potential to close the gap. Reductions of the MOX thermal recycle cost by 50% and the fast reactor recycle system cost by 35% could (together) more than make-up for the fuel cycle cost gap between the open and closed fuel cycles. Improvements on the HLW loading (2.5 to 10× higher than the once-through) in the repository could also close about a third of the fuel cycle gap

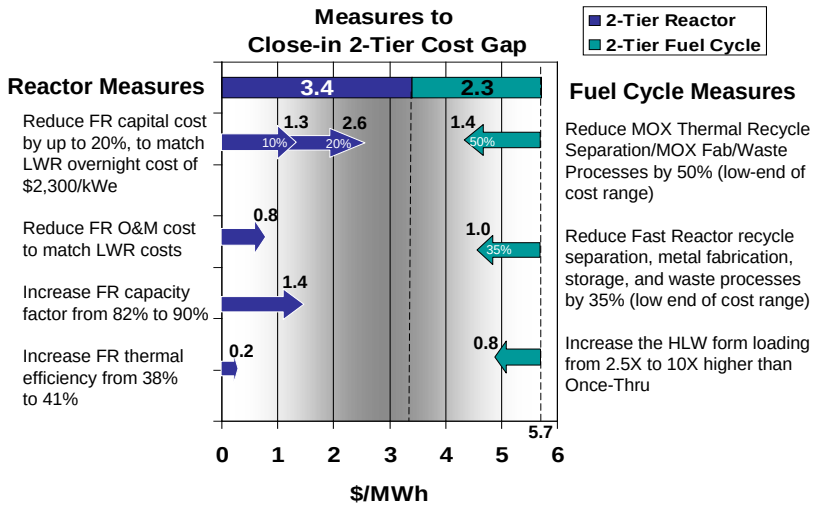


Figure 31. Measures to close the 2-tier to once-through cost gap.

Figure 32 shows the impact of different cost reduction measures intended to bring the 1-tier closed fuel cycle system closer in cost to the once-through fuel cycle system.

Due to the larger proportion of fast reactors used in the 1-tier as opposed to the 2-tier, the majority (or 80%) of the cost gap is due to reactor capital costs, with the remainder due to fuel cycle costs. The blue arrows on the upper left of the figure show the impact of reducing FR capital costs. Reactor measures match the 2-tier and consist of cost reductions to FR capital costs and improved operations, resulting in higher capacity factors and improved designs, which in turn results in higher thermal efficiency (such as through higher outlet temperatures or more efficient energy conversion technologies).

Fuel cycle improvements could also help to offset the costs of reactor capital costs. Fuel cycle improvements could be made through improved waste form loading (via research), reductions in aqueous and Echem separations costs (through a number of process-related measures), reduced Cs/Sr decay storage costs (alternate designs, etc.), and reductions to the cost of greater-than-class-C (GTCC) conditioning of zirconium and stainless steel resulting from aqueous processing.

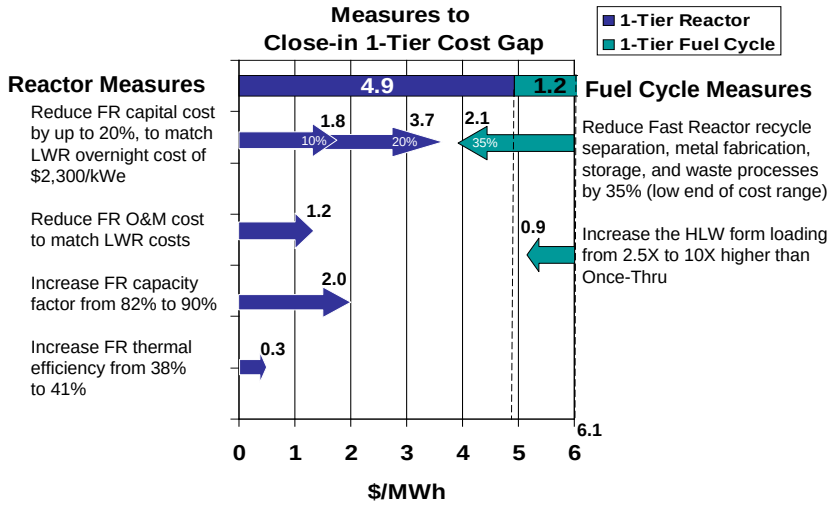


Figure 32. Measures to close the 1-tier to once-through cost gap.

4.2.3 Transportation Costs in Perspective

Operation of the GNEP fuel cycle will require the movement of nuclear materials in a number of compositions, forms, and transportation modes. While overall transportation costs are included in the system-level cost analyses, this subsection details these costs. The report "Once-Through, Single and Dual Tier Fuel Cycles Transportation Cost Analyses" (Bailey 2008) provides an economic comparison of the transportation and associated infrastructure requirements for the once-through fuel cycle and the 1-tier and 2-tier fuel cycles. In the study, the cost to transport fuel cycle and waste materials through each step of the nuclear fuel cycle was assessed, for which the overall results are summarized in Figure 33. This analysis assumes economic conditions that favor larger fuel cycle facilities where key fuel recycle operations (fuel separation, fabrication, and storage) are collocated to minimize transportation.

The estimated expenditures for transportation represent a small portion of the overall fuel cycle costs, amounting to less than 7% (6.7% for the once-through fuel cycle and 3.7% in the 1-tier and 2-tier). Transportation costs in the closed fuel cycles are substantially less than the once-through fuel cycle. The largest transportation cost component is the shipment of LWR used fuel, which constitutes about half the transportation cost in the once-through fuel cycle, and about 40% in the 1-tier and 2-tier cases. The closed cycles avoid about 40% of the "front-end" costs, which are partly offset by the additional transportation required to process the recycled fuel.

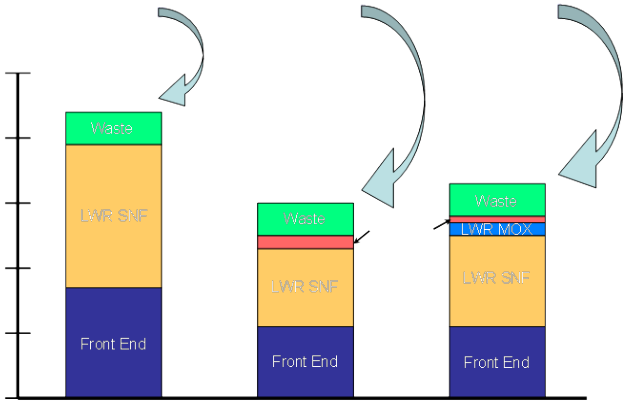


Figure 33. Once-through, 1-tier, and 2-tier nuclear fuel cycle transportation costs.

4.3 Fuel Cycle Cost Objectives

The objectives for advanced fuel cycles presented in Section 1.3 included two economic goals:

- At all times, ensure that advanced fuel cycle technologies cause no significant decrease in the economic competitiveness of nuclear electricity, and
- The system should remain as economical as possible.

Systems cost analyses indicate there are large cost uncertainties with all the fuel cycle strategies, and that systems using a closed fuel cycle are about 10% more expensive than open cycle systems. Closed fuel cycle cost uncertainties are driven by technology uncertainties for fast reactors, used fuel separation, "hot" (remote handling) fuel fabrication, and process waste disposition. In closed systems, the resources needed to produce reactor fuels will be less sensitive to uranium resource and market pressures and will produce less waste subject to disposal in future geological repositories. A further insight is that future nuclear energy costs appear very competitive to other base-load source of energy, especially if carbon constraints are imposed.

Further design studies are needed to reduce the cost uncertainties with respect to fast reactor, fuel separation and fabrication, and waste disposition. The results of this work can help provide insight to the economic conditions needed to keep nuclear energy (including closed fuel cycles) economically competitive in the U.S. and globally.

5. SYSTEM IMPACTS

Section 1.3 of this report provided a number of objectives and goals for advanced fuel cycles. This section looks at some of the outcome-based objectives and assesses how transition to a closed fuel cycle addresses these objectives and goals.

5.1 Drawdown of Used Fuel Inventories

One of the largest current issues associated with nuclear energy in the U.S. is the management of used fuel. With no disposal or reprocessing pathways currently available, inventories of used fuel continue to accumulate at power plants.

One of the objectives in the GNEP Statement of Principles includes this statement:

- Advanced fuel cycles technologies, when available would help . . . draw down inventories of civilian spent fuel in a safe, secure, and proliferation-resistant manner.

The 2005 AFCI Report to Congress contained a similar goal:

- For the longer term, improve spent fuel management to reduce onsite storage at nuclear power plants.

The scenarios used in this report all achieve a reduction of onsite storage, assuming ample geologic disposal space (once-through scenario) and used fuel reprocessing capacity (nominal 1-tier and 2-tier scenarios) is available. Figure 8 in Section 3.1.2 provided a histogram of the location of used fuel for the once-through scenario, showing the draw down of onsite storage as the used fuel is transferred to geologic disposal. Figure 12 in Section 3.1.3 provided a histogram for the 1-tier scenario, showing a more pronounced draw down as used fuel is reprocessed. Both histograms show the total amount of used fuel in storage at the end of the century to be higher than today, due primarily to the growth of nuclear energy and the need for minimum cooling of used fuel before it can be efficiently transported.

In the once-through scenario, stored commercial used fuel increases from current values of 57,000 MTiHM to roughly 150,000 MTiHM while nuclear electricity generation increases from 90 GWe-year to 400 GWe-year. On an energy-output normalized basis, current storage is 640 MTiHM/GWe-year while storage in 2100 is ~380 MTiHM/GWe-year, or a 40% reduction. Of the 150,000 MTiHM, almost half (66,000 MTiHM) is cool enough to efficiently transport and could be located away from reactors while awaiting disposal.

In the 1-tier scenario, stored commercial used fuel increases to just under 70,000 MTiHM, essentially all of which is still cooling prior to reprocessing. On an energy-output normalized basis, the storage in 2100 is ~170 MTiHM/GWe-year, or a 73% reduction.

5.2 Uranium Impacts

Uranium dominates nuclear fuel cycles because it is both the primary fuel and (unless consumed) the largest mass of waste. The objectives presented in Section 1.3 included an objective and two quantitative goals associated with uranium use:

- Enhance energy security by extracting energy recoverable in spent fuel and depleted uranium, ensuring that uranium resources do not become a limiting resource for nuclear power.
  - In the short term, develop the technologies needed to extend nuclear fuel supplies by up to 15% by recycling the fissile material in spent nuclear fuel.
  - In the long term, extend nuclear fuel resources more than 50-fold by recycling uranium in spent fuel and depleted uranium, thereby converting current waste into energy assets.

This section assesses domestic uranium requirements to support an ongoing and expanding amount of nuclear electricity generation, along with the potential to reduce natural uranium needs by closing the fuel cycle. (The next section discusses uranium waste.)

5.2.1 Uranium Savings from Closing the Fuel Cycle

The AFCI 2005 Report to Congress included a summary of the global predicted retrievable uranium resources as a function of cost based on different resource models. Figure 34 from that report shows considerable uncertainty associated with uranium availability. For perspective, the current global uranium demand rate is 64,600 tonnes U/year (WNA 2008) and the projected global uranium used through the end of the century in the Reference Scenario in Section 2 is ~24 million tonnes.

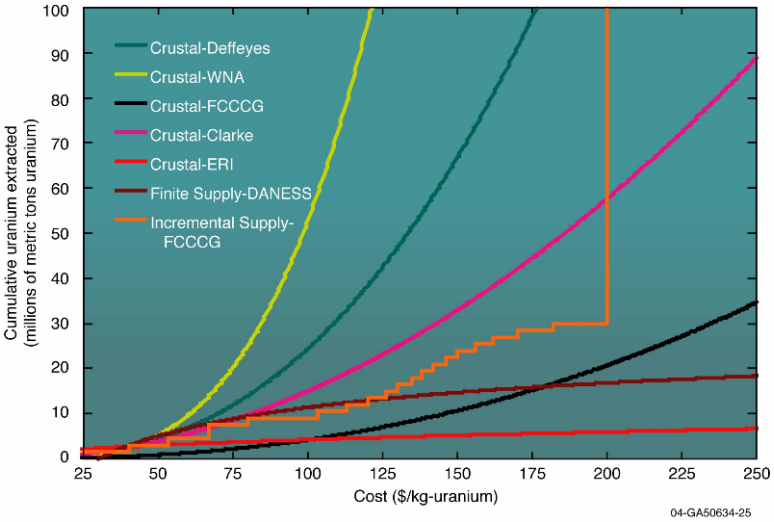


Figure 34. Comparison of uranium resource studies: predicted retrievable uranium (in millions of tonnes) as a function of cost.

Figure 35 shows a time history of projected domestic uranium usage for the once-through and nominal 1-tier and 2-tier scenarios. While fast reactors do have some impact on uranium usage in the later part of the century, the limited number of fast reactors minimized their impact. Even though the MOX cycle avoids some UOX, the 2-tier system still requires more uranium ore than 1-tier, again due to fewer fast reactors.

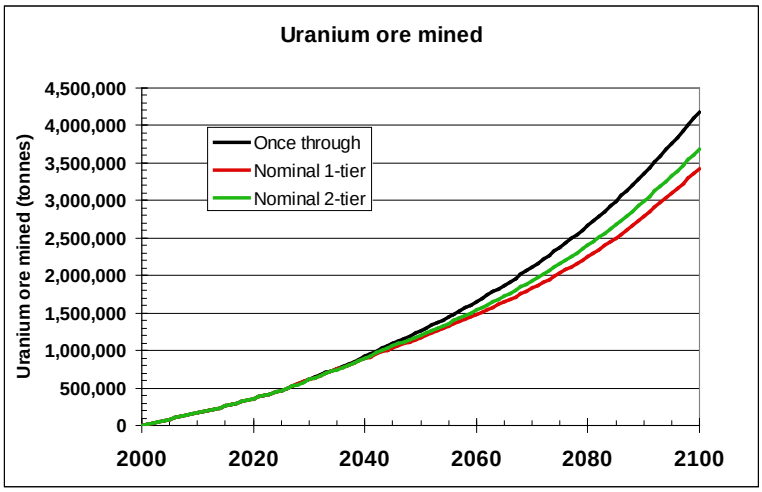


Figure 35. U.S. uranium ore required 2000–2100 for once-through, 1-tier, and 2-tier.

Sensitivity analyses were performed to determine the importance of conversion ratio on uranium use. Figure 36 shows the U.S. uranium ore requirements during 2000–2100 for the nominal 1-tier scenario with both growth rate and fast reactor conversion ratio varied. The amount of uranium required is much more sensitive to growth rate than to fast reactor conversion ratio. Even though higher conversion ratios result in more fast reactors, they are built too late in the century to have a significant impact.

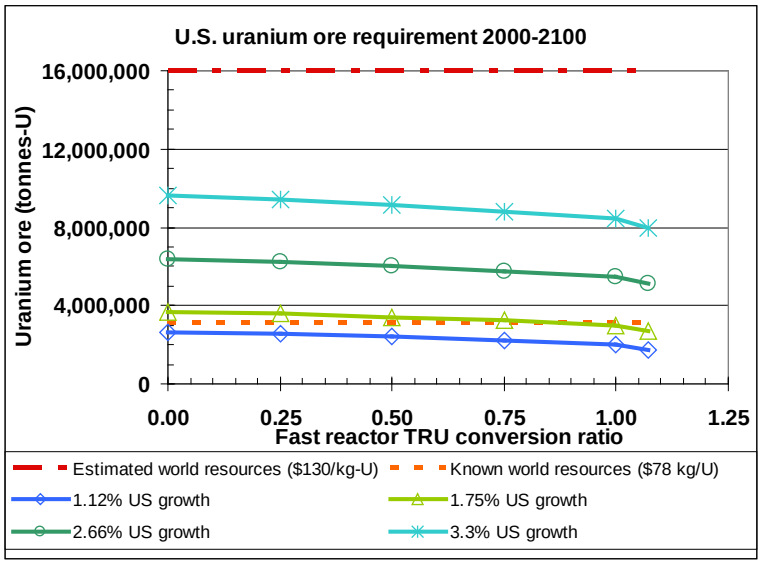


Figure 36. U.S. uranium ore required for 2000–2100 as a function of nuclear growth rate and fast reactor TRU conversion ratio.

5.2.2 Why Uranium Savings are Limited

A closed fuel cycle reduces requirements for natural uranium by more effectively using the uranium that is mined. However, there is a large difference between the theoretical savings based on a static analysis and the actual saving based on a dynamic analysis of the fuel cycle transition. For systems in static equilibrium with TRU conversion ratio of 1 and above, close to 100% of the energy content in the original uranium ore can be used, versus less than 1% used in the once-through fuel cycle. Thus, a 100-

fold energy improvement factor is theoretically possible. This theoretical savings is very sensitive to conversion ratio. A static equilibrium calculation at the nominal TRU conversion ratio of 0.50 gives an improvement factor of 1.55; roughly 1% of the original uranium ore energy content is used.

The static equilibrium performance is not achieved in practice. Using the dynamic analysis VISION model, Figure 37 shows the uranium usage improvement factor for the time period 2000–2100, compared with the static equilibrium improvement factors for the 1-tier scenario. The dynamic analysis improvement factors are lower than the static equilibrium factors because of the slowness in building fast reactors (as discussed in Section 3.2), the direct disposal of 63,000 tonnes of used fuel in a geologic repository, and the need for useful recycle material to make repeated passes through a reactor (which compounds any recycling losses).

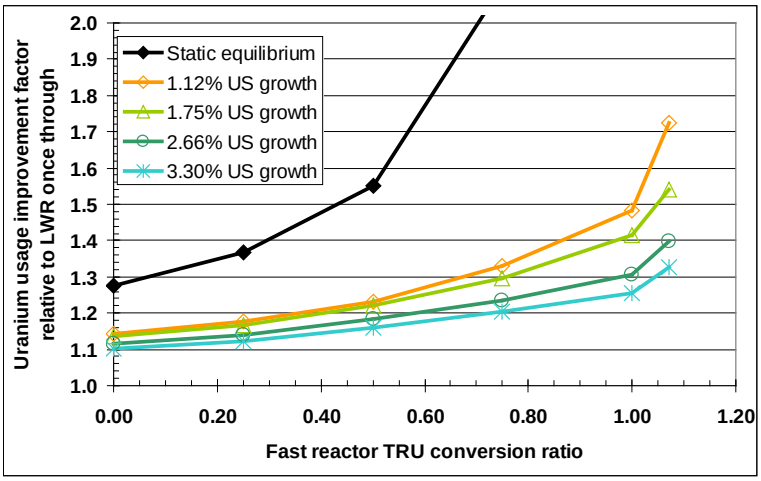


Figure 37. Static equilibrium versus dynamic analysis of uranium usage improvement factors relative to once-through as a function of both growth rate and conversion ratio.

The uranium objective includes improved utilization of both uranium reclaimed during recycled (RU) and depleted uranium (DU) generated from enrichment. At the nominal conversion ratio of 0.5, Figure 37 shows that all growth rates achieve savings of more than 15% and meet the near-term quantitative goal. However, all of the scenarios fall well short of the long-term goal. The long-term goal can only be met by eventually converting to all fast reactors with a conversion ratio of 1.0 or higher (to support growth), or alternately to a system composed of LWRs operating on 100% cores of MOX and fast reactors with high enough conversion ratios to produce TRU for both their own fuel and the LWR MOX fuel.

For 1-tier fuel cycles, Figure 38 shows how much RU and DU would be consumed in fast reactors at static equilibrium. At the nominal fast reactor conversion ratio of 0.5, only 1.3% of the RU and none of the DU are used as fuel. Use of RU increases to 4.2% at a conversion ratio of 0.75. As the conversion ratio approaches 1.0, all of the uranium (both RU and DU) is eventually used as fuel (other than processing losses).

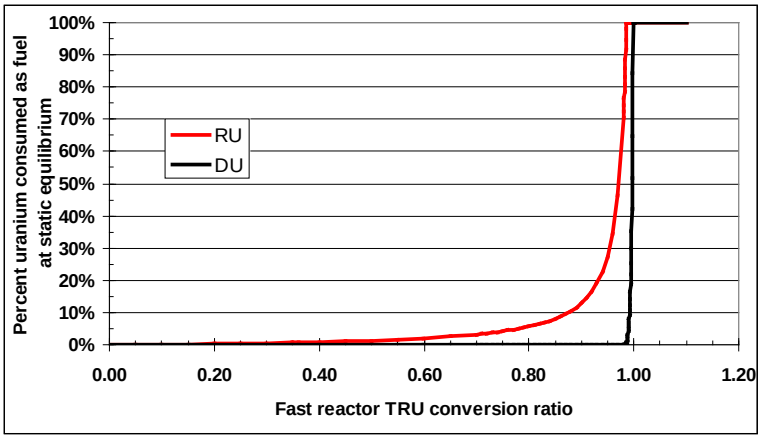


Figure 38. Percent of RU and DU used as fast reactor fuel with fast reactors and LWRs in static equilibrium.

5.2.3 Excess Uranium

Uranium not consumed as fuel is currently stored or disposed. Large amounts of excess uranium are generated in the front end of the fuel cycle during enrichment operations. At current enrichment levels and tails assays, roughly one-eighth of natural uranium becomes low-enriched uranium used in LWR UOX fuel and the other seven-eighths become DU, which is currently stored pending disposal or potential reuse. In the once-through fuel cycle, only ~5% of the enriched uranium is consumed and the rest disposed with the used fuel. In the closed fuel cycles, the uranium not consumed in LWR UOX cycle is separated, but as shown in the previous section, little of this RU is recycled (either in fuel or via re-enrichment) and most is stored (see Figure 38). Excess uranium mass is far greater than the total waste generated by nuclear energy using these options.

Figure 42 shows the mass of DU, RU, and all wastes for the once-through and nominal 1-tier scenarios (2-tier is very similar to 1-tier). (The pre-2000 inventory of ~500,000 tonnes of DU is not shown.) The mass of DU dominates in each case, with the higher mass in the once-through case reflective of the overall higher uranium usage.

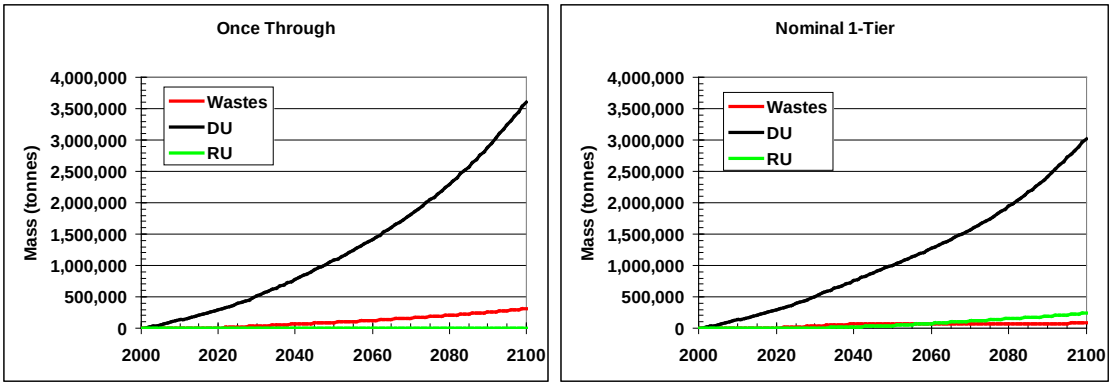


Figure 39. VISION calculations of the mass of RU, DU, and wastes for once-through nominal 1-tier scenarios.

In the once-through fuel cycle, there is no RU; the waste is primarily used nuclear fuel. In the nominal closed fuel cycle scenarios, the mass of waste is primarily the 63,000 tonnes of used fuel that is

direct disposed in the geologic repository, which is several times lower than in the once-through fuel cycle. The mass of other wastes is minimal in comparison, as discussed in the next section. The closed fuel cycle scenarios do have a significant mass of RU. The fraction of RU and DU that is excess depends on the details of the fuel cycle; in the nominal scenarios, all of the DU and 98.7% of the RU is excess. If disposed, the DU can qualify as low-level waste suitable for near-surface burial. Whether the RU is suitable for near-surface burial or not depends on whether Tc-99 and other long-lived contaminants are removed.

5.3 Waste Management Impacts

One of the primary purposes for closing the nuclear fuel cycle is to enable improvements in radioactive waste management. Specifically, the GNEP Statement of Principles includes the objective to significantly reduce nuclear waste and simplify its disposition. The approach to achieving this objective is to reuse components of irradiated reactor fuel that would otherwise be disposed of as waste. The primary components for reuse are uranium and the fissile transuranic elements that are both problematic for disposal and useful as reactor fuel. In the process of actinide recycle, all other components of used reactor fuel become potentially separable for reuse or individually optimized disposal. This fundamentally changes the nature of waste management.

Radioactive waste management represents a complex blend of policies, laws, regulations and standards as well as technical alternatives and engineering design trade-offs. There is no single simple metric that describes waste management impact. For this reason, one of the system goals cited in Section 1.3 includes multiple metrics:

- Reduce the current and future burden related to geologic disposal of spent nuclear fuel in terms of waste volume, heat load, radiotoxicity, and number of repositories needed.

The impact on these metrics of transitioning to a GNEP closed fuel cycle is discussed below.

5.3.1 Waste Streams

In a once-through fuel cycle the primary sources of waste are DU from enrichment (if disposed) and used fuel. With recycle, the used fuel waste stream is replaced via separations with a number of other streams, including material to recycle and material to dispose as waste. Under GNEP, advanced separation flowsheets proposed include the aqueous UREX+ family and Electrochemical (Echem) processes.

The UREX+ process uses several extraction steps to separate U, Tc, Cs/Sr, FP, Ln, and Pu/MA into six separate streams. Additional extractions could possibly be added to separate and recover Pu/Np, Am, and Cm. Fuel cladding and hardware are combined in a separate stream. Residual fuel undissolved solids (UDS) not dissolved and extracted are caught on filters and can be treated separately or combined with the FP stream that contain the same elements. Aqueous processing also releases FP gases including ^{3}H, I, ^{14}C, Kr, Xe.

Echem is a totally dry process conducted in molten chloride salts that makes use of electrochemical dissolution, selective reduction (plating), and absorption to separate groups of elements. Processes are being developed to separate U, Pu/MA, Cs/Sr, Ln/FP, and cladding/hardware/transition metals in five separate streams. Echem also releases gaseous FP, though substantially more of the iodine and carbon are held in the molten salts.

In the above separations, the TRU is recycled along with a portion of the U, while all other streams end up as waste. Streams that include fission products typically are high-level waste (HLW) while those

with activated metals (cladding, etc,) may qualify as GTCC low-level waste (LLW). Some fission products (Cs/Sr and some gasses) may be stored for extended periods to allow them to decay.

The above waste streams come directly from the components of separated fuel. Other wastes generated include Balance of Plant and Job Control Wastes. The first category is from all of the ancillary processes that support a reprocessing facility including analytical laboratories, waste water treatment, heating, ventilation and air conditioning and decontamination activities. The second category encompasses the consumables used to minimize exposure during maintenance activities, including containment tents, personal protective equipment, tools, and general combustibles such as rags, bags, and tags wastes. These low level wastes can be Class A/B/C or GTCC, depending on the source and concentration.

Fuel fabrication generates some waste and this will continue regardless of a fuel reprocessing strategy. Due to the value of enriched uranium, fabricators design and operate their facilities to minimize losses. If fuel is reprocessed, and actinide elements are recycled, several operations that are now done in glove boxes will require remote handling. Fuel fabrication will be more complex and will generate GTCC wastes. Losses of actinides must be minimized to meet GNEP goals for maximizing benefit to the repository.

Current systems analyses of waste focus on used fuel and HLW and GTCC waste generated by used fuel separations. Reprocessing Balance of Plant and Job Control wastes and other wastes from fuel fabrication, facility D&D and normal reactor operations are not included in this report. They are being included in the ongoing Integrated Waste Management Strategy analyses.

5.3.2 Waste Masses and Volumes

The two primary metrics for waste quantity are mass and volume. The mass is typically measured in tonnes, and specified as either the mass of just the radioactive waste elements or the mass of the solid waste form which includes the radioactive elements and a matrix (such as glass) in which the waste is contained. For used fuel the radioactive waste elements are contained in the fuel while the "matrix" includes the fuel cladding and other hardware of the fuel assembly. Volume is typically measured in cubic meters, and represents the volume of material to be disposed, including immobilizing matrix, binders, fillers, etc., but not including the volume of waste package material.

There are a number of different waste streams generated from any nuclear fuel cycle. Because of the very different nature and disposal pathways for these streams, each should be considered separately.

Figure 40 through Figure 42 show VISION calculations of fuel-derived[v] mass, waste form mass, and waste form volume for once-through, 1-tier, and 2-tier fuel cycles for the following waste streams:

- Intact used (spent) nuclear fuel (SNF), including the 63,000 MTiHM of used fuel assumed to be direct disposed in the nominal 1-tier and 2-tier scenarios.
- HLW that includes most fission products and any uranium and transuranics lost to waste. The amount lost is based on the efficiency of the recycle process.
- "Decay Storage," consisting primarily of separated Cs and Sr. Isotopes of these elements are high decay heat producers with moderate half-lives. The high decay heat makes these elements harder to

[v]. Fuel-derived mass includes the mass of the remaining uranium, all fission products (whether radioactive or stable), and the transuranics produced, equivalent to the initial heavy metal mass.

dispose in a heat-limited Yucca Mountain-type geologic repository. Decay storage may also be used for gaseous fission products with moderate half-lives, such as Kr.

- GTCC waste, consisting primarily of cladding and activated non-fuel metals.

Figure 40 shows that the closed fuel cycles[w] provide a dramatic reduction in total disposed fuel-derived waste mass. This represents one of the primary drivers for closing the fuel cycle. The 1-tier waste masses are dominated by the 63,000 MTiHM of direct disposed used fuel, with the other wastes contributing minimal additional mass even though they are derived from much larger amounts of energy generation.

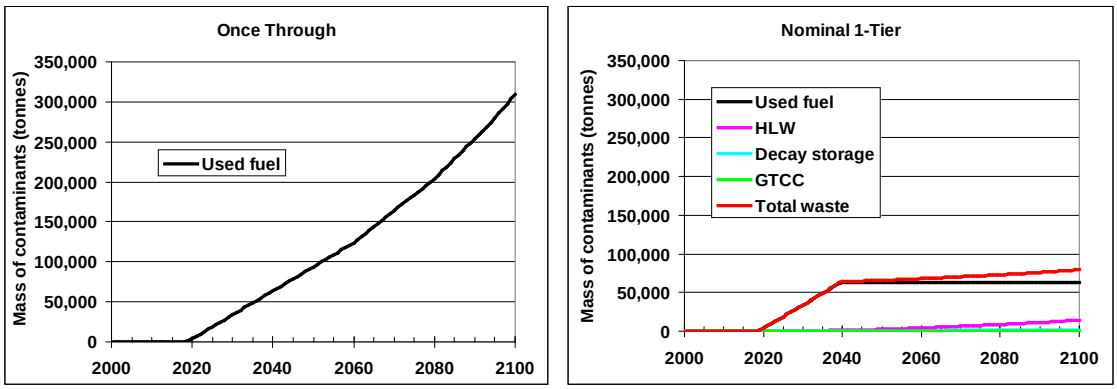
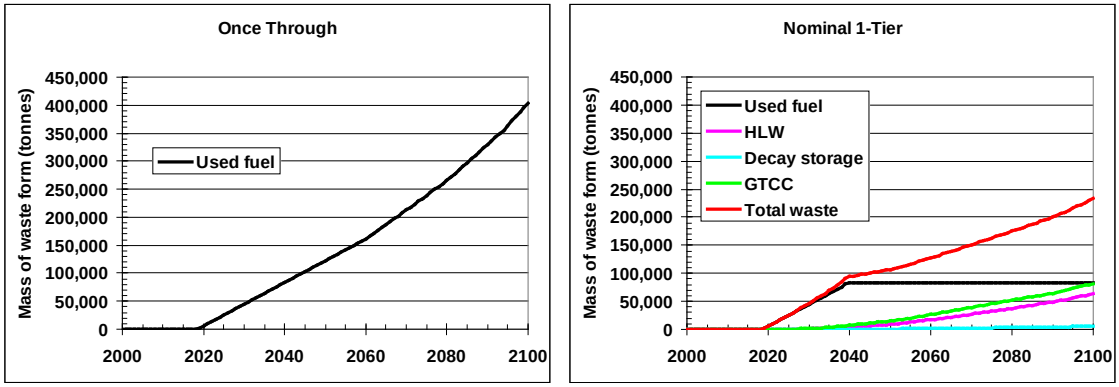


Figure 40. Mass of radioactive material to be disposed of as waste for once-through and 1-tier nominal scenarios.

The waste form mass in Figure 41 indicates the same trends as the contaminant mass results, with closed fuel cycles showing similar reductions compared to once-through used fuel. The 2-tier fuel cycle (not shown) has slightly higher LLW-GTCC values and slightly lower HLW values versus 1-tier due to differences in how the cladding is processed in aqueous versus electrochemical separations. The higher total masses in both graphs compared to Figure 40 reflect the significant added mass from cladding, immobilization matrices, and other non-radioactive components of the waste streams. Cladding is the largest contributor to the higher total mass for the once-through scenario, while the mass of the glass matrix in HLW and the cladding in GTCC waste are primarily responsible for the higher total mass in the 1-tier scenario.



[w]. In this section, 1-tier and 2-tier results are nearly identical, so only the 1-tier results are shown.

Figure 41. Waste form mass for once-through and 1-tier nominal scenarios.

The waste volume results in Figure 42 indicate a similar trend of lower values for the closed fuel cycles. The decay storage elements are contributing a somewhat higher (but still small) share to the total because these wastes tend to have low mass loading.

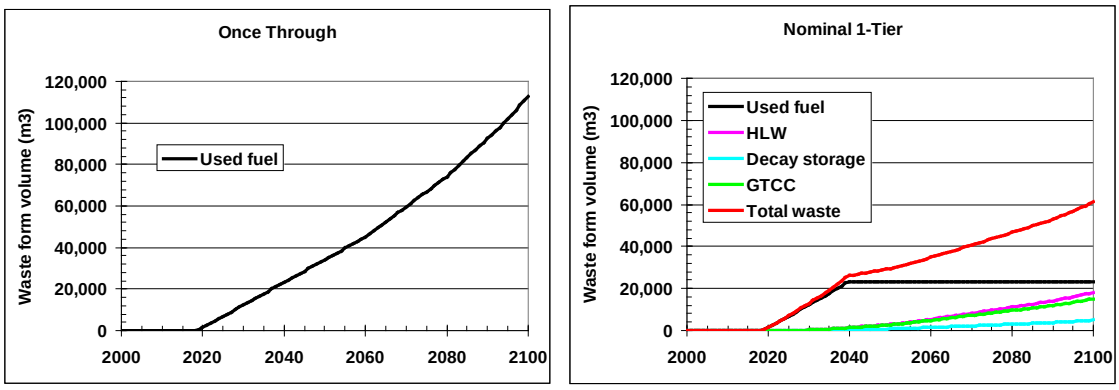


Figure 42. Waste form volume for once-through and 1-tier nominal scenarios.

5.3.3 Long-term Radiotoxicity

Another metric used to quantitatively compare radioactive waste management alternatives is long-term radiotoxicity (LTR). Radiotoxicity is a measure of the intrinsic hazard that a material represents, and is useful as a basic comparator of waste streams in the absence of a specific disposal pathway. (Another metric, long-term dose, requires specific waste form, packaging, and disposal site information, so is less useful for general comparisons of fuel cycle alternatives.) Because waste management analysis is concerned primarily with the long-term storage or permanent disposal of the waste streams, radiotoxicity is evaluated based on the isotopes (including decay products) 1,000 years after discharge from a reactor. The LTR is calculated by multiplying the quantity of each isotope by their respective dose conversion factors and summing the result.[x] The fuel cycle performance objectives cited in Section 1.3 include a quantitative goal for long-term radiotoxicity:

- In the intermediate and long terms, reduce the long-lived radiation dose sources by a factor of 10 and radiotoxicity by a factor of 100, simplifying the design of a waste isolation system.

Radiotoxicity of nuclear waste streams have often been compared to the radiotoxicity of natural uranium ore, usually as it exists in the ground with all the uranium decay daughter nuclides in equilibrium. Such a comparison of the natural uranium to several different fuel cycles is shown in Figure 43, as discussed in the 2005 AFCI report to Congress (DOE 2005). The transuranic elements heavily dominate this metric with more than 99% of the 1,000-year radiotoxicity coming from Pu, Am, Np and Cm and their daughter products. Uranium and fission products each contribute only slightly to the long-term radiotoxicity. The effect of this is seen in Figure 43 where limited recycle in thermal reactors (one MOX pass) only reduces the TRU content fractionally compared to once-through, and sustained recycle

[x] The dose conversion factors are a measure of radiation-based toxicity for each isotope if ingested, accounting for differences in where elements concentrate in the body and how different tissues are impacted by the associated decay radiation, as In the intermediate and long terms, enable repeated recycling to reduce disposed transuranics by a factor of more than 100, delaying the need for additional geologic repositories for a century or more, even with growing energy production.developed by the International Commission for Radiological Protection (ICRP).

(including multiple passes in fast reactors) eliminates most of the TRU, resulting in dramatic reduction in radiotoxicity. This was the motivation behind another quantitative goal:

- In the intermediate and long terms, enable repeated recycling to reduce disposed transuranics by a factor of more than 100, delaying the need for additional geologic repositories for a century or more, even with growing energy production.

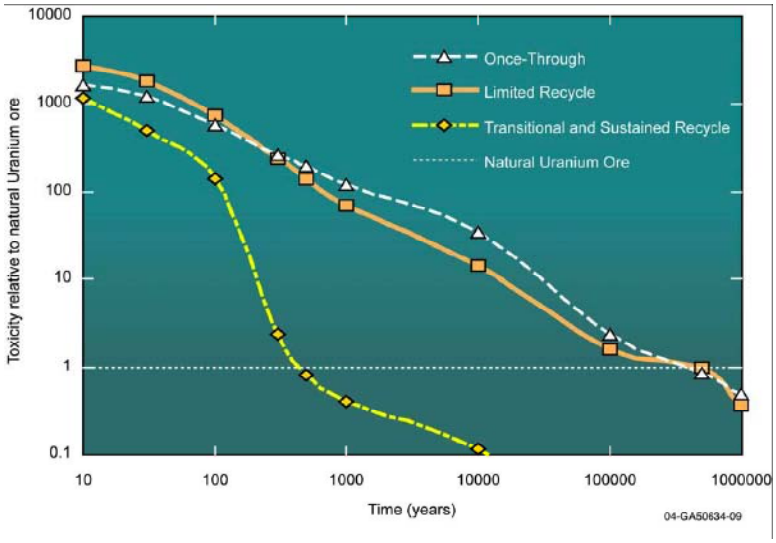


Figure 43. Radiotoxicity of fuel cycle waste relative to uranium ore.

The charts in Figure 44 show where the material contributing to LTR is located for the once-through and 1-tier and 2-tier nominal scenarios. The green band on the recycle cases represents the reduction in LTR compared to once-through achieved through consumption or avoidance of the contributing isotopes. The 1-tier case more effectively reduces LTR because there are more fast reactors consuming TRU while the MOX phase of the 2-tier case results in more ^{238}Pu, ^{241}Am, and ^{234}U, which are significant LTR contributors (either directly or via their decay products). The yellow band reflecting used fuel in dry storage is eventually eliminated in the recycle cases, while dry storage continues for once-through due to additional cooling needed prior to geologic disposal. The blue bands show the LTR from material in geologic disposal (in both used fuel and HLW).

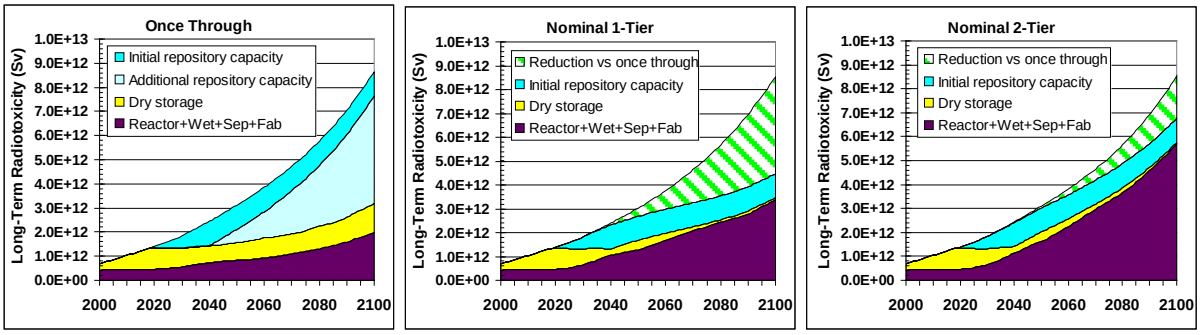


Figure 44. Time history and location of long-term radiotoxicity for once-through, 1-tier, and 2-tier nominal scenarios.

Accrued LTR improvement

Systems studies have assessed LTR reduction in two ways. One method is the accrued reduction versus once-through considering only the recycle passes that have occurred and accounting for the LTR remaining in used fuel. This is equivalent to looking only at the green slices in the previous set of graphs. The result of this method is shown in Figure 45 for the closed fuel cycles, considering only reprocessed fuel. In this method, the LTR reduction starts at 1.0 (no reduction) and builds over time with additional recycle passes and the metric shows the accumulated benefit to date. MOX-Pu fuel in LWRs does little to "consume" LTR, so the benefit is small in the 2-tier scenario (and comes primarily from avoiding the generation of additional TRU in UOX-fueled LWRs).

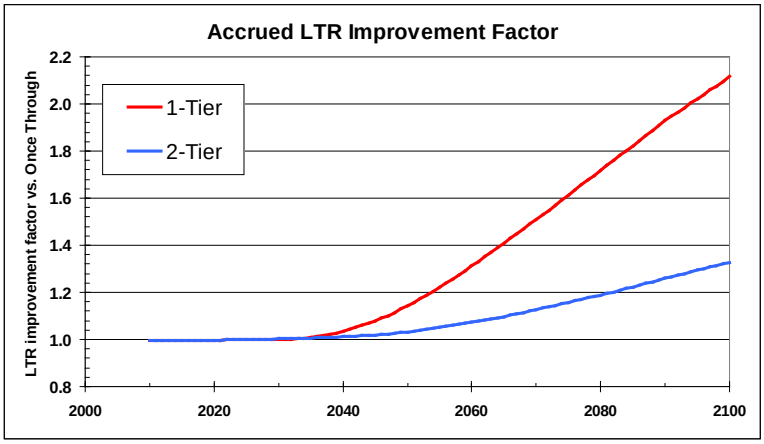


Figure 45. Accrued LTR improvement for reprocessed fuel in the 1-tier and 2-tier scenarios.

LTR versus recycle efficiency

The second method for assessing LTR is to assume continuing recycle and consider only the LTR that accumulates in disposed waste. This method is a more direct measure of repository impact. For the closed fuel cycles the impact of recycle efficiency (the ability of the recycling processes to avoid TRU losses into the processing waste streams) can have a direct impact on LTR. Figure 46 shows the LTR improvement factor in disposed waste as a function of recycle efficiency for reprocessed fuel. (Note the graph only addresses the fuel sent through separations and does not include the 63,000 MTiHM of direct-disposed fuel.) In this method, the improvement factor always starts at the reciprocal of the recycle loss rate and then declines due to the compounding impact of TRU losses in moving from the initial recycle to multiple recycles (because it takes more than one cycle to consume the TRU). The quantitative goal to reduce LTR by a factor of 100 is met through a TRU recycle efficiency of roughly 0.5% loss per recycle. This is consistent with part of a third quantitative goal:

- In the short term, develop and demonstrate fuel cycle technologies and facilities that remove more than 99.5% of transuranics from waste destined for geologic disposal.

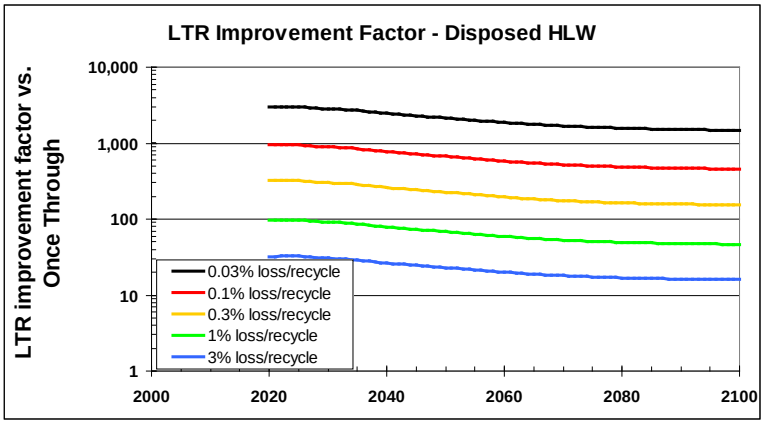


Figure 46. LTR improvement factors for 1-tier versus once-through at different recycle efficiencies.

Long-term Decay Heat

A common theme in the objectives for advanced fuel cycles is to reduce the amount of geologic disposal needed. To evaluate how an advanced fuel cycle might achieve this requires consideration of the key factors that affect the technical capacity of a geologic repository for HLW. One of the important constraints on repository design and technical capacity is the long-term decay heat generated by HLW and/or used fuel. For any specific repository site and waste stream, the long-term heat generation characteristics of the waste, site specific temperature design limits, and the hydrothermal response of the site combine to determine the waste loading density that is allowable. This density and the available repository area determine the technical capacity of the repository. The allowable waste loading density may be constrained by either area density (i.e., MT/km^2) for the repository footprint or linear density (i.e., MT/m) in emplacement drifts.

Decay heat comes from the radioactive decay of the collection of radionuclides present, and it changes continuously as the mix of radionuclides (and any radioactive daughter products) changes. Repository design can also be constrained by short-term heat load, which is dominated by fission products, or long-term heat load, which is dominated by transuranics. Short-term heat can be both an operational issue and a waste loading constraint. Assuming that fuel is cooled for at least a few years after discharge from a reactor, the remaining short-term heat is dominated by ^{137}Cs and ^{90}Sr, both with half-lives of about 30 years.

The most completely characterized geologic repository site with the most fully developed design constraints available for comparative analysis of decay heat issues is the Yucca Mountain repository project. Figure 47 shows the sensitivity of recycle efficiencies for the removal of both actinides (right scale) and Cs/Sr (left scale) based on Yucca Mountain-like design constraints (Wigeland 2006).

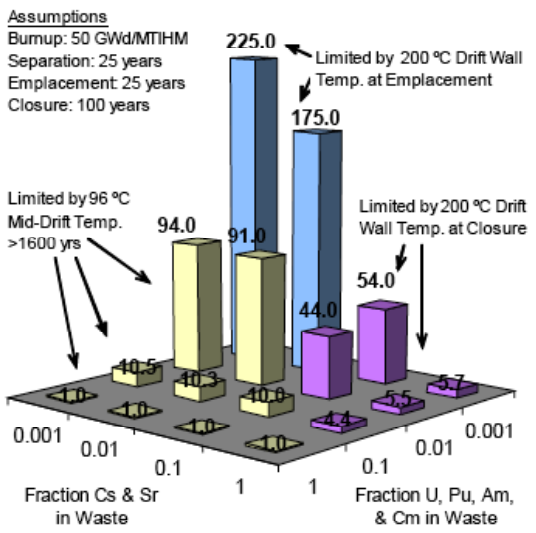


Figure 47. Heat-limited repository capacity improvement factors (Wigeland 2006).

Cs and Sr are the primary contributors to short-term heat, impacting repository performance during the time period from when waste is emplaced up to when the repository is closed. If Cs and Sr are not managed, heat-constrained repository capacity improvement factors are limited to less than a factor of 6. (Note that Cs and Sr are not significant contributors to LTR.)

Separate management of short-term decay heat might be achieved through extended ventilation, decay storage prior to disposal, or design of a custom high/short-term heat repository. As there are no comparable alternatives for long-term decay heat (LTH) management, this section examines LTH in more detail, and uses it as a simplified metric for repository capacity.

The integrated decay energy between 50 and 1,500 years after emplacement[y] is the metric used in systems analyses to evaluate long-term decay heat impacts on repository capacity. This captures most of the post operational heat generated from typical waste streams. The integral is used because most long-term thermal design criteria for disposal facilities are based on gradual heat buildup, and are therefore driven by the total heat put into the system over time. This integral captures a portion of the heat from Cs and Sr decay, but is dominated by heat from the transuranic elements and their decay daughter chains. While the specific activity of these actinides may be less than the fission products, the actinides typically support a long chain of radioactive daughters, and many of the decays are alpha decay which typically releases large amounts of energy. Not surprisingly, many of the LTH results are qualitatively similar to the LTR (radiotoxicity) results, which are also dominated by the transuranic elements.

The charts in Figure 48 show quantities of LTH and where it is located during the evolution of once-through, 1-tier, and 2-tier fuel cycles. The green band on the recycle cases represents the reduction in LTH compared to once-through. The 1-tier case more effectively reduces LTH compared to 2-tier, primarily due to the increased creation of higher actinides in the MOX recycle portion of the 2-tier case, and the larger fraction of fast spectrum reactors. Note that most of the remaining LTH in these cases is in fuel in the reactors or recently discharged and in initial cooling ("wet storage"). Note the inclusion of

y. This time period is based on the Yucca Mountain design, which includes at least 50 years of forced ventilation cooling after waste emplacement before final backfilling of drifts. Analysis has shown the peak mid-drift temperature is reached by 1500 years.

decay storage (magenta area in Figure 48). If decay storage is not used (for Kr, Xe, Cs, and Sr), this portion would add to repository LTH.

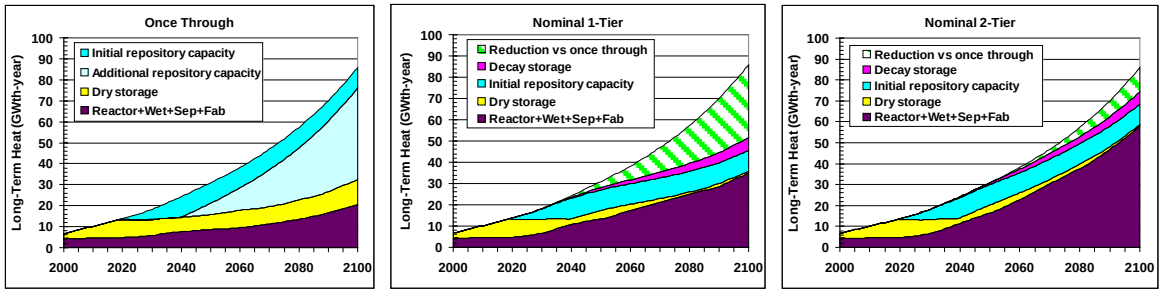


Figure 48. Location of long-term decay heat for once-through, 1-tier, and 2-tier nominal scenarios.

Accrued LTH improvement

As with LTR, systems studies have assessed LTH reduction via the accrued reduction versus once-through considering only the recycle passes that have occurred and accounting for the LTH remaining in used fuel. This is equivalent to looking only at the green slices in the previous set of graphs. The result of this method is shown in Figure 49 for the closed fuel cycles, considering only reprocessed fuel. Similar to LTR, the LTH reduction builds over time with additional recycle passes, and the metric shows the accumulated benefit to date. MOX-Pu fuel in LWRs does little to "consume" LTH, so the benefit is smaller in the 2-tier scenario.

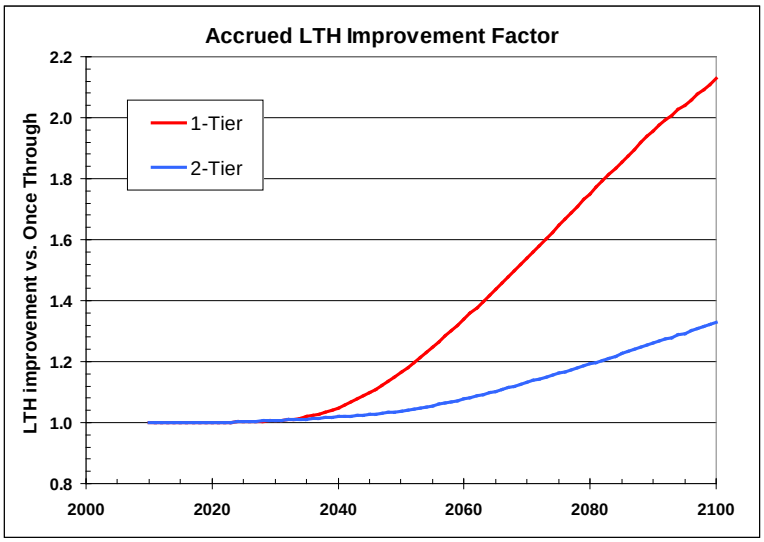


Figure 49. Accrued LTH improvement for reprocessed fuel in the 1-tier and 2-tier scenarios.

LTH versus recycle efficiency

The LTH has also been assessed assuming continuing recycle and considering only the LTH that accumulates in disposed waste. This method is a more direct measure of repository impact. Because the LTH is dominated by the transuranic elements, the fraction of TRU that is lost to waste in the separation processing can be an important factor in how much LTH reduction is achieved. Figure 50 shows the LTH improvement factor in disposed waste as a function of recycle efficiency for reprocessed fuel.

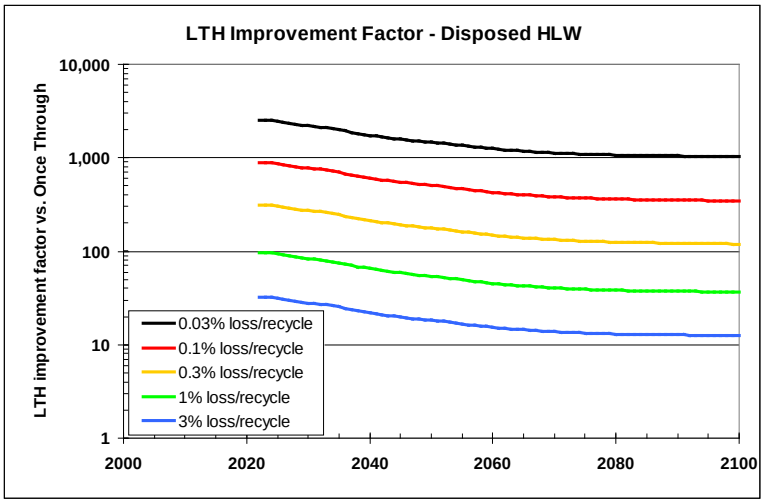


Figure 50. LTH improvement factor for reprocessed fuel as a function of recycle efficiency.

LTH for Cs/Sr direct disposal versus decay storage

Figure 51 shows the accrued LTH improvement factor for recycle with and without separate management of the Cs/Sr decay. Note in the 2-tier scenario without separate Cs/Sr management the system initially performs worse than once-through due to the increased buildup of non-fissile transuranics in the MOX cycle. Specifically, the MOX cycle increases the relative amounts of ^{238}Pu and ^{241}Am, which are the two greatest contributors to LTH.

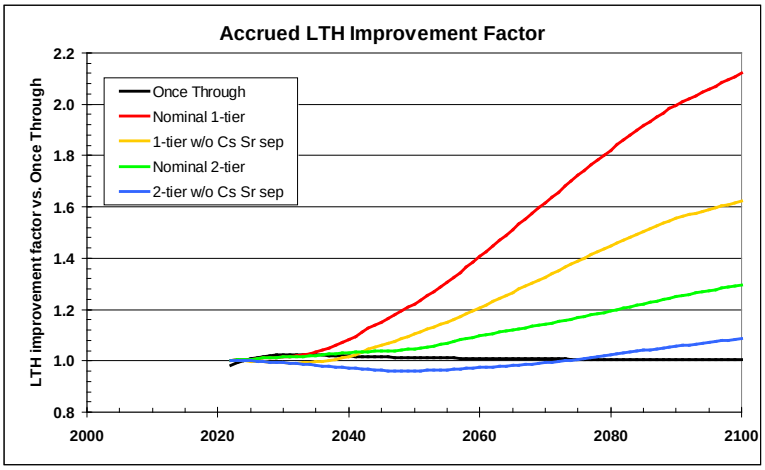


Figure 51. LTH improvement factor accrued with and without Cs/Sr separation.

5.3.4 Alternatives for Disposal

In addition to the changes in waste stream characteristics from closed fuel cycles discussed above, separation of fuel into different components potentially enables optimized waste forms and alternative disposal pathways. Evaluations are in progress to consider waste forms that are customized for specific waste components and may provide more robust disposal performance than intact used fuel. In addition, disposal pathways more optimized for specific waste streams may be viable technical alternatives in the future. These concepts are discussed in the Integrated Waste Management Strategy report (Gombert 2008).

5.4 International Impacts

Section 2 presented scenarios for global nuclear energy growth, concluding with an assessment of the uranium usage levels and used fuel inventories assuming a once-through fuel cycle. The previous subsections have presented the impacts on uranium use and waste management of transitioning to closed fuel cycle technologies in the U.S. If these same technologies were available internationally, similar impacts may be obtained.

The impacts would vary between countries/regions based on the timing of new technology introduction, local nuclear growth rates, differences in waste regulations and waste repository concepts, and the extent of existing nuclear generation capacity and fuel cycle facilities. Some areas of the world have large existing reactor fleets which may be retired in similar timeframes to the legacy U.S. fleet, while other areas have no significant existing infrastructure. If advanced fuel cycle technologies were deployed in areas with little current infrastructure, the waste impacts per unit of energy produced may be larger than those shown in this report.

Commercial reprocessing facilities already exist in France, the United Kingdom, Russia, and Japan, using current technologies that manage plutonium but not the minor actinides. These facilities achieve many, but not all, of the impacts of advanced recycling technologies.

Globally there is almost no deployment of fast reactors, and just as in the U.S. deployment would be slow due to limited material for startup cores. However, some countries with existing reprocessing facilities have stores of separated material which could be used in fast reactor startup cores.

6. CONCLUSIONS AND PATH FORWARD

The current GNEP advanced fuel cycle approach is the outgrowth of years of research and analysis. Objectives and technical goals established in earlier AFCI reports to congress are consistent with the GNEP approach of transitioning to continuous recycle of used nuclear fuel and employing fast reactors to manage transuranics in either a 1-tier or 2-tier recycling system.

Analyses presented in this report have confirmed the potential of substantial growth in global nuclear energy envisioned by GNEP and have quantified the impact of recycling on used fuel management.

6.1 Key Findings

The analyses have highlighted a number of key findings associated with nuclear energy growth and fuel cycle transitioning. These include:

- With projected growth, a once-through fuel cycle in the U.S. will require over 4,200,000 tonnes of additional uranium by the end of the century and generate an additional 410,000 tonnes of used fuel (including 5,300 tonnes of TRU) needing geologic disposal.
- The impact of a closed fuel cycle is highly dependent on the rate of deployment of fuel cycle facilities. The size and timing of UOX separations facilities is the primary driver behind the rate of deployment of TRU-burning fast reactors. The fast reactor deployment rate in turn impacts the amount of TRU both generated and consumed.
- Fast reactor deployment rates will be much lower than the levels predicted by simple "equilibrium" calculations due to multiple system constraints. Sensitivity studies have identified the most important constraints (in order) to be separations capacity and timing, nuclear growth rate, fast reactor TRU conversion ratio, used fuel cooling time, and fast reactor introduction timing. A 2-tier system with a MOX recycle stage imposes additional constraints that result in further reductions and delays.
- Transuranics management needs to account for both the TRU consumed in fast reactors and the additional TRU generation avoided due to fast reactors replacing some LWRs. Each factor reduces TRU quantities by over 1,000 tonnes during the century. The more TRU "at work" in fast reactors, the more total TRU is reduced.
- Later fast reactor deployment can result in large inventories of separated TRU requiring secure storage, unless MOX is used in LWRs or separations is delayed (which moves the system back toward the current situation of excess used fuel in storage).
- The location of used fast reactor fuel recycling facilities (onsite versus centralized) also has a significant impact on the rate of fast reactor deployment, impacting the amount of TRU tied up in used fuel.
- A closed fuel cycle does little to reduce uranium needs in this century due to the constraints on fast reactor deployment. The use of higher conversion ratios does not significantly change this finding.
- The impact of continuous recycling of used fuel on waste management is large, with both the long-term radiotoxicity and long-term decay heat of waste from recycled fuel needing geologic disposal reduced by more than a factor of 100 versus a once-through system.
- A closed fuel cycle employing advanced technologies is projected to increase the cost of nuclear-generated electricity by only 5–6 mils (~10%), but the cost uncertainties are large. The primary contributor to the increased cost is the projected capital cost of fast reactors, with fuel recycling costs contributing less than 40% of the total cost difference.

- With either a once-through or closed fuel cycle, nuclear costs are projected to be competitive with fossil fuels with or without a carbon tax.

6.2 Path Forward

While the analyses presented in this report provide answers to a number of questions concerning the transition to an advanced fuel cycle, they also indicate where additional analyses would be beneficial. Areas of future analysis and tradeoff studies include:

- While the analyses presented in this report provide answers to a number of questions concerning the transition to an advanced fuel cycle, they also indicate where additional analyses would be beneficial. Areas of future analysis and tradeoff studies include:
- Assessing phased fuel cycle transition options, including the initial fielding of mature technologies followed by a later phase-in of advanced technologies. Assessing the flexibility gained from initial use of a 2-tier system that transitions to a 1-tier system as fast reactors become more prevalent and assessing the differences on system cost profiles and repository benefits. This also includes the use of heterogeneous cores in fast reactors and the management of minor actinides in 2-tier systems.
- Supporting major technology decisions and requirements development through integrated analyses. Examples include the fast reactor fuel type, separations options and efficiency targets, the utility of decay storage, and the impacts of waste form and disposal options.
- Extending the types of analyses provided to include transportation and storage packaging options, buffer storage needs, impacts of facility availability, variations in feedstock, changing conversion ratios and approaches to improve system reliability, flexibility, and performance.
- Extending the scope of analyses to include additional reactor and fuel types, impacts of expansion of nuclear energy beyond electricity generation, and assessment of global transitions including fuel take-back systems and grid-appropriate reactors.

7. REFERENCES

Bailey 2008 Bailey, George F. and James D. Smith, 2008, "Draft Once-Through, Single, and Dual Tier Fuel Cycles Transportation Cost Analyses," GNEP-SYSA-ECON-SS-RT-2008-0000251, January 2008.

Bunn 2003 Bunn, M., S. Fetter, J. P. Holdren, and B. van der Swaan, 2003, "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," Harvard University, Cambridge, MA, 2003.

Clarke 2007 Clarke L., J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, and R. Richels, 2007, "Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations," Climate Change Science Program Synthesis and Assessment Product 2.1, Part A, 2007.

Deffeyes 1980 Deffeyes, Kenneth S., and Ian D. MacGregor, 1980, "World Uranium Resources," Scientific American, Vol. 242, No 1, 1980.

Deutch 2003Deutch, J., and E. Moniz (Co-chairs), 2008, "The Future of Nuclear Power: An Interdisciplinary MIT Study," Cambridge, Massachusetts Institute of Technology, 2003, http://web.mit.edu/nuclearpower, Web page visited May 30, 2008.

DOE 2001 U.S. Department of Energy, 2001, "Report to Congress – The Advanced Accelerator Applications Program Plan." March 2001.

DOE 2002 U.S. Department of Energy, 2002, "Generation-IV Roadmap: Report of the Fuel Cycle Crosscut Group," 2002.

DOE 2003 U.S. Department of Energy, 2003, "A Technology Roadmap for Generation IV Nuclear Energy Systems," Issued by the U.S. DOE Nuclear Energy Advisory Committee and the Generation IV International Forum, December 2003.

DOE 2003a U.S. Department of Energy, 2003, "Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research," Office of Nuclear Energy, Science, and Technology, January 2003

DOE 2003b U.S. Department of Energy, 2003, "Advanced Fuel Cycle Initiative (AFCI) Comparison Report, FY 2003," Office of Nuclear Energy, Science and Technology, October, 2003.

DOE 2003c U.S. Department of Energy, 2003, "The U.S. Generation IV Implementation Strategy – Preparing Today for Tomorrow's Energy Needs," September 2003.

DOE 2004 U.S. Department of Energy, 2004, "Advanced Fuel Cycle Initiative (AFCI) Comparison Report, FY 2004," Office of Nuclear Energy, Science and Technology, September 2004.

DOE 2005 U.S. Department of Energy, 2005, "Report to Congress – Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary," Office of Nuclear Energy, Science, and Technology, May 2005.

DOE 2005a U.S. Department of Energy, 2005, "Advanced Fuel Cycle Initiative (AFCI) Comparison Report, FY 2005," Office of Nuclear Energy, Science and Technology, May 2005.

DOE 2006 U.S. Department of Energy, 2006, "Report to Congress – Spent Nuclear Fuel Recycling Program Plan," May 2006.

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

DOE 2006b U.S. Department of Energy, 2006, "The U.S. Generation IV Fast Reactor Strategy," Office of Nuclear Energy, DOE/NE-0130, December 2006.

DOE 2007 U.S. Department of Energy, "Global Nuclear Energy Partnership Statement of Principles," http://www.gneppartnership.org/docs/GNEP_SOP.pdf, Web page visited May 30 2008.

DOE 2008 U.S. Department of Energy, Global Nuclear Energy Partnership website, http://www.gneppartnership.org/, Web page visited May 30, 2008.

Dooley 2004 Dooley James J., and S.J. Friedman, 2004, "A Regionally Disaggregated Global Accounting of CO_2 Storage Capacity: Data and Assumptions," Battelle Pacific Northwest Division, PNWD-3431, 2004.

EAWG 2007 Economic Analysis Working Group, 2007, "Global Nuclear Energy Partnership Economic Tools, Algorithms, and Methodology," INL/EXT-07-13293, GNEP-SYSA-ECON-SS-RT-2007-000354, Draft, September 2007.

EAWG 2008 Economic Analysis Working Group, 2008, "Draft GNEP Economic Analysis Report." GNEP-SYSA-ECON-SS-TR-2008-000067, May, 2008.

EPACT 2005 Energy Policy Act of 2005 (Public Law 109-058), http://www.epa.gov/oust/fedlaws/publ_109-058.pdf, Web page visited May 30, 2008.

Edmonds 2002 Edmonds, J., P. Freund, and James J. Dooley, 2002, "The role of carbon management technologies in addressing atmospheric stabilization of greenhouse gases," *Greenhouse Gas Control Technologies, Proceedings of the Fifth International Conference on Greenhouse Gas Control Technologies*, CSIRO, Collingswood, VIC, Australia, 2001, pgs 46–51, 2002.

EIA 2006 Energy Information Administration, 2006, "Annual Energy Review 2006," U.S. Department of Energy (DOE), Washington, D.C., http://www.eia.doe.gov/emeu/aer/contents.html, Web page visited May 30, 2008.

EIA 2007a Energy Information Administration (EIA), 2007, "Assumptions to the Annual Energy Outlook 2007," U.S. Department of Energy (DOE), Washington, D.C., pp 90, 2007.

EIA 2007b Energy Information Administration, 2007, "Annual Energy Outlook 2007," U.S. Department of Energy (DOE), Washington, D.C., http://www.eia.doe.gov/oiaf/archive/aeo07/index.html, Web page visited May 30, 2008.

EIA 2008 Energy Information Administration, 2008, "Annual Energy Outlook 2008 (Revised Early Release)," U.S. Department of Energy (DOE), Washington, D.C., www.eia.doe.gov/oiaf/aeo/index.html, Web page visited May 30, 2008.

Freund 1997 Freund, P., and W.G. Ormerod, 1997, "Progress toward storage of carbon dioxide," Energy Conversion and Management, Volume 38, S199-S204, 1997.

GNEP 2007 Global Nuclear Energy Partnership Technical Integration Office, 2007, "Global Nuclear Energy Partnership Technology Development Plan," GNEP-TECH-TR-PP-2007-00020, Rev 0, July 25, 2007.

Gombert 2008 Gombert, Dirk, Joe Carter, Alex Cozzi, Robert Jones, Gretchen Matthern, Mark Nutt, Steve Priebe, and Ken Sorenson, 2008, "Global Nuclear Energy Partnership Integrated Waste Management Strategy," GNEP-WAST-AI-RT-2008-000214, March 2008.

Gregg 2003 Gregg and Worrall, 2003, "Effect of Highly Enriched/Highly Burnt UO2 Fuels on Nuclear Design Parameters and Economics," Advances in Nuclear Fuel Management III (ANFM 2003), Hilton Head Island, South Carolina, October 5–8, 2003.

Herring 2004 Herring, J. Stephen, 2004, "Uranium and Thorium Resources" The Encyclopedia of Energy, Cutler J. Cleveland, Editor-in-Chief, Academic Press, 2004.

Hoffman 2007 Hoffman, E., 2007, "Updated Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios," ANL-AFCI-189, May 2007.

Hotelling 1931 Hotelling, H, 1931, "The Economics of Exhaustible Resources," Journal of Political Economy 39: 137–175, 1931.

ICRP The ICRP Database of Dose Coefficients: Workers and Members of the Public, Version 2.01, Pergamon, Distributed by Elsevier Science Ltd, ISBN 0 08 043 8768.

Jacobson 2008 Jacobson, Jacob J., Gretchen E. Matthern, Steven J. Piet, and J. Grimm, 2008, "VISION User Guide," INL/MIS-07-13102, Rev 2.2, February 16, 2008.

Keeling 2004 Keeling, C.D., and T.P. Whorf, 2008, "Atmospheric Carbon Dioxide Record from Mauna Loa," Carbon Dioxide Research Group, Scripps Institution of Oceanography, University of California, LaJolla, California, http://cdiac.ornl.gov/trends/co2/sio-mlo.htm, Web page visited May 30, 2008.

Kim 2006 Kim, S.H., J.A. Edmonds, J. Lurz, S.J. Smith, and M. Wise, 2006, "The O^{bj}ECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation," The Energy Journal, Special Issue #2, 63–91, 2006.

Kim 2008 Kim, S.H., and J. Edmonds, 2008, "The Potential of Nuclear Energy for Addressing Climate Change," GNEP-SYSA-PMO-MI-DV-2008-000179, The Joint Global Change Research Institute, Battelle, PNNL, February 2008.

Michaels 1994 Michaels, G.E., and T.D. Welch, 1994, "Evaluation of Disposition Options for Reprocessed Uranium," ORNL/TM-12326, May 1994.

NRC 2001 Nuclear Regulatory Commission, 2001, "Licensing Requirements for Land Disposal of Radioactive Waste," Title 10, Part 61, Code of Federal Regulations (10CFR61), Originally published Federal Register, Volume 47, page 57463, Dec. 27, 1982, amended at 54 FR 22583, May 25, 1989, and 66 FR 55792, Nov. 2, 2001.

NRC 2005 Nuclear Regulatory Commission, 2005, "Memorandum and Order in the Matter of Louisiana Energy Services," CLI-05-05, Docket No. 70-3103-ML, January 18, 2005. NRC 2005 Nuclear Regulatory Commission, 2005, "Memorandum and Order in the Matter of Louisiana Energy Services," CLI-05-05, Docket No. 70-3103-ML, January 18, 2005.

NRC 2008a Nuclear Regulatory Commission, "Expected New Nuclear Power Plant Application," http://www.nrc.gov/reactors/new-licensing/new-licensing-files/expected-new-rx-applications.pdf, Web page updated May 23, 2008, Web page visited May 30, 2008.

NRC 2008b Nuclear Regulatory Commission, "Power Uprates," http://www.nrc.gov/reactors/operating/licensing/power-uprates.html, Web page visited May 30, 2008.

NRC 2008c Nuclear Regulatory Commission, "New Reactors," http://www.nrc.gov/reactors/new-reactor-licensing.html, Web page visited May 30, 2008.

OECD 2003 Organisation for Economic Co-operation and Development and International Atomic Energy Agency, 2003, "Uranium 2003: Resource, Production and Demand," IAEA, Vienna, Austria and the OECD/NEA, Paris, France, 2003.

OECD 2005 Organisation for Economic Co-operation and Development and International Atomic Energy Agency, 2005, "Uranium 2005: Resources, Production and Demand," NEA No. 6098, 2005.

NOAA 2008 National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Earth System Research Laboratory, 2008, "Atmospheric Carbon Dioxide-Mauna Loa," http://www.esrl.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html, Web page visited May 30, 2008.

Peck 1996 Peck, S.C., and Y.H. Wan, 1996, "Analytical Solutions of Simple Greenhouse Gas Emission Models," Chapter 6 of *Economics of Atmospheric Pollution*, eds. E.C. Van Ierland and K. Gorka, Springer Verlag, New York, 1996.

Piet 2006 Piet, Steven J., Gretchen E. Matthern, Jacob J. Jacobson, C.T. Laws, L.C. Cadwallader (INL), A.M. Yacout, R.N. Hill (ANL), James D. Smith, A.S. Goldmann, and George Bailey (SNL), 2006, "Fuel Cycle Scenario Definition, Evaluation, and Trade-offs," INL report, INL/EXT-05-00727, September 2006.

Schneider 2008 Schneider, Erich and William Sailor, 2008, "Long Term Uranium Supply Estimates," Nuclear Technology**,** LA-UR-05-8879, forthcoming, 2008.

Senate 2003 Senate Report 107-220, Energy and Water Development Appropriation Bill, 2003.

Shropshire 2007 Shropshire, David E., K.A. Williams, W.B. Boore, James D. Smith, Brent W. Dixon, M. Dunzik-Gougar, R. Adams, Dirk Gombert, and E. Schneider, 2007, "Advanced Fuel Cycle Cost Basis," Idaho National Laboratory, INL/EXT-07-12107, 2007.

Shropshire 2008 Shropshire, David, et al, 2008, "2008 Advanced Fuel Cycle Cost Basis," INL/EXT-06-11536, March, 2008.

Sproat 2008 Sproat III, E.F., Director, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, 2008, "Statement to House Appropriations Subcommittee on Energy and Water Development," FY 2009 Appropriations Hearing, April 10, 2008.

Steyn 2003 Steyn, Julian J., 2003, "Uranium Resources: Need For 21st Century Advanced Fuel Cycles," Energy Resources International, Inc., NEI International Fuel Seminar, 2003.

UN 1999 United Nations Environment Programme, 2008, "Introduction to Climate Change," http://www.grida.no/climate/vital/07.htm, Web page visited May 30, 2008.

U of C 2004 University of Chicago, 2004, "The Economic Future of Nuclear Power," Argonne National Laboratory, August 2004.

Wigeland 2006 Wigeland, Roald A. et al., 2006, "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," Nuclear Technology, Volume 154, April 2006.

WNA 2007 World Nuclear Association, 2007, "Nuclear Power in the World Today" June 2007.

WNA 2008 World Nuclear Association, 2008, "World Nuclear Power Reactors 2006-08 and Uranium Requirements," http://www.world-nuclear.org/info/reactors.html, published March 20, 2008, Web page visited May 30, 2008.

Appendix A

Systems Analysis Approach

Appendix A – Systems Analysis Approach

A-1. Introduction

The GNEP systems analyses are the primary vehicle being used by the Department of Energy to develop answers to important questions about the potential behavior and performance of advanced fuel cycle systems. Systems analyses provide information that helps guide program development and inform GNEP program decisions.

Questions being addressed by DOE through its systems analyses include:

- What are the advantages and disadvantages of proceeding to GNEP facilities?
  - Do the facilities and their sequencing fit together?
  - What is the urgency?
- What are the potential implications of realizing the GNEP vision?
  - What is the impact on the environment in terms of future waste management (e.g., the need and timing for a second geologic repository)?
  - What is the potential for and impact of energy recovery from spent fuel?
  - What is the impact on uranium requirements for the nuclear energy enterprise?
  - What is the impact on security and proliferation risk?
  - What is the impact on the cost of nuclear power?

The associated systems analysis activities fall into three general categories: (1) developing a description of the deployed GNEP systems, (2) establishing the needed characteristics of the facilities to enable a successful deployment, and (3) defining a plan to achieve a transition to a recycle fuel cycle in the future, assuming that the GNEP technologies are successfully developed, adequate funding is made available, and any applicable legal, regulatory and other contingencies are addressed. These categories are further described as follows:

- Identify the necessary types, performance characteristics, and capacities of facilities necessary for an appropriate balance among the facilities associated with a recycle fuel cycle system:
  - Evaluate alternative mixes of LWRs and advanced recycling reactors required to: (a) consume the transuranics from the current fleet of commercial LWRs, and (b) support growth of nuclear power generation.
  - Evaluate the advantages and disadvantages of decentralized versus centralized fuel cycle facilities.
  - Estimate the quantities and characteristics of waste that will be produced and evaluate whether the recycling could postpone the need for a second geologic repository to the next century or beyond.
  - Evaluate how additional separations and decay storage would impact waste quantities and costs.
  - Estimate, with reduced uncertainty, the economic performance of a recycle fuel cycle system.
- Determine the necessary sizes and the timing of the initial facilities to realize GNEP advanced recycling technologies:
  - Assess the separations capacity needed to provide the transuranics for fuel for the initial advanced recycling reactor.
  - Establish the projected life-cycle costs of the initial facilities.

  - Take into account the need to implement international fuel services and the potential impact on domestic facilities.
- Describe potential pathways to achieve a transition in the future from initial facilities to full deployment:
  - Describe potential schedules for deployment of subsequent LWR spent fuel separations.
  - Describe potential schedules for deployment of industrial-scale, remote-handling fuel fabrication equipment and facilities.
  - Describe potential schedules for using mixed oxide (MOX) fuel in LWRs
  - Describe potential schedules for deployment of subsequent advanced recycling reactors.
  - Assess the need for process storage for spent fuel and for decay storage of selected fission products (e.g., cesium and strontium).
  - Describe the infrastructure that would be needed for transporting spent fuel, transuranics-bearing fresh fuel, and wastes to appropriate processing, reactor, and disposal facilities.

A-2. Approach

Systems analyses assess options and uncertainties in the performance of nuclear fuel cycles. The general approach is to first develop criteria based on policy objectives, then analyze the available options against the criteria. Results are reviewed, then provided to program management in order to inform decisions. If necessary, this process may be repeated with more refined criteria and more focused analysis. The DOE's first round of this analytical approach was the discovery phase analyses conducted within the AFCI program and its predecessors. The current report provides initial discovery phase analysis results, assessing the transition phase of the fuel cycle as a first step toward optimization of technical options.

Systems analysis is often constrained by available data. Current data on the cost and performance of full actinide separations, transmutation fuels, and fast spectrum reactors are limited to that provided by bench-scale research and extrapolations from past technology efforts. Additional technology development and demonstration will yield improved data and reduce uncertainty. Conceptual and preliminary design work on the envisioned facilities will provide significantly better information on the cost of the initial facilities, the Advanced Fuel Cycle research and development program, and the deployment systems.

A variety of systems analyses are required to assess the viability, performance, and dynamic impact of nuclear fuel cycle technology options. These analyses must be done for both domestic and international scenarios. The areas of emphasis are as follows:

- Defining future nuclear energy scenarios
- Fuel cycle architecture definition
- Fuel cycle analysis
  - Transmutation analysis
  - Material transportation, storage and disposal analysis
  - Economic analysis
- Systems integration.

The results of these analyses provide technical and cost information to support further definition of the GNEP program objectives and development and deployment pathways. To ensure that high quality

information is used to support important decisions, this information undergoes an internal technical review before its release.

A-2.1 Future Nuclear Energy Scenarios

Nuclear fuel cycles are often assessed in the context of potential future scenarios for nuclear energy growth. It is impossible to accurately predict the future, so various growth scenarios are examined, with a focus on the trends that are observed in the fuel cycle deployment, and the sensitivity of those trends to various parameter changes. Currently, future scenarios for nuclear energy are focused on the domestic assessment, but later will be expanded to include international aspects, including nuclear fuel supply services and use of reactors sized for the electricity grids of developing countries.

A-2.2 Fuel Cycle Architecture Definition

Various nuclear fuel cycle architectures can be defined and assessed from a systems analysis perspective. High level architectures define the major elements of the fuel cycle and primary nuclear material flow paths. Fuel cycle architectures can be fundamentally characterized by certain basic attributes. From the standpoint of used or spent nuclear fuel, there are once-through, limited recycle, and continuous recycle fuel cycles. In once-through fuel cycles, the used fuel discharged from the reactor is disposed of directly into a repository. With limited recycle, the used fuel is recycled once or a limited number of times and then disposed of in a repository. With continuous recycle, the used fuel is recycled repeatedly, and can be used to provide fuel for new reactors that may be built as well. In Figure A-1, the flow depicted by the red arrow represents a once-through cycle, whereas the circular flow depicted by the green arrows is representative of recycle architectures, limited if the used fuel is disposed of in the repository after one or more cycles, continuous if fuel is recycled repeatedly and consumed in producing energy.

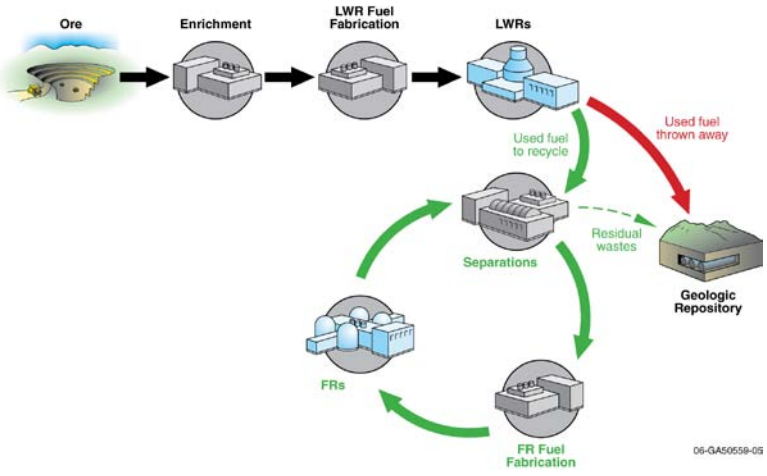


Figure A-1. Fundamental fuel cycle architectures.

A-2.3 Fuel Cycle Analysis

As part of the AFCI systems analysis work, various potential fuel and reactor configurations have been assessed for transmutation potential, and additional configurations are under evaluation. Fuel cycle

analysis systematically assesses the fuel cycle system performance of proposed technology and implementation options. Static or dynamic analyses can be performed in analyzing nuclear fuel cycles. In general, static analyses assume constant nuclear energy production levels whereas dynamic analyses take into account changes in nuclear production levels and other parameters over time. Static analyses for architectures designed to recycle all the transuranics are often performed under "equilibrium" or steady-state conditions, where the amount of transuranics produced in the system is about equal to the amount consumed (aside from minor losses) so that the net production of transuranics for the entire fuel cycle is about zero.

Dynamic analyses examine the timing and interaction of reactors, fuel cycle facilities and material flows, including feedbacks from each facility, time lags, and the system response to changes as the system evolves from initial facilities to full deployment. Dynamic analyses are also used to evaluate the timing and material flows for fuel cycle facilities. Current AFCI fuel cycle models address all aspects of the fuel cycle from "cradle to grave" and include the ability to assess a wide range of fuel cycle options. These models range from spreadsheets to the detailed VISION[a] dynamic simulation model that uses a modular approach to model the fuel cycle.[b] VISION tracks total mass and over 60 isotopes through the fuel cycle from initial mining or creation in a reactor to final disposition via transmutation or as waste, along with associated volumes, masses, material forms, and process unit costs.

Figure A-2 shows a schematic of the U.S. nuclear fuel cycle used for VISION. It is organized into a series of modules that include all of the major facilities and processes involved in the fuel cycle, starting with uranium mining and ending with waste management and disposal. The arrows in the diagram indicate the mass flow of the fuel. VISION also includes information about facility capacities and logic that control and constrain the addition of new facilities and how materials are transformed within the system (transmutation in reactors, split fractions in separations facilities, decay during storage, etc.). The mass flows are combined with cost and waste conditioning data to provide insight into economics, waste disposition, and transportation issues of the fuel cycle.

A wide variety of scenarios for future nuclear energy capacity deployment strategies and technologies have been assessed using these models, and promising alternatives will continue to be investigated. The impact of uncertainties in process, reactor, and waste disposal performance is also evaluated.

Three specific areas of fuel cycle analysis are discussed in the next subsections.

A-2.3.1 Transmutation Analysis

The present Transmutation Analysis element of the GNEP Systems Analysis Campaign is a continuation of work that has been performed under the programs that preceded GNEP (i.e., ATW, AAA, and AFCI) under various names (Reactor Performance Analysis, etc.). Over the past several years, the focus has been on performing reactor physics and other nuclear-related analyses (dose, criticality, etc.) to evaluate the performance of various accelerator and reactor-based concepts for addressing programmatic mission objectives. The primary role of the reactor or other nuclear systems is to contribute to the management of the used nuclear fuel from commercial LWRs by irradiating actinides (and possibly other long-lived fission products) in the used fuel to extract the energy potential and to transmute isotopes that adversely affect repository performance into more benign products. The bulk of the work has

a. The Verifiable Fuel Cycle Simulation of Nuclear Fuel Cycle Dynamics (VISION) was developed by the national laboratories in collaboration with universities to support fuel cycle systems analyses.

b. Additional models are used for analysis of global energy systems, including the O[bj]ECTS MiniCAM integrated assessment model, a long-term, globally integrated assessment model of energy-economy interactions and greenhouse gas (GHG) emissions.

concentrated on managing the TRU in LWR used fuel. The principal outputs from the analyses include parameters related to reactor performance (e.g., mass flows, charge and discharge isotopics, power distributions, doses, etc.), and safety related parameters (e.g., reactivity coefficients, control worths). These parameters may be used "stand alone" to provide an initial estimate of the performance characteristics and viability of a given concept, or as input to scenario analyses with the VISION code where the reactor(s) are just one element in the over-all fuel cycle model (Jacobson 2007).

Concepts that have been evaluated include accelerator-driven systems where the transuranics are located in a subcritical blanket surrounding a spallation neutron source, commercial light-water reactors and fast spectrum reactors, either individually (single-tier), or in combination, and to a lesser degree, gas-cooled thermal reactors. A comprehensive summary of earlier work is given in "Comprehensive Summary of AAA and AFCI Transmutation Analysis Studies" (Taiwo 2007). The focus of recent analyses has been on evaluations of two recycle strategies:

- Single Tier Fast Reactor: Under this scenario all the TRU elements from LWR used fuel are separated together and continuously recycled in sodium-cooled fast spectrum Advanced Recycling Reactors (ARRs) in a "homogeneous" mode (i.e., all fuel rods contain all the TRU). The characteristics of the ARR have been evolving in terms of the conversion ratio, the power level, cycle length, etc. In addition, the option of "heterogeneous" recycle where fuel rods/assemblies may contain different TRU elements is also being explored.
- Dual Tier Thermal Fast Reactor: Under this scenario (U, Pu) from LWR used fuel is fabricated into "conventional" (U, Pu) MOX fuel and undergoes one pass through an LWR prior to the multi-recycle in the ARR.

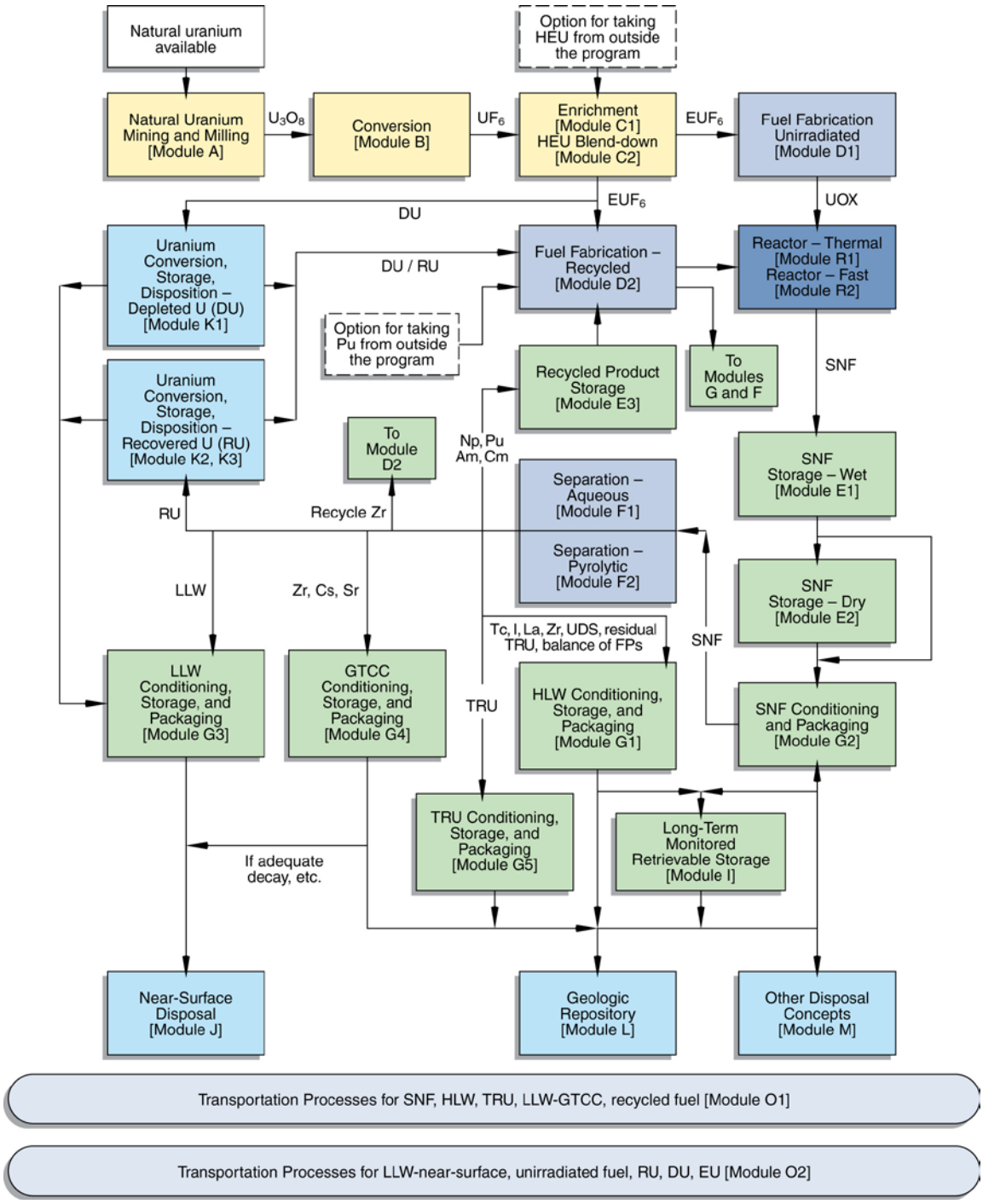


Figure A-2. Fuel cycle modules used in systems modeling.

Recent results describing the performance of metal and oxide-fueled ARRs spanning a range of conversion ratios are described in Hoffman 2006, Hoffman 2007, and Ferrer 2007.

A-2.3.1.1 Transmutation Analysis Methodologies

Most of the analyses are performed with "standard" reactor analysis programs that have generally been benchmarked against experimental and operating data. The analyses simulate the performance of

the reactor under various fuel loading, performance, and fuel management constraints. The simulations vary in the level of fidelity and sophistication employed in the modeling, ranging from scoping calculations to detailed benchmark calculations.

LWR Analyses

Analyses for LWRs have typically been limited to two-dimensional infinite lattice assembly calculations, or "colorset" geometries, where four neighboring assemblies are modeled, again as an infinite lattice, in conjunction with the linear reactivity model to translate the results to full-core loadings. The adequacy of this approach for scoping calculations has been well demonstrated by comparison to more detailed models. In these calculations the detailed internal geometry of the assembly is represented, but core effects are only approximately reproduced. A three-dimensional model of the core would be required for more accurate modeling, especially for highly heterogeneous configurations, but this level of detail has not generally been warranted. The fuel assembly codes that have been used historically include BOXER (Paratte 1996), DRAGON (Marleau 2000), TRITON (DeHart 2006, ORNL 2005), and WIMS8 (WIMS). Candidate codes that would provide the capability for full three-dimensional modeling with thermal feedback are being reviewed.

It should be noted that complementary calculations for some configurations have also been performed over the years under the "Neutronics Analysis" element of the Fuels Campaign and its predecessors. These calculations have included thermal-hydraulic calculations with COBRA-3 (COBRA 2001, and selected transient/accident analyses with RELAP-3D (RELAP 2003) with the objective of screening potential implementation scenarios for transmutation fuels in LWRs to assess their viability.

Fast Reactor Analyses

Calculations for the ARR sodium-cooled fast reactors have been performed primarily with the Argonne National Laboratory (ANL) REBUS-3 code system [13]. The modeling includes a full three-dimensional representation of the reactor, and typically evaluates "equilibrium" cycle performance for "startup cores" where the feed fuel is from an external source such as LWR used fuel, or "recycle cores" where the bulk of the discharged fuel from a given cycle is recycled into the next cycle, and only needed makeup fuel comes from an external source. Recently, these calculations have been augmented by more detailed cycle-by-cycle analyses, including an initial examination of various intermediate transition cycles.

Detailed Isotopic Modeling

The above reactor calculations account for all the materials present in the reactor core that affect reactor characteristics and performance. However, certain applications require more detailed information on the isotopics (e.g., transportation and handling, repository performance). For these cases a hybrid approach has been used where the approaches described above are combined with the ORIGEN-2 code (ORNL 2002) (or more advanced versions of ORIGEN [ORNL 2005]) which consider several thousand isotopes, including all those that are required for evaluations of the non-reactor portions of the fuel cycle.

Benchmark Analyses

Monte Carlo calculations have been used to benchmark selected results from the above approaches. The MCNP/MCNPX (LNL 2005) and MONTEBURNS (LNL 2003) codes have been used to confirm the results from the more approximate design methods since they have the ability to model the geometry and nuclear data with minimal approximations. The Monte Carlo simulations have been especially valuable as "synthetic experiments" to validate the results from the design codes for configurations outside the range of those for which the standard design-basis codes have typically been applied (e.g., inert matrix/fertile free fuels, fuels with high transuranic loadings).

Verification Activities

A "Verification Plan for Transmutation Analyses" is described in (Todosow 2007). The verification activities focus on reviewing and documenting the bases for the assumptions discussed in Section 2, and verifying the bases for, and the analyses and results of calculations that impact current GNEP-related scenarios.

The verification of the assumptions used in the reactor analyses that are in the purview of other GNEP campaign elements (e.g., cooling times prior to re-processing for various options, times for fuel fabrication and transportation) are being coordinated through the GNEP Technical Integration Office (TIO).

The verification of analyses performed under the Systems Transmutation Analysis (TA) tasks over the years has been *de facto* an integral part of the activities since multiple laboratories and computer codes have been involved. The detailed approach to be followed for verifying calculations is expected to evolve as the effort proceeds. It is anticipated that needed/desirable sensitivity studies and/or additional analyses will be identified, and will be prioritized based on programmatic needs and performed as needed.

A key element of this activity will be to ensure that data passed on to the VISION team for scenario studies, and/or used "stand alone," receives an appropriate review and is documented.

A-2.3.2 Material Transportation, Storage and Disposal Analysis

Closing the nuclear fuel cycle with advanced recycle technologies enables fundamental changes in the nature of the waste management challenges, with the potential for dramatic improvements in repository capacity and reduced long-term hazard. In addition, any change to the existing nuclear fuel cycle raises important questions regarding the storage, transportation, and disposal of radioactive materials. Many system-wide features and processes are interconnected by their impact on the materials to be handled and the wastes to be disposed. At the same time, while the analysis of safety and operational issues for the major fuel cycle facilities are covered in reports focused on those systems, the auxiliary facilities and the transportation links between all facilities are not covered elsewhere. Therefore, it has fallen to the systems analyses to cover a broader range of assessments in the area of material storage, transportation, and disposal.

In general, these analyses are conducted through extraction of composition and quantity data from other elements of the program and synthesis into system-wide analysis tools such as VISION. Data is also developed through common spreadsheet models. Geologic repository thermal and long-term performance analysis is conducted with simplified models that are benchmarked against large calculations performed for existing repository programs. Data and parametric dependencies are obtained from both domestic and international studies of radioactive waste management. At this time there are no large model development activities in the material storage, transportation, and disposal areas. Where technical alternatives beyond past or current practice are required, they are generally developed by groups of experts in the field and documented in topical reports.

One component of the GNEP systems design is the development of an integrated waste management strategy for the GNEP fuel cycle. This strategy was developed to ensure an optimized, safe, acceptable pathway will be available to disposition all wastes. Separation of the components of spent fuel enables tailored management to be developed for each component. Development of the strategy includes evaluation of all separated streams, byproducts, and process wastes from fuel fabrication, reactor operation, and spent fuel separations. Options for disposition of each stream are being assessed, including recycle or disposal pathways, appropriate waste forms, and conversion and transportation requirements. The integrated waste management strategy also assesses the impact of regulations on disposition options. The strategy is a major factor in the material transportation, storage, and disposal analyses.

A-2.3.3 Economics Analysis

The economic analysis component includes several activities. First, the basis for analyses is sound cost information. Since 2004, the AFCI has been developing an economic cost basis and capabilities to perform engineering economic comparisons of advanced fuel cycles. The initial "AFC Cost Basis" report was produced in 2004, with annual updates in 2005, 2006, and 2007 (Shropshire 2007). This database addresses the fuel cycle using the same modular approach employed by the fuel cycle systems modules in Figure A-2. Each module includes a major function or facility for which cost information is gathered. This information ranges from market prices for well established functions, such as uranium enrichment, to extrapolations from past facilities and design studies for functions such as advanced separations. The database provides ranges for the costs, reflecting the uncertainty of both market rates and estimates for technologies that have not been demonstrated at scale. The database is constantly updated as new references are assessed. The most current "AFC Cost Basis" report was completed in March 2008, is 614 pages, and contains approximately 400 reference citations (Shropshire 2008).

Fuel cycle cost assessments are developed using the cost basis database. These assessments identify the full costs for each stage of the fuel cycle based on module unit costs and the associated mass flows required for a balanced (equilibrium) system. The total cost for the fuel cycle is developed for a given scenario of industry size and technology mix. These assessments use probability cost distributions for each of the modules to produce an uncertainty cost range to describe each fuel cycle strategy.

The "GNEP Economic Tools, Algorithms, and Methodology" report (EAWG 2007) contains cost models and methodologies used in these assessments. These capabilities were developed to evaluate the economic ramifications of a range of GNEP fuel cycle scenarios, including determination of which components have the largest uncertainty, and which components have the largest impact on overall cost.

As a precursor to the economic analysis, all the applicable general and case-specific assumptions for the front-end, reactor, back-end, and recycling requirements are identified. The economic analysis contains cost sensitivity analysis, including cost distributions and the cost sensitivity due to specific variables of interest. The analysis identifies key cost drivers that have the greatest impact on economic discrimination between alternatives. System uncertainties, such as process performance, which have a large influence on costs, are identified and evaluated in combination with the uncertainties that are intrinsically associated with the input cost values. The costs of transportation are also evaluated in the sensitivity analysis to bound the magnitude of these costs relative to the total cost of electricity and describe their primary uncertainties and sensitivities.

The economic analyses are then performed using primarily two cost models: one static and one dynamic. Generation IV Excel Calculations of Nuclear Systems (G4-ECONS) is a spreadsheet model that provides static (snapshot-in-time) cost analysis and was used to generate the total equilibrium costs for each system. The spreadsheet data are evaluated for their cost uncertainty using a software program called Decision Programming Language. VISION.ECON is a system dynamics model that provides dynamic costs analysis consistent with the cases and types of analyses being performed by the GNEP Analysis and Integration team. The software also has a capability to perform sensitivity analyses. For verification purposes, the static spreadsheet model is used as a check on the dynamic results.

Sensitivity analyses are performed to identify which drivers contribute the most to the total cost uncertainty. The most important technology-based cost drivers become the focus of redoubled efforts to obtain better data. The impact of major non-technical cost drivers are also assessed to determine which options are least impacted by external conditions such as interest rate changes.

Finally, extra costs associated with initial fuel cycle system deployment are assessed. These include the higher costs of FOAK facilities and the learning required through construction and operations experience to achieve lower NOAK.

Economic assessments are now being integrated (EAWG 2008) with the other components of systems analysis to better understand the relative costs of different technology options and tradeoffs between cost, performance, and proliferation measures. This includes interaction with industry to understand their perspectives on future nuclear costs, refining cost estimates in areas of high cost uncertainty using information generated by the GNEP facility design efforts, performing additional sensitivity studies of front-end fuel cycle market effects, identifying ways to maximize facility economies of scale/production, and understanding the financial differences associated with international versus domestic deployment of GNEP technologies.

A-2.4 Systems Integration

The previous subsections described how systems analysis is being used to understand the behavior and performance of an advanced fuel cycle system from multiple perspectives. Each perspective addresses performance against one or more of the GNEP objectives. Systems integration activities combine all of the above analyses to understand how well different fuel cycle scenario and technology options balance all objectives (both domestic and international).

The systems integration activity requires analysts to synthesize systems analyses in each area to develop a comprehensive knowledge of the fuel cycle system and how improvements in one area reinforce or counteract improvements in other areas. This knowledge must be combined with a thorough understanding of the intent of policy makers to assess and develop a balanced, integrated system.

Results of systems integration analyses help inform program development, which in turn refines performance requirements. As the integrated system understanding improves, program direction improves and program requirements become more focused. This process is reflected in the evolution from a wide range of fuel cycle options under consideration within the AFCI program to more focused fuel cycle architecture, for both the initial facilities as well as the subsequent facilities, for the GNEP mission.

A-3. References

COBRA 2001, "COBRA-EN: Code System for Thermal-Hydraulic Transient Analysis of Light Water Reactor Fuel Assemblies and Cores," PSR-507, RSICC, ORNL, May 2001.

DeHart 2006, DeHart, M. D., and A. P. Ulses, 2006, "Lattice Physics Capabilities of the SCALE Code System Using TRITON," Proc. PHYSOR-2006, Vancouver, British Columbia, Canada, Sept. 10–14, 2006.

EAWG 2007, Economic Analysis Working Group, 2007, "Global Nuclear Energy Partnership Economic Tools, Algorithms, and Methodology," INL/EXT-07-13293, GNEP-SYSA-ECON-SS-RT-2007-000354 (Internal GNEP report), Draft, September 2007.

EAWG 2008, Economic Analysis Working Group, 2008, "Draft GNEP Economic Analysis," GNEP-SYSA-ECON-SS-RT-2008-000067, Draft, May 2008.

Ferrer 2007, Ferrer, Roald M., M. Asgari, S. E. Bays, and B. Forget, 2007, "Fast Reactor Alternative Studies: Effects of Transuranic Groupings on Metal and Oxide Sodium Fast Reactor Designs," INL/EXT-07-13236, 2007.

Hoffman 2006, Hoffman, E.A., W.S. Yang, and R.N. Hill, 2006, "Preliminary Core Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios," ANL-AFCI-177, September 29, 2006.

Hoffman 2007, Hoffman, E. A., 2007, "Updated Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios," ANL-AFCI-189, May 31, 2007.

Jacobson 2007, Jacobson, Jacob J., Gretchen E. Matthern, Steven J. Piet, and J. Grimm, 2007, "VISION User Guide - VISION (Verifiable Fuel Cycle Simulation) Model," INL/MIS-07-13102, Rev 1.1, November 2007.

LNL 2003, Los Alamos National Laboratory, 2003, "MONTEBURNS2.0: An Automated, Multi-Step Monte Carlo Burnup Code System," Code Package PSR-455, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, July 2003.

LNL 2005, Los Alamos National Laboratory, 2005, "MCNP/MCNPX EXE: Monte Carlo N-Particle Transport Code System Including MCNP5 1.40 and MCNPX 2.5.0 and Data Libraries," Code Package CCC-730, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2005.

Marleau 2000, Marleau, G., A. Hebert, and R. Roy, 2000, "A User Guide for DRAGON, Version DRAGON_000331 Release 3.04, Technical Report IGE-174 Rev. 5," Institut de Genie Nucléaire, Département de Genie Mécanique, Ecole Polytechnique de Montréal, April 2000.

ORNL 2002, Oak Ridge National Laboratory, 2002, "ORIGEN 2.2 – Isotope Generation and Depletion Code," CCC-371, June 2002.

ORNL 2005, Oak Ridge National Laboratory, 2005, "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," ORNL/TM-2005/39, Version 5, Vols. I–III, April 2005, Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-725.

Paratte 1996, Paratte, J. M., K. Foskolos, P. Grimm, and C. Maeder, 1996, "The PSI Code System ELCOS for LWR Core Analysis," Paul Scherrer Institute, Villigen PSI, February, 1996.

RELAP 2003, RELAP5-3D Version 2.2.4, INEEL, October 20, 2003.

Shropshire 2007, Shropshire, David E., K. A. Williams, W.B. Boore, James D. Smith, Brent W. Dixon, M. Dunzik-Gougar, R. Adams, Dirk Gombert, and E. Schneider, 2007, "Advanced Fuel Cycle Cost Basis." Idaho National Laboratory, INL/EXT-07-12107, 2007.

Shropshire 2008, Shropshire, David, et al., 2008, "2008 Advanced Fuel Cycle Cost Basis," INL/EXT-06-11536, March 2008.

Taiwo 2007, Taiwo, T. A. and R. N. Hill., 2007, "Comprehensive Summary of AAA and AFCI Transmutation Analysis Studies," ANL-AFCI-198, Argonne National Laboratory, September 30, 2007.

Todosow 2007, Todosow, M. et al., 2007, "Verification Plan for Transmutation Analysis," BNL-AFCI-2007-002, November 30, 2007.

Toppel 1983, Toppel, B. J., 1983, "A User's Guide to the REBUS-3 Fuel Cycle Analysis Capability," ANL-83-2, Argonne National Laboratory, 1983.

WIMS, WIMS, "WIMS - A Modular Scheme for Neutronics Calculations," User's Guide for Version 8, Serco Assurance, 1998.

Appendix B
Additional Systems Analysis Reports and Papers

Appendix B – Additional Systems Analysis Reports and Papers

This appendix includes a compendium of systems analysis reports. This is not a complete listing, as several minor reports and many technical papers are not included. The documents are listed in reverse chronological order by year.

2008

Bailey, George, and J. D. Smith, "VISION Dynamic Simulation Model Benchmark Comparison Report." GNEP-SYSA-AI-QA-RT-2008-000249, February 14, 2008.

Bailey, G. F., and J. D. Smith, "Once-Through, Single and Dual Tier Fuel Cycles Transportation Cost Analyses." GNEP- SYSA-ECON-SS-RT-2008-000251, January 29, 2008.

Ferrer, Rodolfo M., Samuel E. Bays, and Michael Pope, 2008, "Sensitivity Analysis of Reprocessing Cooling Times on Light Water Reactor and Sodium Fast Reactor Fuel Cycles," INL/EXT-08-14200, April 2008.

Ferrer, Rodolfo M., Samuel E. Bays, and Michael Pope, 2008, "Evaluation of Homogeneous Options: Effects of Minor Actinide Exclusion from Single and Double Tier Recycle in Sodium Fast Reactors," INL/EXT-08-14034. March 2008.

Gombert, Dirk, Joe Carter, Alex Cozzi, Robert Jones, Gretchen Matthern, Mark Nutt, Steve Priebe, and Ken Sorenson, 2008, "Global Nuclear Energy Partnership Integrated Waste Management Strategy," GNEP-WAST-AI-RT-2008-000214, March 2008.

Jacobson, Jacob J., Gretchen E. Matthern, Steven J. Piet, and J.Grimm, 2008, "VISION User Guide," INL/MIS-07-13102, Rev 2.2, February 16, 2008.

Jacobson, Jacob J., Gretchen E. Matthern, Steven J. Piet, and J.Grimm, 2008, "VISION User Guide," INL/MIS-07-13102, Rev 2.2, February 16, 2008.

Kim, Son H., and Jae Edmonds, 2008, "The Potential of Nuclear Energy for Addressing Climate Change," GNEP-SYSA-PMO-MI-DV-2008-000179, February 2008.

Pope, Michael, Samuel E. Bays, Rodolfo Ferrer, 2008, "Evaluation of Heterogeneous Options: Effects of MgO versus UO_2 Matrix Selection for Minor Actinide Targets in a Sodium Fast Reactor," INL/EXT-08-14039, March 2008.

Schweitzer, T. M., 2008, "Improved Building Methodology and Analysis of Delay Scenarios of Advanced Nuclear Fuel Cycles with the Verifiable Fuel Cycle Simulation Model (VISION)," Master's Thesis, North Carolina State University, Department of Nuclear Engineering, May 2008.

Taylor, J. P., D. E. Shropshire, and Jacob J. Jacobson, 2008,"A Vision of Advanced Nuclear System Cost Uncertainty," Proceedings of the 2008 International Conference on Nuclear Engineering, May 12–15, Orlando, Florida, 2008.

Yee, S., 2008, "Fuel Loading and Transmutation of Recycled Nuclear Fuel for the Verifiable Fuel Cycle (VISION) Model," Master's Thesis, Ohio State, June 2008.

2007

Asgari, M., B. Forget, Steven J. Piet, Rodolfo M. Ferrer, and Samuel E. Bays, 2007, "Computational Neutronics Methods and Transmutation Performance Analyses for Light Water Reactors," INL/EXT-07-12472, March 2007.

Bays, Samuel E., 2007, "Heterogeneous Transmutation Sodium Fast Reactor," INL/EXT-07-13252, September 2007.

Cipiti, Benjamin B., James D. Smith, and Ken B. Sorenson, 2007, "Fast Reactor Recycle Fuel Thermal Load," SAND2007-6595, October 2007.

Collins, E. D., G. D. DelCul, J. P. Renier, and B. B. Spencer, 2007, "Preliminary Multicycle Transuranic Actinide Partitioning-Transmutation Studies," ORNL/TM-2007/24, February 2007.

Ferrer, Rodolfo M., M. Asgari, Samuel E. Bays, and B. Forget, 2007, "Fast Reactor Alternative Studies: Effects of Transuranic Groupings on Metal and Oxide Sodium Fast Reactor Designs," INL/EXT-07-13236, September 2007.

Ferrer, Rodolfo M., M. Asgari, Samuel E. Bays, and B. Forget, 2007, "Computational Neutronics Methods and Transmutation Performance Analyses for Fast Reactors," INL/EXT-07-12466, March 2007.

Forget, B., M. Asgari, Rodolfo M. Ferrer, and Samuel E. Bays, 2007, "Impact of Including Higher Actinides in Fast Reactor Transmutation Analyses," INL/EXT-07-13247, September 2007.

Gombert, Dirk, et al., 2007, "GNEP Integrated Waste Management Strategy Waste Treatment Baseline Study," GNEP-WAST-AI-RT-2007-000324, September 2007.

Gombert, Dirk, et al., 2007, "2007 Draft Global Nuclear Energy Partnership — Materials Disposition and Waste Form Status Report," GNEP-WAST-AI-TR-2007-00013, February 2007.

Hoffman, E. A., T. A. Taiwo, and R. H. Hill, 2007, "Preliminary Physics Studies of Heterogeneous Recycle in the Advanced Burner," ANL-AFCI-206, September 28, 2007.

Hoffman, E.A., 2007, "Updated Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios," ANL-AFCI-189, May 31, 2007.

Jun Li, Man-Sung Yim, Steven J. Piet, and David McNelis, 2007, "Use of integrated decay heat limits to facilitate spent nuclear fuel loading to Yucca Mountain,". Global 2007, Boise, Idaho, September 2007.

Piet, Steven J., et al., 2007, "Benchmark and Verification Plan for the VISION Model," GNEP-SYSA-AI-SS-PL-2008-000009, Rev 0, November 15, 2007.

Piet, Steven J., et al., 2007, "Current Assessment of the Benefits of Recycling in Thermal Reactors," INL report to DOE, February 2007.

Radel, Tracy E., 2007, "Repository Modeling for Fuel Cycle Scenario Analysis**,"** Master of Science Thesis (Nuclear Engineering), University of Wisconsin-Madison, 2007.

Shropshire, David E., et al., 2007, "Global Nuclear Energy Partnership Economic Tools, Algorithms, and Methodologies Report," INL/INT-07-13117, GNEP-SYSA-ECON-SS-RT-20078-000354, September 2007.

2006

Hoffman, E. A., W. S. Yang, and R. N. Hill, 2006, "Preliminary Core Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios," ANL-AFCI-177, September 29, 2006.

Piet, Steven J., Gretchen E. Matthern, Jacob J. Jacobson, C. T. Laws, L. C. Cadwallader (INL), A.M. Yacout, R.N. Hill (ANL), James D. Smith, A.S. Goldmann, and George F. Bailey (SNL), 2006, "Fuel Cycle Scenario Definition, Evaluation, and Trade-offs," INL report, INL/EXT-05-00727, September 2006.

Piet, Steven, Jacob Jacobson, Gretchen Matthern, Chris Laws, and Latif Yacout, 2006, "VISION (Verifiable fuel cycle Simulation) Model Status and Path Forward," September 28, 2006.

Piet, Steven J., B. W. Dixon, Jacob J. Jacobson, C.T. Laws, Gretchen E. Matthern, David E. Shropshire (INL), R.N. Hill, A.M. Yacout (ANL), James D. Smith, and A.Goldmann (SNL), 2006, "Current Comparison of Advanced Fuel Cycle Options," Waste Management 2006, Tucson, Arizona, February 26–March 2, 2006.

Shropshire, David E., K. Williams, James D. Smith, and W. Boore, 2006, "Advanced Fuel Cycle Economic Sensitivity Analysis," INL/EXT-06-11947, December 2006.

Shropshire, David E., K. A. Williams, W. B. Boore, James D. Smith, B.W. Dixon, M. Dunzik-Gougar, R.D. Adams, and Dirk Gombert, 2006, "2006 Advanced Fuel Cycle Cost Basis," INL/EXT-06-11536, July 2006.

Taiwo, T. A., T. K. Kim, J. A. Stillman, R. N. Hill, M. Salvatores, and P. J. Finck, 2006, "Assessment of a Heterogenous PWR Assembly for Plutonium and Minor Actinide Recycle," Nuclear Technology, 155, pp. 34–54, July 2006.

Wigeland, Roald A., E. E. Morris, and T. H. Bauer, 2006, "Criteria Derived for Geologic Disposal Concepts," Ninth Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation (9IEMPT), Nîmes, France, September 25–29, 2006.

Wigeland, Roald A., et al., 2006, "Separations and Transmutation Criteria to improve Utilization of a Geologic Repository," Nuclear Technology, Vol. 154, April 2006.

2005

Cadwallader, L. C., Steven J. Piet, S. O. Sheetz, D. H. McGuire, and W. B. Boore, 2005, "Off-Normal Events in U.S. Fuel Cycle Facilities for AFCI Applications," INEEL/EXT-04-02257, September 2005.

Dixon, Brent W., and Steven J. Piet, 2005, "Spent Fuel Management Options," Nuclear Plant Journal, May 2005.

Goldman, S., 2005, Inert Matrix Fuel Burnup Calculations using a Multi-Recycle Strategy in Light Water Reactors," INL internal report, August 2005.

Halsey, W. G., 2005, "Advanced Fuel Cycle Initiative (AFCI) Repository Impact Evaluation FY-05 Progress Report," UCRL-TR-215380, September 15, 2005.

Hoffman, E. A., 2005, "Blending Strategies for Recycling of Inert-Matrix and Mixed-Oxide Fuels in LWRs," ANL-AFCI-158, September 30, 2005.

Hoffman, E. A., 2005, "Preliminary Report on Blending Strategies for Inert-Matrix Fuel Recycling in LWRs," ANL-AFCI-149, March 31, 2005.

Jacobson, Jacob J., Gretchen Matthern, Steven Piet, and Abdellatif Yacout, 2005, "Modeling the Nuclear Fuel Cycle," Proceedings for the 23rd International System Dynamics Conference, Boston, Massachusetts, September 2005.

Kim, T. K., T. A. Taiwo, R. N. Hill, W. S. Yang, and F. Venneri, 2005, "A Feasibility Study of Reactor-Based Deep-Burn Concepts," ANL-AFCI-155, August 31, 2005.

Morris, E. E., and T. H. Bauer, 2005, "Modeling of the Repository Behavior of TRISO Fuel," ANL-AFCI-160, September 29, 2005.

Piet, Steven, Brent Dixon, David Shropshire (INL), Robert Hill, Roald A. Wigeland (ANL), Erich Schneider (LANL), and James D. Smith (SNL), 2005, "Objectives, Strategies, and Challenges for the

Advanced Fuel Cycle Initiative," paper 182a, Annual Meeting of the American Institute for Chemical Engineering, Atlanta, Georgia, April 2005.

Taiwo, T. A., and R. N. Hill, 2005, "Summary of Generation IV Transmutation Impacts," ANL-AFCI-150, June 30, 2005.

Wigeland, Roald A., T. H. Bauer, and E. E. Morris, 2005, "Waste Management Aspects of Various Fuel Cycle Options," Proceedings of the IAEA Technical Meeting on Fissile Materials Management Strategies for Sustainable Nuclear Energy, Vienna, Austria, September 12–15, 2005.

Yacout, A. M., R. N. Hill, and Steven J. Piet, 2005, "System Dynamics Studies of Advanced Fuel Cycle Scenarios," Proceedings of GLOBAL 2005, Tsukuba, Japan, October 9–13, 2005.

2004

Collins, E. D., and J. P. Renier, 2004, "Summary of AFCI Systems Studies on Actinide Partitioning and Transmutation in LWRs: Americium-Curium Management Options," SSTS04020, September 2004.

Dixon, Brent W., and Steven J. Piet, 2005, "Impact of Nuclear Energy Futures on Advanced Fuel Cycle Options," Americas Nuclear Energy Symposium, Miami, Florida, October 2004.

Herring, J. Stephen, Philip E. MacDonald, and Kevan D. Weaver, 2004, "Thorium-Based Transmuter Fuels for Light Water Reactors," Nuclear Technology, Vol 147, pp. 84–101, July 2004.

Hill, R. N, et al., 2004, "Systematic Intercomparison of Transmutation Concepts," ANL-AFCI-133, September 30, 2004.

Kim, T. K., 2004, "Evaluation of Spent Nuclear Fuel Characteristics of Advanced CANDU Reactor (ACR-700)," ANL Intra-Laboratory Memo, September 3, 2004.

Piet, Steven J., Brent W. Dixon, J. Stephen Herring, David E. Shropshire (INEEL), and Mary Lou Dunzik-Gougar (ISU-INEEL), 2004, "Answering Key Fuel Cycle Questions," Americas Nuclear Energy Symposium, Miami Beach, Florida, October 2004.

Piet, Steven J., Ralph G. Bennett, Brent W. Dixon, J. Stephen Herring, David E. Shropshire, Mark Roth, James D. Smith, Robert Hill, James Laidler, and Kemal Pasamehmetoglu, 2004, "On-Going Comparison of Advanced Fuel Cycle Options," Americas Nuclear Energy Symposium, Miami Beach, Florida, October 2004.

Salvatores, M., et al., 2004, "The Physics of TRU Transmutation – A Systematic Approach to the Intercomparison of Systems," PHYSOR2004, April 2004.

Stillman, J.A., 2004, "Intrinsic Proliferation Resistance Metrics for Separated Streams of Reactor-Grade Transuranic," October 25, 2004.

Stillman, J. A., T. H. Bauer, R. N. Hill, and Roald A. Wigeland, 2004, "Follow-Up Analyses for the ANTT Review," ANL-AFCI-132, September 2004.

Stillman, J. A., 2004, "Homogeneous Recycling Strategies in LWRs for Plutonium, Neptunium, and Americium Management." Argonne National Laboratory," ANL-AFCI-124, August 2004.

Wigeland, Roald A., and T. H. Bauer., 2004, "Repository Benefits of AFCI Options," ANL-AFCI-129, September 3, 2004.

Yang, W. S., Y. Kim, R. N. Hill, T. A. Taiwo, and H. S. Khalil, 2004, "Long-Lived Fission Product Transmutation Studies," Nuclear Science and Engineering, 146, pages 291–318, 2004.

2003

Hill, R. N., 2003, "Comparison of Fast Reactor Potential," ANL-AFCI-115, September 30, 2003.

Kim, T. K., 2003, “PWR Spent Nuclear Fuel Composition and Decay Heat Values for System Scenario Studies,” July 18, 2003.

Salvatores, M. et al., 2003, “Systematic Assessment of LWR Recycle Strategies,” ANL-AFCI-100, September 2003.

Wigeland, Roald A., T. H. Bauer, T. H. Fanning, and E. E. Morris, 2003, “Repository Impact of LWR MOX and Fast Reactor Recycling Options,” Proceedings of Global 2003, ANS/ENS International Winter Meeting, New Orleans, Louisiana, November 16–20, 2003.

2002

Briggs, L. L., T. A. Taiwo, T. K. Kim, 2002, “Practical Considerations for Extended Burnup in a Tier 1 Thermal Spectrum System,” ANL-AAA-026, August 28, 2002.

Kim, T. K., J. A. Stillman, and T. A. Taiwo, 2002, “Assessment of TRU Stabilization in PWRs,” ANL-AAA-020, August 14, 2002.

Taiwo, T. A., 2002, “Feasibility Study of a Proliferation Resistant Fuel Cycle for LWR-Based Transmutation of Transuranics,” ANL-AAA-027, 2002.

Appendix C
Assumptions Used in Dynamic Analysis

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Assumptions Used in Dynamic Analysis

This appendix documents assumptions used in the Dynamic Systems Analysis Report for Nuclear Fuel Recycle (DSARR) analysis using the VISION Model. It is organized with the most general and basic assumptions first (Section C.1), followed by top-level assumptions (Section C.2). The assumptions on nuclear power growth and reactor parameters, separation, and fuel are given in Sections C.3, C.4, and C.5. Waste management assumptions are detailed in Section C.6.

The analysis assumptions do not define a reference case or attempt to definitively predict the future. Rather, the assumptions define nominal assumptions for purposes of exploring the potential dynamic behaviors of once-through, 1-tier, and 2-tier recycle of used fuel. Parameters were chosen to be consistent with the following hierarchy:

1. DOE and GNEP documents and instructions through January 2008 (DOE 2006, GNEP 2007).
2. GNEP System Analysis Campaign Director (Dr. Kathryn McCarthy) instructions in January reflecting GNEP Campaign Directors' consensus on assumptions, and modified through April 2008 (Campaigns 2008).
3. Waste management data from the evolving Integrated Waste Management Strategy (D Gombert) through March 2008 (Gombert 2007, Gombert 2007a, Gombert 2008).
4. VISION analysts' interpretation and derivation of parameters through April 2008.

C-1. Top-Level Assumptions

The DSARR assesses whether nuclear power with GNEP deployment can meet growing demand, draw down the amount of used nuclear fuel, and reduce the future geologic disposal burden; it also shows how the deployment of fast reactors consumes transuranic elements. However, the direction in the DOE documents is too general to use in a dynamic simulation model, so key analysis assumptions about input and output parameters must be derived starting with the following top-level assumptions.

- Scenarios should be based on expanding nuclear power, so a growth rate is assumed.
  - Nuclear growth should be sustainable, so parameters on uranium utilization and geologic disposal requirements are tracked.
  - Uranium supplies are not assumed to be a constraint during the 21st century (DOE 2006).
- The recycle system should be deployable within 20–25 years (DOE 2006A), with advanced fast reactors deployed "in due course" and recycle technologies deployed "when available," so the Campaign Directors for reactors, separations, and fuels were consulted on reasonable timeframes for deployment of their respective technologies:
  - The initial fast reactor is an "advanced recycle reactor prototype" with a 1 GWth reference capacity, available in 2022 (GNEP 2007). Commercial-scale reactors would begin deployment 10 years later, after transmutation fuels have been developed and qualified (Campaigns 2008).
  - The initial LWR used fuel separations plant would be available in 2020 (GNEP 2007). A range of LWR separations capacities is incrementally deployed within the different scenarios. Fast reactor used fuel separation capacity is deployed as needed (Campaigns 2008).

  - The initial fast reactor would operate on U/Pu fuel for the first 10 years while it is used to test and qualify U-TRU transmutation fuels. After this development period, all fast reactors operate on transmutation fuels (Campaigns 2008).
- TRU is managed throughout the system, so information on TRU quantities at all stages of the fuel cycle is tracked.
  - Proliferation risk is to be reduced and stocks of separated civilian plutonium are to be eliminated. Since the U.S. does not separate pure civilian plutonium (NEP 2001), this is interpreted as stocks of transuranics should be reduced and stocks of separated TRU kept to a minimum.
- Stocks of stored used fuel should be drawn down, so used fuel inventories are tracked and a scenario is included that has sufficient separations capacity to eliminate storage of spent fuel beyond the minimum necessary for initial cooling prior to shipment and separations.
  - The first geologic repository is assumed to open in 2017 and be filled with 63,000 tonnes of used LWR UOX fuel at a rate that grows to 3,000 tonnes iHM/year per planning for the Yucca Mountain repository. This fuel is never retrieved (per DOE).
  - Except where noted, all cases analyzed in this report assume that sufficient LWR UOX separation capacity is eventually deployed so that the backlog of used UOX fuel is eliminated by the end of the century. This assumption is used to provide a common basis for the various analyses. "Backlog" means all fuel that is sufficiently old that it could be transported offsite or put into dry storage.
  - Except where noted, all oxide fuel (UOX or MOX) discharged from LWRs is assumed to require 10 years of wet cooling ("wet" storage) before being transported or put into dry storage (Campaigns 2008). Thus, all used UOX/MOX fuel older than 10 years is modeled as being in dry storage or in a repository.
- Except as noted, all cases analyzed in this report assume that all transuranic material is recovered and recycled, except for processing losses during chemical separation of used fuel and fabrication of new fuel from the recycled product (Campaigns 2008). Thus, the report does not address other strategies where one or more of the transuranic elements (neptunium, plutonium, americium, curium, etc.) are deliberately discarded as waste. As such, the only transuranic material in waste streams is from processing losses.
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C-2. Top-Level Assumptions

Table C.1 shows the overall time line of the DSARR simulations. Note the juxtaposition of several different times of events.

Table C.1. Overall time line and specifications.

1-tier	2-tier	Event
2000		To match historical data from DOE Energy Information Administration (DOE 2007), all calculations used the following specifications for 2000: • Nuclear electrical generation of 86.0 GWe-year, or 754 billion kW-hour. • Total electrical generation of 434 GWe-year, or 3802 billion kW-hour. • The nuclear market share of electricity generated was 19.83%.
2000-2007		Nuclear market share and effective number of reactors adjusted to approximate the actual growth in nuclear electricity generation from uprates and restart of the 104th reactor

1-tier	2-tier	Event
2008-2014		No nuclear growth
2015		New LWRs start coming on line; nuclear power grows at 1.75%/year
2017		Yucca Mountain (Mtn) repository starts accepting used commercial fuel
2020		1st LWR UOX separation unit (800 tonnes-iHM/yr)
2022		1st fast reactor (0.38 GWe capacity) – 10 years with UPu fueling
2028		1st legacy (pre-2000) LWRs decommissioned
2030		2nd LWR UOX separation unit (1600 tonnes-iHM/yr)
N/A	2037	1st MOX separation plant (89 tonnes-iHM/yr, i.e., 1/9th the capacity of the first UOX separation plant)
2032–2036	2047–2051	Fast reactor deployed ≤1 GWe capacity/yr at 0.50 TRU conversion ratio, with collocated fuel fabrication and separation plants
2037–2041	2052–2056	Fast reactor deployed ≤2 GWe capacity/yr at 0.50 TRU conversion ratio, with collocated fuel fabrication and separation plants
2038		Yucca Mtn repository filled to 63,000 tonnes-UOX-iHM
2040–2100		Additional LWR UOX separation units as needed, in modules of 1600 tonnes-iHM/yr tailored to eliminate used UOX fuel backlog by 2100. Deploy ≤3000 tonne-iHM/yr in any given year. Total LWR UOX separation ≤6000 tonne-iHM/yr in 2060.
NA	2047–2100	Additional LWR MOX separation units as needed, in modules of 178 tonnes-iHM/yr (1/9th of corresponding UOX unit), offset 17 years from the corresponding UOX plant. (17 years = 1 year fuel fabrication, shipping and staging, 5 years in reactor, 10 years cooling, 1 year shipping and separations staging.)
2042	2057	Fast reactor deployment limited only by supply of transuranic material; fuel fabrication and separation plants are collocated and co-deployed
2055		Last legacy LWR decommissioned
2100		Ensure “available” backlog of used UOX (and MOX) processed

Table C.2 lists key parameters that define the scenarios analyzed in this report, other than those specifying introduction of used LWR separation capacity and fast reactors. With these parameters, the total recycle time for LWR used fuel is 11 years (10 years in wet storage for cooling, 0.5 years at separation facility, and 0.5 years being made into new fuel). The total recycle time for fast reactor used fuel is 2 years (1 year in wet storage for cooling, 0.5 years at separation facility, and 0.5 years being made into new fuel).

Table C.2. Parameters defining scenarios.

Parameter	GNEP nominal case	Basis
Nuclear power growth rate (%/year)	1.75%	Calculated to match electricity generation levels in 2060 specified by DOE
Year nuclear growth starts (i.e., first new LWR come on line)	2015	No nuclear growth from 2007 to 2015, per DOE

Parameter	GNEP nominal case	Basis
LWR burnup (MWth-day/kg-iHM)	51	Consistent with fuel currently in reactors based on burnup trends, and analysis of data at [DOE 2004]
Time at separation facility (years)	0.5	Engineering estimate, including processing and lead-lag storage
Time at fuel fabrication facility (years)	0.5	Engineering estimate, including processing and lead-lag storage
Minimum cooling time for LWR used UOX fuel before transport or offsite separation (years)	10.0	Based on cooling needed prior to efficient transportation, then rounded up to allow for higher burnup fuels or MOX fuels without changing the value
Minimum cooling time for LWR used MOX fuel before transport or offsite separation (years)	10.0	To be consistent with MOX
Fast reactor conversion ratio	0.50	Per Dr. Robert Hill, Director of the GNEP Fast Reactor Campaign
Fast reactor fuel type	Metal	Selected to minimize fuel cycle delays otherwise masking other behavior. Oxide is assessed via sensitivity analyses.
Fast reactor fuel burnup (MWth-day/kg-iHM)	132	Hoffman 2007 value for metal fuel at 0.50 conversion ratio
Minimum cooling time for fast reactor used fuel before separation (years)	1.0	Based on Experimental Breeder Reactor-II experience
Reactor licensing time (years)	2	Provides appropriate delay between reactor order and operation
Reactor construction time (years)	4	
Used LWR fuel permanently emplaced in Yucca Mtn repository (tonnes-iHM)	63,000	Per DOE
Assumed lifetime of existing 104 LWRs (years)	60	Original license time was 40 years. As of February 2008, about half have either received or are under review for license extension to 60 years.[NRC 2008a] Most if not all of the rest are expected to apply for license extension.[NRC 2008]
Retirement of existing 104 LWRs First four LWR offline Last legacy reactor offline	 2029 2055	Based on above assumption that all current reactors' licenses include one 20 year extension. This extension was applied to the data for each reactor [NRC 2008] to derive a histogram of reactor retirements

C-3. Nuclear Power Growth and Reactor Parameters

The growth of nuclear power and reactor deployment are inherently linked. The hierarchy of calculations is as follows: initial conditions, total electricity growth rate of 1.2%/yr (starting in 2015), assumed nuclear market share and hence growth in nuclear electricity, retirement of pre-2000 LWRs (Subsection C.3.1), and reactor deployment (Subsection C.3.2). Subsection C.3.3 describes alternative nuclear growth scenarios and Subsection C.3.4 describes reactor design parameters.

C-3.1 Retirement of Reactors

For reactors operating in 2000, the original operating lifetimes ranged from 37 to 40 years (DOE 2007b). The input for DSARR is based on the assumption that all will be extended an additional 20 years, so that the operating licenses range from 57 to 60 years. Reactors deployed during the simulation are automatically retired after their specified lifetimes.

C-3.2 Reactor Deployment

For DSARR, VISION was run with the following deployment rules:

1. During the specific time periods denoted in Table C.1, constrain fast reactor deployment to values provided by the Campaign Directors (1 and 2 GWe capacity built per year).
2. During all of the simulation, constrain fast reactor deployment on the basis of TRU fuel supply (Campaigns 2008).
3. If fast reactor deployment is not adequate, deploy MOX-capable LWRs.

VISION tracks the number of LWRs that are MOX capable versus not MOX capable and will not allow more MOX fuel to be used than required by the number of MOX-capable LWRs. Simulations were started with 16% of the LWR fleet being MOX-capable. M. Todosow estimated that 100% of new LWRs could be fully MOX-capable, so that is assumed in DSARR calculations. However, simulations show that the MOX fraction never exceeds 20% of the LWR fuel and rarely exceeds 10%. So, these assumptions on MOX capability are not particularly important and do not constrain the simulations.

C-3.3 Alternative Growth Scenarios

Since growth is a key parameter with considerable uncertainty, sensitivity analyses were performed using a range of alternate growth scenarios. Alternative growth scenarios were defined based on DOE requests to assess 100, 150, 200, 300, and 400 GWe-year in 2060. In all cases, growth is assumed to start (resume) in 2015 consistent with the nominal case described above. The nominal nuclear growth rate was defined to be a constant 1.75%/year; this curve passes through ~200 GWe-year in 2060. To make comparisons among cases clearer, the other cases were also analyzed with a constant growth rate, the value determined by matching 100, 150, 300, 400 GWe-year in 2060.

The growth rate of total electricity is specified to be 1.2%/year per DOE,[a] but this is not directly relevant as VISION uses both total electricity growth and nuclear market share to calculate nuclear generation. So, the specifications of 1.75% nuclear growth and 1.2% total electricity growth were used to derive the required market share input parameters. If a different total electricity growth were specified, the market share values could change but the actual nuclear electricity would not.

Table C.3 lists key parameters for five nuclear growth cases, derived from the above specifications.

The domestic market share values in Table C.3 that stem from the above specifications can be compared with the independent assessment of market share calculated in Section 2. The Section 2 Reference Scenario leads to nuclear market shares of 20% global and 25% domestic (Kim 2008), which is similar to the nominal DSARR value of 28% arising from 1.75%/year growth.

Table C.3. Constraints on fast reactor deployment.

Nuclear growth rate starting in 2015	Electricity market share in 2100 (%)	Nuclear generation in 2060 (GWe-year)	Nuclear generation in 2100 (GWe-year)
0.23%	7.7	100	110
1.12%	16.5	150	234
1.75%	28.1	200	400
2.66%	60.4	300	856
3.30%	103.3	400	1,466

The 550-ppm scenario from Section 2 leads to nuclear market shares of 33% global and 41% domestic, which is between the 1.75% and 2.66% cases here. Without CO_2 sequestration technologies, the 550-ppm scenario in Section 2 instead leads to 50% global and 58% domestically, which is quite close to the 2.66%/year in Table C.3.

Recall that none of the scenarios in Section 2 reflect the potential for nuclear power to substantially enter the transportation sector. The higher growth cases in Table C.3 reflect the possibility that nuclear contributes to the transportation sector either directly via substantial electrification of transportation, which is currently petroleum-dominated, or indirectly via production of hydrogen or other fuels for use in transportation.

C-3.4 Reactor Design Parameters

Table C.4 lists several reactor-related parameters used in the DSARR analyses. The two most important parameters are the fast reactor TRU conversion ratio and the time lags between reactor discharge and when used fuel can be separated. Therefore, these parameters were varied in sensitivity analyses.

a. DSARR analyses base the amount of total electricity from the initial value (433.7 GWe-year), growing at a user-defined growth rate. The user-defined growth rate can be varied by year; however, to reduce complexity and better understand trends, the DSARR calculations were performed at a constant 1.2%/year growth in total electricity. The assumed value of 1.2%/year matches the average annual growth estimated by the Energy Information Administration (EIA) for 2007 to 2030.[DOE2007a]

C-4. Separation Parameters

There are two major types of parameters for separation facilities: deployment of separation capacity and specification of separation efficiencies. In addition, three generic assumptions are made:

- Once deployed, separation capacity is never retired; thus, if a separation plant reaches the end of its economic lifetime, it is assumed to be replaced by a plant with equivalent separation capacity.
- Separation plants operate year around at their rated separation capacity.
- Separation plants are only used for the type of fuel for which they have been built because the fuels have significantly different compositions requiring different equipment sizing, shielding, criticality controls, etc. for safe and efficient plant performance.

Table C.4. Reactor-related parameters.

Parameter	Nominal Value for LWRs	Nominal Value for Fast Reactors	Source or Rationale
TRU conversion ratio	NA	0.50	Per Dr. Robert Hill(a)
Reactor capacity (GWe/reactor)	0.928	0.38	Average for legacy LWRs in 2000, size of 1st FR (b,c)
Thermal efficiency (GWe/GWth)	34%	38%	LWR industry averages per Dr. Robert Hill
Capacity factor	90%	82%	LWR industry averages [DOE 2007] and information derived from [Hoffman 2007a]
Licensing time (years)	2	2	Assumed based on standard designs and Nth of a Kind (NOAK)
Construction time (years)	4	4	
Reactor lifetime (operating and economic) years	60	60	LWR license trends and Dr. Robert Hill

a. R. Hill is the Campaign Director for GNEP Fast Reactor Technology.

b. The capacity per LWR does not impact calculation of total capacity (GWe) nor total generation (GWe-year); however, the average capacity (0.928 GWe/reactor) x average capacity factor (90% FPY/CY) x the initial number of reactors (103) must match the actual total nuclear generation (86 GWe-year) in 2000.

c. The capacity per fast reactor does not impact calculation of total capacity nor total generation from fast reactors. VISION uses a fixed average capacity per fast reactor. 0.020 GWe is the lowest common denominator of the specifications of 0.38 GWe (first fast reactor), 1.0 GWe (first learning period), and 2.0 GWe (second learning period).

C-4.1 Separation Capacities

Table C.5 shows the assumptions on when separation capacity is deployed. The first UOX separation unit is 800 tonnes-iHM/year and all others are 1600 iHM/year. Both sizes are based on discussions with Dr. Terry Todd, GNEP Separations Campaign Director. The first plant size is consistent with unit sizes built internationally, while the additional plants are based on limited additional economies of scale as the size increases and minimizing transportation by having multiple regional plants rather than a single central plant. The first UOX separation plant is always assumed operational in 2020 (GNEP 2007); the second, in 2030 (to allow for learning from startup of the first plant before beginning construction of the

second). Thereafter, UOX separation plants are tailored to ensure that used fuel backlog is eliminated by 2100. For the nominal 1-tier case, the 3rd UOX separation unit is in 2050 and the last one is 2089. For the nominal 2-tier case, the 3rd UOX separation plant is also 2050, a fourth is in 2080 and fifth in 2095. MOX units have 1/9th the capacity (in units of iHM/year) and are delayed 17 years relative to corresponding UOX plants. Fast reactor separation units are assumed co-located with fast reactors and deployed in concert with them.

Table C.5. Separation capacity deployment assumptions.

<table>
<tr><th colspan="2">1-tier</th><th>2-tier</th><th>UOX Separation</th><th>MOX Separation</th><th>Fast Reactor Fuel Separation</th></tr>
<tr><td colspan="2">2020</td><td></td><td>1st LWR UOX separation unit (800 tonnes-iHM/yr)</td><td></td><td></td></tr>
<tr><td colspan="2">2022</td><td></td><td></td><td></td><td>Co-located and matched in size with 1st fast reactor (0.38 GWe capacity)</td></tr>
<tr><td colspan="2">2030</td><td></td><td>2nd LWR UOX separation unit (1,600 tonnes-iHM/yr)</td><td></td><td></td></tr>
<tr><td>N/A</td><td></td><td>2037</td><td></td><td>First MOX separation plant (89 tonnes-iHM/yr (i.e., 1/9th the capacity of the first UOX separation plant)</td><td></td></tr>
<tr><td>2032–2036</td><td></td><td>2047–2051</td><td rowspan="3">Additional capacity as needed, in increments of 1,600 tonnes-iHM/yr.(a,b)</td><td rowspan="3">Additional units as needed, in modules of 178 tonnes-iHM/yr, delayed 17 years from the corresponding UOX plant.</td><td>Co-located and matched in size with fast reactors deployed at ≤1 GWe/yr</td></tr>
<tr><td>2037–2041</td><td></td><td>2052
2056</td><td>Co-located and matched in size with fast reactors deployed at ≤2 GWe/yr</td></tr>
<tr><td colspan="2">Thereafter</td><td></td><td>Co-located with and matched in size as fast reactors are deployed.</td></tr>
<tr><td colspan="2">2100</td><td></td><td>Ensure “available” backlog processed</td><td></td><td></td></tr>
</table>

a. Additionally, DOE imposed a constraint that no more than 3000 tonnes-iHM-UOX capacity is deployed in a single year and no more than 6000 tonnes-iHM-UOX/yr total deployed before 2060. Neither constraint proved to be limiting for the nominal cases.

b. The analysts additionally assumed that units would not be deployed sooner than a decade after the previous unit.

C-4.2 Separation Facility Ramp-Up

Table C.6 shows the specification of how the large UOX or MOX separation units come on line: 6-year ramp for the first unit of each type; 4-year ramp for subsequent units. The specification came from the previous Campaign Director for Separations.

Table C.6. LWR separation capacity ramp-up profiles.

	First UOX or MOX separation unit	Subsequent UOX or MOX separation units
Year 1	5%	10%
Year 2	10%	30%
Year 3	20%	60%
Year 4	40%	100%
Year 5	60%	
Year 6	100%	

C-4.3 Separation Efficiencies

Tables C.7, C.8, and C.9 provide the separation efficiencies for the cases in this study. Note that these tables also specify which elements in used fuel are assumed to go into each separation stream and at what output mass flows for the respective separation facilities. The amount of RU and TRU going to waste is nominally 0.1%. (Exception: for electrochemical, the amount of RU going to waste is 3.3%.) Otherwise, the parameters are set to be consistent with the evolving integrated waste management strategy (Gombert 2007, Gombert 2007a, Gombert 2008, Gombert 2008a).

Table C.7. Separation efficiency for 1-tier separation of UOX & 2-tier separation of MOX (UREX+1a).

	RU Pu recycle stream	TRU recycle stream	RU stream	I stream	Gas stream	Tc stream	Cs Sr stream	LnFP stream	Discard stream	UDS stream	Zr SS stream
Ra to Pa	Not used							100	Not Used	Not used, 25% of the Tc goes with this stream, but is included with the Tc waste for ultimate disposal anyways	Not used such mass accounted for via co-flows
U			99.9					0.1			
Np		99.9						0.1			
Pu		99.9						0.1			
Am		99.9						0.1			
Cm-Cf		99.9						0.1			
H-3					99.9			0.1			
C-14								100			
Kr					99.9			0.1			
Sr, Cs							99.9	0.1			
Tc						99.9		0.1			
I				99.9				0.1			
FP other								100			

RU = recovered uranium, FP = fission product, Ln = lanthanides, UDS = undissolved solids.
VISION release 2.2 does not separately track Lanthanide isotopes; the mass of lanthanides is included with FP other.

Table C.8. Separation efficiency for 2-tier separation of UOX.

	RU Pu recycle stream	Np Am Cm recycle stream	RU stream	I stream	Gas stream	Tc stream	Cs Sr stream	LnFP stream	Discard stream	UDS stream	Zr SS stream
Ra to Pa								100	Not used	Not used, 25% of the Tc goes with this stream, but is included with the Tc waste for ultimate disposal anyways	Not used Such mass accounted for via co-flows
U	1.3		98.6					0.1			
Np		99.9						0.1			
Pu	99.9							0.1			
Am		99.9						0.1			
Cm-Cf		99.9						0.1			
H-3					99.9			0.1			
C-14								100			
Kr					99.9			0.1			
Sr, Cs							99.9	0.1			
Tc						99.9		0.1			
I				99.9				0.1			
FP other								100			

RU = recovered uranium, FP = fission product, Ln = lanthanides, UDS = undissolved solids.
The 1.3% U mixed with Pu produces a 50:50 UPu product
VISION release 2.2 does not separately track Lanthanide isotopes; the mass of lanthanides is included with FP other.

Table C.9. Separation efficiency of electrochemical processing used for 1-tier/2-tier separation of FR metal fuel.

	RU TRU recycle stream	TRU recycle stream	RU stream	I stream	Gas stream	Tc stream	Cs Sr stream	LnFP stream	Discard stream	UDS stream	Zr SS stream
Ra to Pa		Not used		No iodine stream included with CsSr stream		No Tc stream included with metal waste stream			Not used Process salt accounted for as the waste form material for the FP stream	Not used such mass included in FP stream	100
U	3.4		93.3								3.3
Np	99.9										0.1
Pu	99.9										0.1
Am	99.9										0.1
Cm-Cf	99.9										0.1
H-3					99.9						0.1
C-14											100
Kr					99.9						0.1
Sr, Cs							99.9				0.1
Tc											100
I							99.9				0.1
FP other								50			50

RU = recovered uranium, FP = fission product, Ln = lanthanides, UDS = undissolved solids.
VISION release 2.2 does not separately track lanthanide isotopes, they are about half the mass of "FP other." So, about half of the "FP other" is lanthanide and assigned to the LnFP stream and the other half of "FP other" mass is assigned to the generic metal waste stream.
The EAS mass balance sends 3.4% U to the TRU product, 3.3% U to the ZrSS waste metals, and the remainder as RU.

C-4.3.1 TRU Bank

The TRU bank is a reserve to ensure an uninterrupted source of TRU for the fast reactors in case the separations plant is shut down for an extended period. The TRU bank, prompted by the Thermal Oxide Reprocessing Plant (THORP) in the UK, recently experiencing an almost 2-year shutdown due to a broken pipe. The TRU bank specification is the amount of TRU needed for one extra core per reactor to a maximum of 2 years of the largest (separation) facility, defined as 3 × 800 tonne/yr separations or about 62 tonnes-TRU.

C-5. FUEL PARAMETERS

In this report, fuel fabrication is never constrained; effectively, the model is allowed to fabricate as much fuel as reactors need if TRU or U-Pu source material exists. The model could alternatively be used with fuel fabrication capacity constrained.

Table C.10 summarizes the input and output elemental fuel compositions for the 1-tier scenario. (The actual compositions used include 60 separate isotopes). Table C.11 summarize the same information for 2-tier analyses. For the 2-tier analyses, only one fast reactor conversion ration was used (CR = 0.5).

Table C.10. Elemental composition of 1-tier reactor fuel.

Input	UOX	Fast reactor at CR=0.0	Fast reactor at CR=0.25	Fast reactor at CR=0.50	Fast reactor at CR=0.75	Fast reactor at CR=1.00
Uranium	100%	22.6%	54.5%	70.6%	79.5%	84.8%
Neptunium		3.7%	2.1%	1.4%	1.0%	0.7%
Plutonium		69.5%	40.9%	26.4%	18.4%	13.7%
Americium		3.8%	2.2%	1.4%	1.0%	0.7%
Curium		0.4%	0.3%	0.2%	0.1%	0.1%
Output	UOX	Fast reactor at CR=0.0	Fast reactor at CR=0.25	Fast reactor at CR=0.50	Fast reactor at CR=0.75	Fast reactor at CR=1.00
Uranium	93.4%	19.3%	47.6%	62.3%	70.7%	77.0%
Neptunium	0.1%	1.6%	1.0%	0.7%	0.5%	0.4%
Plutonium	1.2%	43.3%	28.5%	21.2%	16.8%	13.8%
Americium	0.1%	3.2%	1.9%	1.3%	0.9%	0.7%
Curium	0.0%	1.0%	0.5%	0.3%	0.2%	0.2%
Fission products	5.3%	31.5%	20.5%	14.1%	10.8%	7.8%

Fast reactor data from Hoffman2007, values shown are for the first recycle pass of metal fuel in the fast reactor; the composition evolves thereafter each recycle pass.

UOX values are from Kim2003, at 51 MW-day/kg-heavy metal burnup.

CR means transuranic conversion ratio.

Throughout the report, “curium” includes small amounts of elements further up the Periodic Table.

Table C.11 Elemental composition of 2-tier reactor fuel.

Input	UOX	MOX	Fast reactor at CR=0.50
Uranium	100%	90.2%	62.1%
Neptunium			1.1%
Plutonium		9.8%	30.8%
Americium			4.1%
Curium			1.8%
Output	**UOX**	**MOX**	**Fast reactor at CR=0.50**
Uranium	93.4%	88.2%	54.9%
Neptunium	0.1%	0.0%	0.6%
Plutonium	1.2%	6.2%	25.6%
Americium	0.1%	0.3%	3.0%
Curium	0.0%	0.1%	1.9%
Fission products	5.3%	5.2%	14.0%

C-6. Waste Management Parameters

VISION has waste management specifications in the following tables:

- Separation efficiencies: How much of each isotope goes to what separation streams, thereby defining what the major separation streams are (non-waste, Tc, I, etc.).
- Co-flows: Because VISION does not include the mass of cladding or metal fuel alloy material in the main flows, it approximates the mass of such material as a multiplier on the mass of fuel isotopes, that is, on the mass of initial heavy metal.
- Waste disposition: The waste classification of each separation stream - low-level waste that qualifies as Class A, B, or C (LLW-A/B/C), low-level waste that does not qualify as Class C (Greater than Class C or GTCC) transuranic waste (TRU), high-level waste (HLW), decay storage, non-waste. Note that mass sent to "decay storage" does not proceed further during the simulation because decay storage is typically over 100 years in duration but the simulations range from 2000 to 2100.
- Waste form mass fraction (and type): Mass of contaminant/mass of waste form—specify low/medium/high values.
- Waste form density (and type): Mmass of waste form/volume of waste form—specify low/medium/high values.

Key specifications include the following:

- Other than iodine, the only significant gas waste in these calculations is Kr; so the specifications below for "gas stream" are from (Gombert 2007, Gombert 2007a, Gombert 2008) for Kr.
- VISION numbers do not include the C-14 generated from air entrapped in fuel rods in LWRs. Therefore, generally, there is no C-14 in the recipes. Thus, C-14 is set to go to the FP "everything else" waste form.
- VISION numbers do not include H-3 produced in water; only the slight amount generated from fission.
- The characteristics of UOX/MOX aqueous separation are patterned as follows:
  - -1-tier/UOX and 2-tier/MOX is separated into U+TRU+CsSr+I+Tc+everything else (UREX+1a).

- -2-tier/UOX is separated into U+UPu+NpAmCm+CsSr+I+Tc+everything else.

- The nominal case does not include any phased deployment, where the elements separated for reuse and associated separations technology change during the simulation.
- The separation of FR fuel is electrochemical, producing separate waste streams of CsSr (with iodine), gas, metal wastes (with Tc), and everything else (such as lanthanides). All waste streams are either TRU waste or HLW.
- VISION release 2.2 does not track the lanthanide isotopes, the isotopes associated with cladding (Zr, steel), nor the mass associated with process chemicals. The first two are planned for future versions of the model. The mass associated with Zr and steel is approximated with "co-flows" so that the mass is accounted for.
- With the current specifications, nothing is identified as LLW-class A/B/C per se; in the future, calculations would account for material coming out of waste decay storage or co-flow materials.

C-6.1 Co-Flows

VISION includes "co-flows" to approximate the flow of non-fuel materials by linking them with the flow of fuel, Table C.11. A co-flow of 0.25 means that for every kg of fuel, there is 0.25 kg of that material.

Table C.11. Mass of component in co-flow per mass of fuel isotopes.

Co-Flow	UOX	MOX	FR metal fuel
Separation tech for 1-tier	U+TRU+ CsSr+I+Tc+other	N/A	Electrochemical
Separation tech for 2-tier	U+UPu+NpAmCm+ CsSr+I+Tc+other	U+TRU+ CsSr+I+Tc+other	Electrochemical
Zr	0.25 (cladding)	0.25 (cladding)	0.11 (alloy with fuel)
Steel	0.05 (assemblies and core internals)	0.05 (assemblies and core internals)	0.53 (cladding, assemblies and core internals)

C-6.2 Waste Disposition

Table C.12 indicates the disposition for each mass flow leaving separations.

	RU Pu or RU TRU recycle stream	NpAmCm or TRU recycle stream	RU stream	Iodine stream	Gas stream	Tc stream	Cs Sr stream	LnFP stream	Zr SS stream
UOX/MOX separation	Not waste	Not waste	Not waste	GTCC	Decay storage	HLW	Decay storage	HLW	GTCC
FR echem separation (a)		Not used		Not waste(b)		Not used (c)			HLW

a. At present, it is expected that all electrochemical waste streams will be over 100 nCi-TRU/g, hence TRU or HLW.

b. Included with CsSr stream.

c. Included with the ZrSS stream.

C-6.3 Waste Form Mass Fraction and Density

Tables C.13 and C.14 tell VISION what type of waste form is used for each separation stream, as well as the low/medium/high[b] mass fraction (mass-contaminant/mass-waste form) for that waste form. The UOX and MOX values come from Gombert 2007a, Table 20. The FR values come from Gombert 2007, Table 5.

Table C.12. Waste form mass fraction (%).

	I stream	Gas stream	Tc stream	Cs Sr stream	LnFP stream	Zr SS stream
UOX/MOX aqueous separation	Ag zeolite 2.0% 4.45% 6.9%	Absorber 9% 54.5% 100%	Metal alloy 40% 40% 85%	Ceramic 20% 35% 50%	Glass 20% 25% 30%	Metal alloy 93% 96.5% 100%
FR echem separation	Not used	Absorber 3.4% 3.85% 4.3%	Not used	Glass bonded zeolite sodalite - 33% -	Glass - 50% -	Metal alloy - 100% -

Table C.13. Waste form density (tonne/m3).

	I stream	Gas stream	Tc stream	Cs Sr stream	LnFP stream	Zr SS stream
UOX/MOX aqueous separation	Ag zeolite 2.1 2.3 2.5	Absorber 0.004 0.094 0.185	Metal alloy 7.6 7.9 8.2	Ceramic 1.5 2.75 4.0	Glass 2.5 2.85 3.2	Metal alloy 4.6 5.6 6.6
FR Echem separation	Not used	Absorber - 2.5 -	Not used	Glass Bonded Zeolite Sodalite - 2.4 -	Glass - 4.0 -	Metal alloy - 7.75 -

UOX/MOX - where low/high values are given, the middle value is set to the average.
FR - these values are constants per Gombert et al; no low/high values are assigned.

b. The designation of low/medium/high is arbitrary. The VISION developers conceived of this approach to give flexibility. The low and high values come directly from Gombert 2007 and Gombert 2007a. VISION required a medium or nominal value; those came from averaging the low and high value unless D. Gombert specified a particular value, e.g., for the Tc metal allow, the nominal loading is 40% the same as the low value. The high value of 85% is only possible if these metals are put into a separate metal waste form.

C-7. REFERENCES

Campaigns 2008 GNEP Campaign Directors, "Systems Analysis Assumptions," updated through April 2008.

Dixon 2004 Dixon, Brent W., and Steven J. Piet, 2004, "Impact of Nuclear Energy Futures on Advanced Fuel Cycle Options," Americas Nuclear Energy Symposium, Miami, Fl, October 2004.

DOE 2004 Detailed U.S. Spent Nuclear Fuel Data-Table 3, http://www.eia.doe.gov/cneaf/nuclear/spent_fuel/ussnftab3.html, October 2004.

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

DOE 2006A U.S. Department of Energy, Office of Nuclear Energy, 2006, "Report to Congress – Spent Nuclear Fuel Recycling Program Plan," May 2006.

DOE 2007 DOE Energy Information Administration, Annual Energy Review 2006, Report No. DOE/EIA-0384(2006), June, 2007 - Table 8.1 Electricity Overview, 1949–2006 and Table 8.2a Electricity Net Generation: Total (All Sectors), 1949–2006.

DOE 2007a DOE Energy Information Administration, Total electricity generation from EIA, Annual Energy Outlook, Report No. DOE/EIA-0383(2008), December 2007 - Table 8. Electricity Supply, Disposition, Prices, and Emissions (row 43).

DOE 2007b DOE Energy Information Administration, U.S. Nuclear Reactors, data through June 2007, http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/reactsum.html

DOE 2007c Global Nuclear Energy Partnership Statement of Principles, signed by U.S. Secretary of Energy Samuel W. Bodman on September 16, 2007. Currently, 21 countries have signed this document.

GNEP 2007 Global Nuclear Energy Partnership Technical Integration Office Global Nuclear Energy Partnership Technology Development Plan, GNEP-TECH-TR-PP-2007-00020, Rev 0, July 25, 2007.

Gombert 2007 Gombert, Dirk, et al., 2007, "2007 Draft Global Nuclear Energy Partnership — Materials Disposition and Waste Form Status Report," GNEP-WAST-AI-TR-2007-00013, February 2007, Table 5.

Gombert 2007a Gombert, Dirk, et al., 2007, "GNEP Integrated Waste Management Strategy Waste Treatment Baseline Study," GNEP-WAST-AI-RT-2007-000324, September 2007, Table 20.

Gombert 2008 Gombert, Dirk, et al., 2008, "Global Nuclear Energy Partnership Integrated Waste Management Strategy," GNEP-WAST-AI-RT-2008-000214, March 2008.

Gombert 2008a Personal communication.

Hoffman 2006 Hoffman, E. A., W. S. Yang, and R. N. Hill, 2006, "Preliminary Core Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios," ANL-AFCI-177, September 29, 2006.

Hoffman 2007 Hoffman, E. A., 2007, "Updated Design Studies for the Advanced Burner Reactor over a Wide Range of Conversion Ratios," ANL-AFCI-189, May 31, 2007.

Jacobson 2008 Jacobson, Jacob J., Gretchen E. Matthern, Steven J. Piet, and J. Grimm, 2008, "VISION User Guide," INL/MIS-07-13102, Rev 2.2, February 16, 2008.

Kim 2003 Kim, T.K., 2003, "PWR Spent Nuclear Fuel Composition and Decay Heat Values for System Scenario Studies," July 18, 2003. These data are more widely available in Piet2006.

NEP 2001 National Energy Policy – Report of the National Energy Policy Development Group, May 2001. Pages 5–17 and 5–22 that "the United States will continue to discourage the accumulation of separated plutonium, worldwide."

NRC 2008 Nuclear Regulatory Commission web site, "NRC: Power Uprates" status tables, accessed June 26, 2008 –

http://www.nrc.gov/reactors/operating/licensing/power-uprates/approved-applications.html

http://www.nrc.gov/reactors/operating/licensing/power-uprates/approved-applications.html

http://www.nrc.gov/reactors/operating/licensing/power-uprates/expected-applications.html

NRC 2008a Nuclear Regulatory Commission, 2008-2009 Information Digest, NUREG-1350, Volume 20, August 2008.

Piet 2006 Piet, Steven J., et al., 2006, "Fuel Cycle Scenario Definition, Evaluation, and Trade-offs," INL/EXT-06-11683, August 2006.