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Program on Technology Innovation: Advanced Fuel Cycles--Impact on High-Level Waste Disposal

2007 Progress Report

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Program on Technology Innovation: Advanced Fuel Cycles–Impact on Nuclear Waste Management

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Technical Update, December 2007

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PRODUCT DESCRIPTION

The aim of advanced fuel cycles is to improve the sustainability of nuclear energy by enhancing the effectiveness of natural uranium resource utilization and by mitigating waste disposal issues, while keeping the costs of energy products, in particular electricity, economically viable. In addition, this aim has to be achieved under conditions that minimize the risks of diversion of separated fissile materials and their possible misuse for non-peaceful ends. The report presents results from recently published reports on the attributes of several nuclear fuel cycles, with specific emphasis on their inherent spent nuclear fuel and high-level waste management efficiency.

Background

Current civil uses of nuclear power in the United States are based on a once-through fuel cycle involving the irradiation of low-enriched uranium fuel in light-water reactors and the subsequent storage and eventual disposal of the spent fuel. However, continued use of nuclear power may be predicated on improved economics and sustainability, especially when it is assumed that applications of nuclear technology may expand beyond production of electricity, such as production of hydrogen for industrial and transportation applications. These developments may require adoption of a different fuel cycle.

Past and more recent findings published by EPRI, the U.S. Electric Utility Industry's Advanced Reactor Corporation, the National Academy of Sciences, and the Massachusetts Institute of Technology have been in general agreement with regard to support for the present US policy relying on the once-through fuel cycle because of the latter's simplicity, economic advantages, and non-proliferation benefits. However, there is also broad agreement that R&D should be conducted on selected topics to support the safe and cost-effective future application of commercial spent fuel reprocessing and recycling.

Objective

- To review the recent literature on advanced fuel cycles to support the development of an analytical capability to assess various nuclear fuel cycle scenarios with emphasis on their impacts on spent-fuel management efficiency, natural uranium resource utilization, and implementation and operational challenges.

Approach

The research team reviewed several recently published reports mandated by the French Act of Parliament dated 30th December 1991 as well as reports prepared under the auspices of the Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency's (NEA) Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle. The results of this review were augmented by introductory materials of specific relevance to the U.S. situation.

Adopting a slightly modified version of NEA's approach, nuclear fuel cycles can be divided into three main families. The first family includes the current once-through fuel cycle and schemes with only one fuel recycling (mono-recycling of plutonium or plutonium + neptunium) in light-water reactors. These fuel cycles represent current industrial technology and readily

implementable extensions. The second family, consisting of schemes with partially closed fuel cycles, includes multi-recycling of plutonium, possibly in different types of reactors (light-water reactors, fast reactors, and possibly others), but with different schemes in the treatment of minor actinides. The third family, consisting of fully closed fuel cycles, includes schemes in which all transuranics (plutonium, neptunium, americium, and curium) are recycled until they eventually fission. This can be achieved in different types of reactors.

Natural uranium utilization and waste management efficiency (annual mass flow rate and decay heat of fission products and transuranics destined to final disposal, assuming a 0.1% loss in separation processes) were compiled for several representative fuel cycles having reached equilibrium conditions. The results from a limited number of non-equilibrium, or dynamic, analyses were also reviewed.

Results

Overall findings from equilibrium system analyses show that it is possible to envision a strategic progression towards maximal use of uranium resources and maximal reduction of the waste source term; for example, by moving from the once-through fuel cycle to multiple recycling of plutonium in fast reactors to multiple recycling of all transuranics in fast reactors. However, the equilibrium system approach does not take into account the deployment and shutdown phases, respectively preceding and following the equilibrium phase. The deployment phase typically takes several decades during which build-up of transuranics inventories occur until fuel and waste composition reach equilibrium. Multi-recycling leads to high in-pile and out-of-pile transuranics inventories. As a result, when reactors are eventually phased out, transuranics inventories become an important contributor to the waste legacy, unless they are burned in dedicated burners, such a fast burner reactors, over many decades.

EPRI Perspective

Balancing the needs for sustainability (shift to a plutonium economy and reduction in high-level waste burden on permanent geologic repositories), operational efficiencies, and diversion resistance of plutonium-based fuel cycles may eventually require strategies relying on interim storage of spent fuel as well as partitioning and transmutation of plutonium and minor actinides, before final disposal of the high-level wastes in a permanent geologic repository. Although equilibrium system analysis gives indications on the end-states of any transition between today's and any future nuclear energy systems, closing the fuel cycle introduce complex dynamic feedback effects with regard to mass flows, inventories, and isotopic fuel and high-level waste compositions. Integrated process models simulating nuclear energy systems from uranium mining to final disposal of the wastes are needed to properly conduct comprehensive assessments of nuclear energy system strategies and to select the most promising development paths.

Keywords

Nuclear fuel cycles
Reprocessing
Recycling
Minor actinides
Partitioning
Transmutation
Waste management

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This report is dedicated to the memory of Ed Rodwell.

CONTENTS

1
INTRODUCTION

Potential benefits and drawbacks of reprocessing/recycling of spent light-water reactor (LWR) fuel are presently being debated in the U.S. as a result of several international and domestic developments including (a) international efforts to reduce global proliferation risks through several international initiatives, such as the U.S. Global Nuclear Energy Partnership (GNEP) [*Global Nuclear Energy Partnership Strategic Plan*, GNEP-167312, Rev. 0, U.S Department of Energy, January 2007] and the International Atomic Energy Agency's (IAEA) Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) [*Methodology for the Assessment of Innovative Nuclear Reactors and Fuel Cycles; INPRO Report*, IAEA TECDOC-1434, IAEA, Vienna (2003)]; (b) continuing delays with the licensing of the proposed Yucca Mountain geologic repository; and (c) DOE's mandate for making a recommendation for a second U.S. repository by 2010.

Present US Fuel Cycle Policy [Adapted from IAEA, INFCIRC/549/Add.6/5, 11 September 2002]

Current civil uses of nuclear power in the United States are based on a once-through fuel cycle involving the irradiation of low-enriched uranium fuel in light-water reactors and the subsequent storage and eventual disposal of the spent fuel without reprocessing. This "open" fuel cycle, as it is often referred to, is safe, environmentally responsible, and, when combined with effective domestic and international safeguards, proliferation-resistant.

However, continued use of nuclear power may be predicated on improved economics and sustainability, which in turn may require consideration of different fuel cycles.

The May 2001 National Energy Policy Report (NEPR), developed by the National Energy Policy Development (NEPD) Group recommended that "in the context of developing advanced nuclear fuel cycles and next-generation technologies for nuclear energy, the United States should re-examine its policies to allow research, development and deployment of fuel conditioning methods that reduce waste streams and enhance proliferation resistance. In doing so, the United States will continue to discourage the accumulation of separated plutonium worldwide." The NEPR also recommended that the United States consider, in cooperation with international partners with highly developed fuel cycles and a record of close cooperation, developing reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation resistant.

Advanced fuel cycle research offers the prospect of producing additional power from the fissile material in spent fuel while significantly enhancing the capacity for waste storage in a repository and avoiding the accumulation of separated plutonium.

Results from Previous Work

Past and more recent findings published by EPRI [*An Updated Perspective on the U.S. Nuclear Fuel Cycle*, EPRI, Palo Alto, CA: 2006. 1013442], the U.S. Electric Utility Industry's Advanced Reactor Corporation [*The US Advanced Reactor Development Program – A Report by The U.S. Electric Utility Industry's Advanced Reactor Corporation,"* Aug. 1995], the National Academy of Sciences [*Nuclear Wastes: Technologies for Separations and Transmutation*, National Academy Press, 1996], and the Massachusetts Institute of Technology [*The Future of Nuclear Power*, Massachusetts Institute of Technology, 2003] have been in general agreement with regard to support for the present U.S. policy relying on the once-through fuel cycle because of the latter's simplicity, economic advantages, and non-proliferation benefits.

However, there is also broad agreement that R&D should be conducted on selected topics to support the cost-effective future application of separations and transmutation of commercial spent fuel with a focus on factors that strongly influence fuel-cycle economics, especially the costs of reprocessing; minimization of long-lived radionuclides; and need to minimize the possible increase in proliferation risks that could result from commercial use of plutonium in recycled fuels. Reliance on plutonium-containing fuels may be eventually required for economic reasons, given that – absent of discovering increasing amounts of relatively inexpensive uranium sources – present uranium resources are limited, especially when it is assumed that applications of nuclear technology may expand beyond the production of electricity, such as the production of hydrogen for industrial and transportation applications.

Increasing the capacity of the proposed Yucca Mountain geologic repository by separations and conditioning of fission products as well as by partitioning and transmutation of minor actinides (especially neptunium, americium; and curium) involve trade-offs, including greater risks and operational complexities potentially leading to higher short-term doses to workers and public. Balancing the needs for sustainability (shift to a plutonium economy and reduction in HLW burden on repository), operational (ALARA) and cost efficiencies, and minimization of proliferation risks, will eventually require management strategies relying on interim storage, reprocessing, and recycling of some of the spent nuclear fuel constituents in fast reactors before final disposal of the high-level wastes into a permanent geologic formation.

The present report presents results from a selection of recently published reports or articles. The report is the 2007 deliverable of an originally anticipated two-year EPRI Technology Innovation project whose overall objective was to establish a capability to assess various advanced fuel cycle scenarios with emphasis on their impacts on natural uranium resource utilization, spent-fuel management efficiencies, and operational challenges.

During the latter part of 2007, EPRI, on behalf of US utilities, committed to support a project to be conducted at the Massachusetts Institute of Technology (MIT) on closely related topics. As a result, it was decided to re-task the original two-year Technology Innovation project to support the MIT project. The latter is described in the next section.

The Future of the Nuclear Fuel Cycle – Issues and Opportunities

Background

In 2003, an interdisciplinary MIT Study on the "Future of Nuclear Power" offered recommendations for government and industry actions that could enable nuclear power to expand its role in electricity supply and climate-change risk mitigation. The study addressed nuclear reactor and fuel cycle (both open and closed) technologies and economics, safety, waste management, proliferation risks associated with global fuel cycle deployment, technology research, development and demonstration (RD&D) needs, and public attitudes in the United States.

Over the past five years, there have been several material developments, a number of which (but not all) align well with the recommendations put forward in the 2003 Study. Chief among them --as relevant to this project-- are:

- Continued delays and complications, as well as some positive developments, in advancing the Yucca Mountain repository. The most optimistic expectations of the Department of Energy would have the repository in operation starting in 2018, which is 20 years after DOE was to have an operational repository
- Active discussion, including in Congress, of consolidated interim storage, especially for spent fuel from permanently shutdown reactor plants
- Initiation of the Global Nuclear Energy Partnership, aimed at, among other things, the development of advanced nuclear fuel cycles with full actinide recycle.

Demonstration by the private sector of the cost and schedule for building the new generation of light-water reactors is expected within the next ten to fifteen years. However, the industry, the government, and the public remain uncertain about whether this will indeed come to pass in timely fashion. A remaining major obstacle is the failure to resolve spent nuclear fuel disposition, a decade after the government was obligated to begin taking title to this fuel, and still at least a decade away from Yucca Mountain operation.

The need for nuclear energy on one hand and the challenges it faces particularly in the waste area have stimulated much discussion on the issues of consolidated interim storage, uranium availability, readiness, cost and environmental benefits of closed fuel cycles, and concomitant proliferation concerns. Pursuit of closed fuel cycles raises even more complex technological and policy challenges concerning introduction at scale of new reactor types (e.g., fast spectrum reactors), new fuel forms, new separations technologies, new international institutional arrangements, and new system integration and operational issues.

These considerations have led NEI and EPRI to support a new interdisciplinary five-year MIT research program to be carried out under the auspices of the MIT Energy Initiative. Although a series of studies over the proposed project period will be conducted, the overwhelming emphasis will be placed on research, analysis, and recommendations for the "back-end" of the fuel cycle, both open and closed, in the context of the same core question addressed in the 2003 Study: *"What actions are needed to enable nuclear power to be an important contributor to electricity supply in a carbon-constrained world for the long term?"*

Objective

The objective is to develop a sound, technically based strategy for the future of a sustainable nuclear energy fuel cycle.

To achieve this objective, the project will undertake an engineering study of options for managing the technical, economic, environmental, and institutional aspects of the nuclear fuel cycle, with specific emphasis on the "back-end" of the fuel cycle, and their potential consequences. A program for technology development and deployment will be proposed, taking into account uncertainties for managing commercial spent nuclear fuel and ultimate disposal of the wastes.

Task Description

The project will be carried out in two major phases over a five-year period. The first phase – the only one to be described at this time -- will last for 40 months followed by a two-year phase for completion of specific studies and initiation of new studies as warranted by the findings and needs identified in the first phase. Phase 1 will consist of the following tasks:

- Summary Update of the "Future of Nuclear Power" Study

This Summary Update will start with the findings and recommendations of the 2003 report, evaluate the events since 2003, and identify changes, if any, on the margin of the original findings and recommendations. It will, therefore, reflect the new developments since 2003, update the 2003 data base as needed, assess the range of potential use of nuclear energy in a carbon-constrained world, and evaluate and incorporate appropriate results from the many other studies carried out in the last four years, including writings of various study group members.

A particular focus of the Summary Update will be on fuel cycle architecture, based on systems analysis of open and closed fuel cycles with updated data. Goals for the near term (up to ~2020) and beyond will be discussed, and appropriate RD&D and policy actions will be identified. The RD&D analysis will include an in-depth analysis of advanced nuclear fuel cycle technology development – its cost, pace, science, technology, and non-proliferation implications – as currently planned (scale, focus, down-select schedule and content, etc.). This will yield recommendations for the path forward.

In addition, the Summary Study will look at a variety of issues important to the future of nuclear energy. Such topics include, but are not limited to, uranium supply, advanced nuclear fuel cycle economics, and the stability of national energy policy.

A number of areas will not be specifically reviewed, but will be dealt with as input assumptions. These include, but are not limited to, analyses of a realistic Yucca Mountain schedule, and whether the growth rate of nuclear plant build is more or less than that shown in the 2003 Study.

Domestic and international policy options will be presented, with a focus on prioritization of appropriate Administration, Congressional, and industry actions in the near term in order to set the appropriate trajectory.

- Technology Options Assessment

In parallel with the Summary Study, an assessment of the ability to create flexibility identified in each of the technology classes will be conducted. For examples, options to reduce waste volumes from light water reactors (e.g., through higher discharge burnups), use of high-

temperature gas reactors to improve overall uranium utilization (e.g., through higher thermal efficiencies), building of so-called burner reactors that can be flexibly converted to breeders when needed; and options in separation technologies to minimize proliferation potential through intrinsic safeguard measures, such as high radiation levels. The result of this task will form the basis for subsequent in-depth technology evaluations.

- Nuclear Fuel Cycle Simulation Tool

A code aimed at modeling the operation of a nuclear fleet and the associated fuel cycle facilities over long periods of time (decades, even centuries) is needed to analyze the consequences of strategic choices related to nuclear fleet composition (types of reactors and associated fuels) and supporting fuel cycle facilities. Such a code will provide the key platform for many of the subsequent in-depth technology evaluations.

This task will review available simulation tools (CAFCA; DANESS; VISION; COSI) for future applicability in the overall systems assessment. Benchmarking and validation of these tools will be performed to assist in the final selection.

- In-depth Technology Evaluations

Several in-depth technology evaluations that go into great technical depth on specific topics will be performed. Some of these will be launched in the first year. Others will be initiated only in response to the findings and recommendations in the Summary Update.

Key areas are likely to include:

- Technology Choices and Implications for Waste Management: Systematic evaluations of various options for the fuel cycle will be conducted to determine the characteristics of the overall nuclear energy enterprise, including the implications for resource demand and waste disposal. The nuclear fuel cycle simulation tool will be developed further, if necessary, and employed to track the flow of fuel materials in the components of various fuel cycles, from mining to disposal. Both open and closed fuel cycle will be addressed. R&D needs will be identified. Studies will include reactor options, fuel options, separation options, waste forms, and geologic disposal alternatives for nuclear waste.
- Policy and Institutional Issues: Role of long-term interim storage, fuel cycle proliferation risks, regulatory issues, public opinion, globalization of industrial infrastructure, and government effectiveness.

At the end of the project, the many findings and recommendations will be synthesized into a coherent whole.

2
BACKGROUND

Reprocessing & Recycling

Reprocessing is a chemical process that *separates* the constituents of spent nuclear fuel into a number of separate streams. Reprocessing does not change the radioactive characteristics of the used nuclear fuel constituents. The first and foremost benefit of reprocessing is that it enables *recycling* of some of the spent fuel constituents, more specifically plutonium (a potentially valuable by-product for producing energy) and leftover uranium.

Recycling of plutonium and leftover uranium in existing light-water reactors has the potential to decrease the demand for natural uranium resources by up to ~25%, but more realistically by 10 to 20%. Recycling of plutonium and uranium in some *advanced* reactors, such as the so-called fast[1] breeder reactors, has the potential to decrease the demand for natural uranium resources by two orders of magnitude.

Historical Evolution

Back in the late 1950s and 1960s, projections for large-scale deployment of the technology led to the adoption of a strategy based on reprocessing of spent fuel from light-water reactors followed by recycling in fast breeder reactors. This strategy was in support of ensuring long-term sustainability of nuclear generation through minimal use of natural uranium resources. However, due to lengthy delays in breeder reactor development/deployment together with a much slower than anticipated growth in nuclear generation during the 1980s and 1990s – and subsequent lower demand for natural uranium resources – this strategy evolved into a policy toward either:

1. Direct disposal of used fuel (USA, Finland, Sweden, and others). The change in policy was justified by economic considerations (reprocessing costs were substantially larger than the value of the recovered uranium and plutonium) as well as by concerns about nuclear proliferation risks (USA's policy against pure plutonium separation); or
2. Reprocessing of used fuel followed by recycling in light-water reactors (France, Japan, Belgium, and others). This approach was justified by national policies with a long-term outlook toward sustainability and a short-term need to mitigate economic penalties associated with reprocessing and separated plutonium storage costs.

[1] "Fast" reactors are those reactors in which the average kinetic energy of neutrons producing the fission reaction is high, i.e., the neutrons are moving "fast." This is in contrast with existing light water reactors in which the average kinetic energy of neutrons producing the fission reaction is low.

Present U.S. Situation

In the U.S., implementation of the policy calling for direct disposal of spent fuel has encountered significant delays. In addition, the need for a second repository – as originally intended by the 1987 Amendment to the Nuclear Waste Policy Act – as well as domestic and global prospects for significant growth in nuclear generation have provided the motivation to re-visit reprocessing/recycling for their potential benefits to used fuel management, especially with regard to repository capacity increase and waste volume and long-term toxicity reductions.

In general, it can be stated that reprocessing increases the *flexibility* for managing used fuel/nuclear waste. However, to ultimately reduce the waste burden, implementation of advanced reprocessing *coupled with* specific advanced reactor technologies will be required over long periods of time in order to make a significant impact on waste quantities eventually being disposed of in permanent repositories.

Sustainable Nuclear Fuel Cycles

The aim of advanced fuel cycles is to improve the sustainability of nuclear energy by enhancing the effectiveness of natural uranium resource utilization and by mitigating waste disposal issues, while keeping the costs of energy products, in particular electricity, economically viable. In addition, this aim has to be achieved under conditions that minimize the risks of diversion of separated fissile materials and their possible misuse for non-peaceful ends.

Natural Uranium Resources Utilization

Naturally occurring uranium contains three isotopes: U-234, U-235, and U-238. Their abundance and decay characteristics are presented in Table 2-1.

Table 2-1
Natural Uranium Isotopes

U Isotope	Abundance [wt%]	Half Life [Years]	Decay Product
U-234	0.005	2.45 E+5	Th-230 → … → Pb-206
U-235	0.711	7.04 E+8	Th-231 → … →Pb-207
U-238	99.284	4.47 E+9	Th-235 → … → Pb-206

Today, nuclear energy is once again in the forefront of discussion as a potential energy source in response to global warming threats in addition to continued energy security concerns. Uranium prices, responding to perceptions as to the balance between supply and demand, reached unprecedented levels in mid-2007, even after taking inflation into account. As countries after countries are announcing their intent to consider, or reconsider, nuclear energy in their energy supply mix, questions are being raised again about the adequacy of natural uranium resources, given that U-235, with a content of only 0.711% in natural uranium, is the only nuclide that is appreciably fissionable in thermal reactors.

Past experience shows that exploration responds positively to uranium price increases, and that increased exploration activity can be expected to yield new deposits at reasonable costs and

ultimately lead to increases in recoverable resources. However, present reliance on secondary sources[2] (e.g., uranium enriched for military purpose declared excess to national security needs by the United States and the Russian Federation) and two decades of low prices have had significant impacts on the industry in terms of significant reductions in primary production capability. In addition, the amount of time needed to develop a new mine and bring new resources to market has steadily increased over time, in part due to increased regulatory requirements. The challenge in coming years is likely to be less one of adequacy of resources than adequacy of production capacity. Although history suggests that this challenge can be successfully met, the long-term demand for U-235, however, may *eventually* exceed the quantities of uranium economically recoverable in scenarios of nuclear energy revival, including development of nuclear systems for process heat, hydrogen production, water desalination, and possibly others such as district heating.

One alternative for meeting future energy needs is to gradually introduce advanced designs such as fast reactors that rely on "fast" neutrons for sustaining the fission process. A class of fast reactors commonly referred to as fast breeder reactors are able to take advantage of excess neutrons produced by the fission of plutonium (obtained by capture of a neutron by U-238, followed by radioactive decay of U-239 into Pu-239) to regenerate an equal or slightly greater amount of plutonium. This approach enables the efficient utilization of U-238, which comprises >99 wt% of natural uranium. A similar scheme also is possible using U-233 (obtained by capture of a neutron by Th-232, followed by radioactive decay of Th-233 into U-233), which would enable the full utilization of natural thorium resources, which are known to be very large.

Mitigation of Waste Disposal Issues

Management of growing inventories of spent fuel has significant implications with regard to the future sustainability of nuclear energy, as the future of nuclear power depends on public perception of the environmental and health impacts associated with nuclear power plants and associated fuel cycles.

The production of energy from low enrichment uranium fuel in commercial nuclear reactors results in long-lived radiological species as follows:

- *Fission products* are by-products that result from the splitting of the uranium or plutonium atoms. The main long-lived fission products, or LLFP, are Se-79; Zr-93; Tc-99; Pd-107; Sn-126; I-129; and Cs-135 (Table 2-2). All other fission products of interest have half-lives of 30 years or less. Among these, Sr-90 ($T_{1/2}$ = ~28 years) and Cs-137 ($T_{1/2}$ = ~30 years) and their decay products are of special interest, as they are responsible for the major contribution of decay heat up to 60 to 90 years after discharge of the spent fuel from reactors.

- *Actinides* are by-products that typically result from one or multiple neutron captures by uranium nuclides[3]. The main actinides are uranium and plutonium, while the minor

[2] Primary supply exceeded reactor-related uranium requirements until 1991, when that relationship was reversed. Since 1991, the gap between primary supply and uranium requirements has been filled by secondary supply.
[3] All of the radioactive waste produced by fission or neutron capture goes through a series of decays prior to reaching a stable form; all of those nuclides (daughter products) are considered here in aggregate.

actinides, or MA, are neptunium, americium, and curium. Plutonium together with the minor actinides are referred to as the transuranic elements, or TRU. A list of the major and minor actinides is shown in Table 2-3. Actinides become the major contributors of decay heat after 60 to 90 years after discharge of the spent fuel from reactors.

- *Activation products* are by-products that result from the capture of a neutron, sometimes accompanied by radioactive decay, by impurities such as nitrogen and chlorine. The main long-lived activation products are C-14 and Cl-36 (Table 2-4). These two activation products are troublesome contaminants of medium-level ("Greater-than-Class C" or "Intermediate-Level") nuclear wastes.

Table 2-2
Fission Products

Fission Product	Half-life [Years]	Significant Feature
Sr-90/Y-90	2.88E+01	High decay heat
Cs-137/Ba-137m	3.00E+01	High decay heat
Se-79	2.95E+05	Occurs in small concentrations
Zr-93	1.53E+06	~20% of total Zr in spent fuel
Tc-99	2.11E+05	Readily soluble – High mobility in aquifers
Pd-107	6.5E+06	
Sn-126	1E+05	Accompanies a series of stable Sn isotopes
I-129	1.57E+07	Readily soluble - High mobility in aquifers
Cs-135	2.3E+06	Accompanies Cs-137

Table 2-3
Actinides

Actinide	Half-Life [Years]	Parent (precursor)	Daughter (decay product)	Comment
U-232	6.89E+01	Pu-236; (also, Pa-232 and Np-232)	Th-228	Most radiologically significant U isotope
U-233	1.59E+05	Several	Th-229	Fissile
U-234	2.45E+05	Pu-238 (also, Pa-234 and Np-234)	Th-230	
U-236	2.34E+07	Pu-240 (also, Pa-236 and Np-236)	Th-232	
Np-237	2.14E+06	Pu-241	Pa-237	
Pu-238	8.77E+01	Am-242	U-234	
Pu-239	2.41E+04	U-239 and Am-243	U-235	Fissile
Pu-240	6.56E+03	Cm-244	U-236	
Pu-241	1.44E+01	Cm-245	Am-241	Fissile

Actinide	Half-Life [Years]	Parent (precursor)	Daughter (decay product)	Comment
Pu-242	3.73E+05	Cm-246	U-238	
Am-241	4.32E+02	Pu-241	Np-237	
Am-243	7.37E+03		Np-239	
Cm-244	1.81E+01		Pu-240	
Cm-245	8.5E+03		Pu-241	

Table 2-4
Activation Products

Activation Product	Half-life [Years]	Comment
C-14	5.73E+03	From N impurity in fuel
Cl-36	3.01E+05	From Cl impurity in Zircaloy

It is generally accepted that transmutation of long-lived fission products and activation products into shorter-lived/stable nuclides would be problematic because:

- They are produced in elemental mixtures (i.e., a chemical element consists of several isotopes). Given that only one of the isotopes is targeted for transmutation, this would first require isotopic separation; and
- The transmutation yields are very small because of very low capture cross sections.

Therefore, fission products in general, including long-lived fission products, and activation products are considered to be true wastes of the nuclear reactions. These wastes will need to be isolated from the biosphere for periods of time long enough to ensure that they will not result in any significant impact on general public health.

With regard to the actinides:

- Their separation (partitioning) from the other spent fuel constituents is possible on the basis of their different chemical properties (all isotopes of a given actinide element needs to be dealt with); and
- They can be transmuted or "incinerated" through fission. Light-water reactors (LWRs) are well suited for incineration of fissile isotopes (U-235; Pu-239; and Pu-241), but less so for incineration of the majority of actinides. New reactor concepts (fast reactors, accelerator-driven systems, fusion/fission hybrid reactors) have been proposed as potential incinerators. Innovative fuel designs for irradiation in LWRs and high-temperature gas reactors (HTGRs) have also been proposed [See for examples *Actinide Minimization Using Pressurized Water Reactors*, M. Visosky, M.S. Kazimi and P. Hejlar, MIT-NFC-TR-085, June 2006, and *The Helium-cooled Modular Reactor – How to include MHRs in GNEP and Why?*, F. Venneri, M. Campbell, and D.E. Baldwin, MIT Symposium on Rethinking the Nuclear Fuel Cycle, October 2006].

Over the past few years, there has been a significant interest in assessing the potential of "partitioning and transmutation" (P&T) of the actinides as a long-term radioactive waste management option. The main objective of P&T is the reduction in long-term *hazard* of spent fuel by transforming long-lived radionuclides into short-lived or inactive nuclides. In this work, it is intended to evaluate this objective in the context of conventional waste management that addresses overall radiological *risks*, a combination of potential hazards and confining properties of potential hazards. For example, reprocessing/recycling could, in principle, result in long-term hazard reduction, but in reduced short-term hazard confinement.

Partitioning and transmutation ("P&T") is a complex technology that requires spent fuel reprocessing, fuel re-fabrication, and innovative and/or dedicated reactors. The concept of "P&T" has the potential to foster greater public acceptance of the nuclear technology. However, implementation – and more specifically siting and construction of the facilities that would be required – has the potential for substantial opposition.

Proliferation Risks

A critical issue is the risk of diversion of separated fissile materials and their possible misuse for non-peaceful ends. In fact, one of the stated main reasons for the move towards a direct disposal policy for spent fuel management in the U.S. was concern over proliferation.

As defined for uranium and plutonium by the IAEA, proliferation resistance is understood as the possibility to prevent (1) misuse of technology[4] and (2) diversion or theft of weapon-useable fissile materials. Minor actinides, such as neptunium-237 and americium-241, have to be considered as well. Proliferation resistance of spent fuel management options are qualitatively compared by applying intrinsic and extrinsic criteria.

Intrinsic criteria

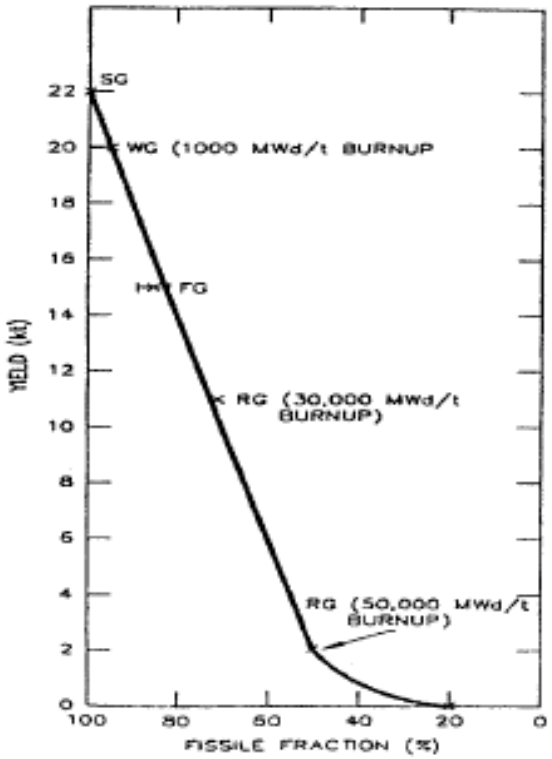
Intrinsic criteria are related to the type of fissile material (e.g., required critical mass) in terms of its attractiveness for nuclear explosive devices, or to the mass flow of fissile material in a treatment (e.g., reprocessing) process.

In particular, plutonium has been, and continues to be, the subject of much attention by the non-proliferation community. Figure 2-1 shows the calculated average explosive yield in kilotons [Bruno Pellaud, Journal of Nuclear Materials Management, Fall 2002, Volume XXXI, No. 1, pp. 30-38] of a nuclear device as a function of the fissile fraction (U-235 or Pu-239), showing the well-known 20%-limit at which explosive yields become vanishingly small. In addition, plutonium quality plays a central role in the making of nuclear weapons, given the high levels of spontaneous fissions and decay heat of Pu-238 and Pu-240. The present practice in the U.S. and IAEA is to deem "weapon usable" all plutonium, except for plutonium with >80% Pu-238. Recent work [G. Kessler, "*Plutonium Denaturing by Pu-238*," Nuclear Science and Engineering, 155, 53-73 (2007) and C.H.M. Broeders and G. Kessler, "*Fuel Cycle Options for the Production and Utilization of Denatured Plutonium*," Nuclear Science and Engineering, 156, 1-23 (2007)]

[4] Only civil fuel cycles for nuclear energy production are considered in this document.

shows that reactor-grade plutonium[5] (labelled as RG in Figure 2-1) with an augmented Pu-238 isotopic content of 6 to 8% can be regarded as proliferation resistant.

Figure 2-1
Calculated Yield Curve (SG = Super grade; WG = Weapon grade; FG = Fuel Grade; RG = Reactor Grade) [Ref. B. Pellaud, Proliferation Aspects of Plutonium Recycling, Fall 2002, XXXI, No. 1, pp. 30-38]



Also of interest is the concept of the "Spent Fuel Standard," which was introduced in the 1994 and 1995 reports of the NAS Committee on International Security and Arms Control (CISAC) [Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium*, Washington, DC: National Academy Press, 1994, 275 pp.; and Panel on Reactor-Related Options, Committee on International Security and Arms Control, National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options*, Washington, DC: National Academic Press, 1995] on the disposition of excess weapons plutonium, as the criterion for judging the adequacy of resistance to theft and proliferation conferred by the intrinsic characteristics of the final plutonium form produced by a disposition option. That standard held that plutonium in its final dispositioned forms should be roughly as difficult to acquire, process, and utilize in nuclear weapons as is the plutonium in typical spent fuel from civilian power reactors.

[5] In discharged LWR fuels with burnup of 30 and 50 GWd/MTU, the Pu-238 isotopic contents would typically be ~1.6% and ~2.8%, respectively. For discharged MOX fuels recycled once in LWRs, the Pu-238 isotopic content would be ~3.8% for a burnup of 50 GWd/MTU.

Extrinsic Criteria

Extrinsic criteria supplement intrinsic criteria. The latter are more institutional in nature, and can be further distinguished between fissile material safeguards measures (design verification, accountancy, containment and surveillance) and physical protection measures against theft and sabotage.

Need for International Agreements & Safeguard Provisions

As judged by the reactions to the U.S. Global Nuclear Energy Partnership, proliferation considerations could affect "to-recycle" or "not-to-recycle" decisions. Weapons-expert opinions vary from "a bomb can in theory (and therefore actually might) be make-able from any plutonium isotopic mix" to "the 238 and 240 isotope contents make impractical a bomb with plutonium from spent fuel taken to today's LWR discharge burnups." With this degree of uncertainty, it is understandable that the Spent Fuel Standard reflects the additional protection/deterrent provided by the very hazardous radiation level of unprocessed commercial spent fuel.

A topical question is can we visualize a separations technology for commercial spent fuel that, although inevitably giving up a good deal of this radiation deterrent, would retain adequate proliferation resistance? A key concern in addressing this question is a vision that U.S. adoption of any separations technology will encourage global use. Then there will be multiple processing locations, each with the potential either for adjusting the process to produce clean reactor-grade plutonium and/or for diversion of no-longer-Spent-Fuel-Standard-protected reactor-grade plutonium to a small undetectable aqueous clean-up unit.

For example, the bulk of the U.S. processing technology development effort over the preceding quarter-century was on a pyro-technology that leaves some of the minor actinides and fission products with the plutonium, thereby retaining some of the radiation deterrent. But it will be very difficult to achieve a consensus that such a mix will not be too hazardous to use in a fuel fabrication plant and then in reactor fuel handling, yet be too hazardous to divert to a small aqueous clean-up unit.

An EPRI review of recent technical literature has not disclosed any new silver-bullet technology; indeed it is difficult to imagine that there could be one.

If something additional to the practical difficulties deriving from the 238 and 240 isotopes is truly needed, there is some possibility that the locations of the less-than-perfect processing scenario facilities could be controlled adequately via international agreement plus adequate safeguards at the permitted locations. However, experience to date is not very encouraging. If doing a particular thing is in a nation's interests, such carrots and sticks as get proffered are frequently inadequate. Also, implementation of a nominally adequate international agreement can prove to be dangerously slow (witness the disposition of surplus weapons-grade plutonium). Notwithstanding this difficulty, establishment of an unprecedented degree of international cooperation plus safeguards is a pre-requisite to a U.S. processing scenario and its inevitable global implications. This discussion introduces the recognition that if/when, in the long-term, processing does become economic (say because of a major and sustained uranium price increase), processing will likely become global anyway, whether or not we are satisfied at that

time with the proliferation risk. This underscores the need for timely, albeit difficult, negotiation of the necessary degree of international cooperation and safeguards in the nuclear power arena.

The plutonium weapons proliferation concerns outlined in the previous paragraph exist also for U-235 weapons in the non-processing (once through) scenario. Prevention of mis-use of enrichment facilities too will need greater international cooperation and improved safeguards to support a major global expansion of nuclear power. This requisite has been expressed, for example, by John Deutch, et al. [*Making the World Safe for Nuclear Energy,* The International Institute for Strategic Studies, Winter 2004-5, 2005), and has resulted in the GNEP approach for an international nuclear fuel supply and take-back regime that would obviate the need for a large number of national enrichment as well as processing facilities. The weak point for a much expanded global non-processing scenario is potentially more enrichment locations susceptible to rogue operation to produce ideal weapons material. By comparison to clandestine enrichment, the processing scenario offers far from ideal weapons material but has the additional susceptibility to theft, and at multiple locations - the processing plants and the downstream fuel fabrication and nuclear power plants and transport paths between them.

The processing scenario has another weak spot. As noted above, if the motivation for processing does eventually include capping a rising uranium price and greatly expanding the supply of nuclear fuel, the scenario must include fast reactors. But demonstration fast reactors to date have included blankets, which produce plutonium with little 238 and 240 contents. This can be avoided if and while the only motivation for processing is the major increase in repository capacity achievable. For this purpose, fast reactors without blankets will suffice. Needing to be determined is whether fast reactors can also be configured to cap a rising uranium price (i.e., breed plutonium) without producing plutonium low in 238 and 240 contents.

Subject to the outcome of the last challenge above, this initial evaluation does not conclude that the processing scenario is worse from proliferation considerations. It may turn out that the proliferation risk difference is not decisive and that the choice between scenarios will hinge on more tangible differences (of which there appear to be two – economics and fast reactor reliability – both encouraging us to stay with non-processing for the near-term).

Economics

Recycle in LWRs

Assessments of the economics of reprocessing and recycling in LWRs usually compare direct disposal following interim storage against prompt reprocessing and recycle. As reprocessing followed by recycling in LWRs leads to uranium savings (less uranium requirements through use of plutonium and reprocessed uranium), cost savings or penalties may result depending on whether reprocessing and MOX fuel fabrication costs are lower or higher than the cost of uranium fuel that would be used for generating the same amount of power, the latter being directly tied to uranium ore, conversion, enrichment, and fabrication costs. There are other factors involved as well, such as credits for disposal of HLW instead of unprocessed spent fuel and for re-usable uranium.

The nominal break-even uranium price (or uranium ore price) is very sensitive to the assumed cost of reprocessing and waste disposal credit. In turn, reprocessing (including waste

conditioning and MOX fuel fabrication) strongly depends on the assumed financial scheme required to attract the capital resources necessary to license and construct the reprocessing complex. In EPRI Report 1013442, dated June 2006, the nominal break-even uranium price was estimated to be ~$300/kgU for reprocessing followed by recycling in existing reactors. Therefore, adoption of spent fuel reprocessing/recycling would result in a cost penalty if actual uranium prices in existing long-term contracts were to be compared to the EPRI-calculated break-even uranium price. However, spot uranium transactions were in the range of $350 – 390/kgU (corresponding to $135 – 150/lb of U_3O_8) in early June 2007. Should this range of price be representative of uranium prices over the next decade, then reprocessing and recycling in existing reactors would be economically competitive on the basis of the model and cost parameters used in the June 2006 EPRI study.

During the past five years, several economic analyses, relevant to the U.S. situation, have been published by MIT [*The Future of Nuclear Power*, MIT, 2003], Harvard [*The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Belfer Center, 2003], and the Boston Consulting Group [*Economic Assessment of Used Nuclear Fuel Management in the United States*, The Boston Consulting Group, 2006]. Using already demonstrated technology (aqueous reprocessing plus MOX fuel fabrication, and recycling in LWRs, but no fast reactors), the cost of nuclear electricity would be increased as shown in Table 2-5.

Table 2-5
Increase in Cost of Nuclear Electricity Estimated From Various Studies

Organization	Cost Increase mils/kWhe
Massachusetts Institute of Technology (MIT)	2.8
Harvard's Belfer Center	1.3
EPRI	1.0
Boston Consulting Group (BCG)	<0.5[6]

Results from any economic analysis always require careful examination of the chosen economic models and cost parameters, including the sensitivity of the results to the reference parameter values.

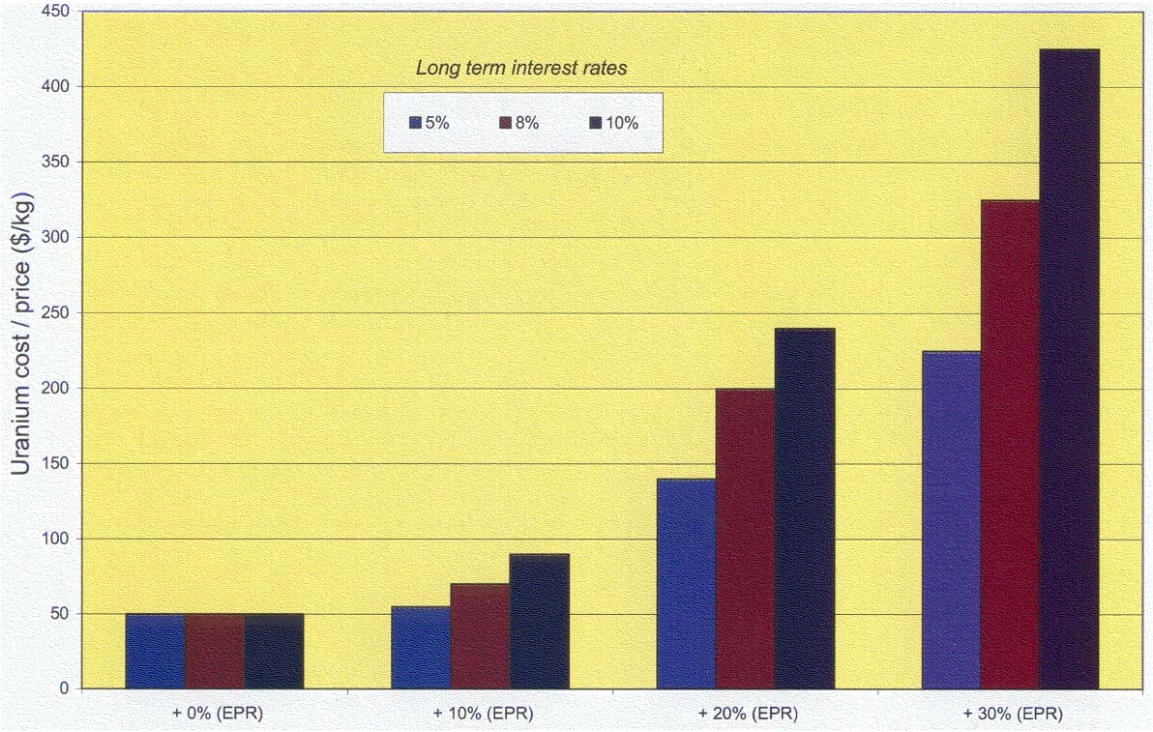
Recycling in Fast Reactors

Break-even uranium prices for recycling in fast reactors are generally lower. However, because (1) of the dominance of capital cost in nuclear power economics, and (2) the expectation that Fast Reactors (FRs) will cost more than LWRs, credible increase in capital cost for the fast reactor would close (and possibly reverse) this difference in break-even uranium costs. See Figure 2-2, which shows the sensitivity of the break-even uranium cost/price as a function of the increase in capital cost for a GEN IV fast reactor compared to a GEN III EPR taking different interest rates into account. However, since recycling reduces the consumption of natural uranium to a limited extent in LWRs, and to a much greater extent (at lest potentially) in FRs,

[6] Based on footnote 24 on page 20 of the BDG report

adoption of MOX recycling in LWRs would dampen, but not stop, uranium price increases, whereas a switch to fast reactors would stop the rise, because fast reactors operating in the breeder mode would not require any more uranium to be mined. At that time, a mix of MOX-LWRs and fast reactors may prove appropriate, at least for a while. If and when fast reactors are deployed to cap a rising ore cost, they will need only a fraction of the plutonium that will have been generated. One of several options for the rest of the plutonium is MOX-LWR, which presumably will be rendered close to economic by the ore cost rise that triggers fast reactor deployment.

Figure 2-2
Illustration of the Relationship Between Uranium Cost and Cost Differential Between Gen IV and Gen III Systems [J.L. Carbonnier, "Merits of fast reactors for an efficient use of uranium ore and reduction of ultimate waste," International Symposium on Rethinking the Fuel Cycle, Cambridge, MA, October 30-31, 2006]



3
STATUS OF REPROCESSING TECHNOLOGIES

There are a number of processes already existing or under active development:

1. The PUREX process is the reference reprocessing technology that is currently implemented in industrial scale facilities in France, Japan, UK, Russia, and India.

   The current reprocessing technology (PUREX) separates the used fuel constituents into three main streams:

   - The first stream contains the leftover uranium, referred to as reprocessed uranium, or REPU (~94% of the original mass of uranium). Reprocessed uranium can be either stored or recycled into existing reactors.

   - The second stream contains the plutonium (~1%). Plutonium can be incorporated into a mixed-oxide fuel[7], or MOX, which is then recycled in existing reactors. Upon discharge from existing reactors, the used MOX fuel is placed in interim storage; used MOX fuel is not presently reprocessed because of the marginal value of its constituents as recycle-able materials in existing reactors.

   - The third stream contains most of the fission products[8] (~5%) as well as the so-called minor actinides[9] (~0.1%). Presently, these constituents are considered to be the ultimate wastes, or high-level wastes, resulting from nuclear generation. This stream is conditioned for geologic disposal by incorporation of its constituents into a glass matrix. Before geologic disposal, these wastes need to be in interim storage for periods of up to 60 to 90 years.

   - In addition to the three streams above, the structural fuel assembly components are compacted and packaged for disposal in a geologic formation (permanent repository).

   The PUREX technology is a well established technology that was originally developed in the U.S. However, it is a difficult technology to implement in a safe and environmentally responsible manner as it requires siting with favorable dispersion characteristics, careful process layout and equipment selection including well thought-out provisions for maintenance/replacement, strict control of process operating parameters, extensive safeguards, etc. The La Hague plant, operated by AREVA NC, is generally considered to be the technology leader for used fuel reprocessing, as it has handled close to 75% of all reprocessed light-water reactor fuel (~23,000 metric tons out of ~30,000 metric tons).

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[7] MOX refers to a mixture of uranium and plutonium oxide.
[8] Fission products are the "ashes" produced by nuclear fission.
[9] Minor actinides consist of the atomic elements neptunium, americium, and curium.

2. Reprocessing technology being readied for potential near-term industrial deployment no longer includes separation of pure plutonium, but rather includes separation of plutonium mixed with some uranium, or possibly separation of plutonium + neptunium mixed with some uranium. These evolutionary processed are based on the PUREX process, and with performances that have already been successfully tested, should be considered ready for industrial implementation. This technology is likely to benefit from:

    - Process improvements based on today's operating experience, which cannot be readily made in existing facilities

    - Co-management of the plutonium (and possibly neptunium) with uranium to address US policy against pure plutonium separation

    - Integration of the MOX fuel fabrication facility within the reprocessing/waste vitrification complex to eliminate transportation of plutonium-bearing compounds between the reprocessing and MOX fabrication facilities.

3. Advanced reprocessing technologies based on the PUREX process are being developed in several countries to (i) minimize proliferation risks, and (ii) enable recycling of minor actinides. Two main options are pursued:

    - Selective separation of minor actinides for interim storage followed by heterogeneous[10] recycling in fast reactors, (DIAMEX-SANEX in France, TALSPEAK in US, TOGDA in Japan).

    - Group actinide separation intended for homogeneous[11] recycling in fast reactors (GANEX in France, UREX+ in US, NEXT in Japan).

    Large-scale implementation of these processes is not likely for several decades. In addition, recycling in fast reactors is required, as specified above.

4. Innovative methods based on pyro-chemistry are also being developed as integral parts of the refueling/waste management system of specific types of fast reactors. They allow for the treatment of different types of highly radioactive fuels with high plutonium content.

    Commercial deployment of these technologies is not likely for several decades.

5. Status

    As already discussed, reprocessing is key to enabling recycling and attendant benefits with regard to natural uranium resources utilization. With regard to its impact on waste management, reprocessing greatly increases the flexibility for managing used fuel/nuclear wastes, but any ultimate benefits/detriments to waste management will depend on subsequent recycling of the separated used fuel constituents.

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[10] Meaning that the minor actinides and nuclear fuel are packaged separately
[11] Meaning that the minor actinides are incorporated into the nuclear fuel.

4
WORLDWIDE SITUATION

Today, all countries are limited to some variant of *interim storage* until geologic repositories become available. In this context, it is interesting to look at three countries (USA, Sweden, and France) focusing on the by-products that would end up in a geologic repository without further significant technological advancements:

- **USA**: Used fuel is stored at the reactor sites.
- **Sweden**: Used fuel is stored at a centralized interim storage facility (CLAB). This requires transportation of used fuel from the reactor sites to the CLAB facility.
- **France**: Used MOX fuel, vitrified high-level wastes, and compacted or conditioned intermediate-level wastes are stored at a centralized interim storage facility (La Hague). This requires transportation of used fuel between the reactor sites and La Hague; transportation of plutonium between La Hague and the MOX fuel fabrication facility (Marcoule), transportation of newly fabricated MOX fuel from Marcoule to 20+ reactor sites. Used MOX fuel is stored at 20+ reactor sites.

Other countries (Belgium, Germany, Japan, etc.) have similar or composite approaches.

A main difference between the U.S. and Sweden/France is that interim storage of used uranium-oxide (UOX) fuel has been implemented at a central facility, resulting in little accumulation of used fuel at the power plant sites. "Centralizing the management of the waste … relieve plant owners of the ongoing liability for facilities that no longer generate revenue, and *(ed: in the U.S.)* would provide a framework for DOE's assumption of direct responsibility for management of spent fuel."[12] The France/Sweden approach requires a supporting infrastructure for transporting used fuel.

Focusing on waste volume and radiotoxicity, there is no difference between U.S. and Sweden. Because France includes a one-time recycling of the plutonium in existing reactors, the physical and radiochemical make-up of the waste streams are somewhat different from used UOX fuel's. Depending on the exact metrics chosen, different conclusions can be arrived at. For example, the *volume* occupied by used fuel assemblies compared to the volume occupied by used MOX assemblies + vitrified high-level waste canisters + intermediate-level waste canisters are generally comparable, when calibrated to the same unit of electricity production. But narrowing the comparison to only used fuel, the volume occupied by used MOX fuel (France) is ~1/8th to 1/6th of the volume occupied by used fuel in U.S./Sweden. With regard to radiotoxicity, plutonium is converted either into fission products (positive outcome) or minor actinides (negative outcome) through recycling. Any potential comparison in terms of radiotoxicity will be dependent on the chosen timeframe because plutonium, fission products and minor actinides undergo radioactive decay over different time frames. For information, through recycling,

[12] Adapted from the Keystone Center's Nuclear Power Joint Report Fact-Finding group's report

reductions in radiotoxicity of ~20% and ~50% are calculated after 1,000 and 10,000 years, respectively.

Potential Impact of Fast Reactors & Advanced Technologies

France's intent is to eventually reprocess the used MOX fuel that is presently in interim storage and recycle its plutonium content in fast reactors. If successful, such an approach would result in sending to a geologic repository only the high- and intermediate-level wastes. This would, of course, alter the observations made in the previous section. The extent by which these observations would be changed would also depend on future availability of advanced reprocessing schemes (including the potential either for separation of minor actinides, or for group actinide separation, as discussed earlier), ability to fabricate targets or fuel with high minor actinide contents, and availability of fast reactors able to safely operate with such fuels. It is to be noted that France is investing a considerable amount of resources in these technologies.

Similarly in the U.S., technologies pursued or proposed under DOE's Generation IV Forum and Global Nuclear Energy Partnership (GNEP) would have similar impacts on waste management, if successful. This would entail reprocessing of at least some of the used fuel presently in storage at reactor sites at some time in the future.

It should be noted, however, that studies of advanced fuel cycles indicate that significant reductions in high-level waste quantities to be disposed of in geologic repositories are achievable only if these advanced technologies are implemented over very long periods of time.

5
IMPACT OF ADVANCED FUEL CYCLES ON WASTE MANAGEMENT

Two recent studies on the impact of fuel cycle scenarios on high-level waste compositions have been reviewed. The two studies are:

- Séparation et transmutation des radionucléides à vie longue – Axe 1 – Dossier Final (Commissariat à l'Energie Atomique, December 2005), which will be referred to as the CEA report
- Advanced Nuclear Fuel Cycles and Radioactive Waste Management (Nuclear Energy Agency, NEA No. 5990, OECD 2006), which will be referred to as the OECD/NEA report

These two studies are not independent of each other as the French Commissariat à l'Energie Atomique (CEA) contributed to the analyses reported in the OECD report.

Fuel Cycle Schemes

The OECD/NEA report considers three families of fuel cycle schemes:

1. Schemes based on current industrial technology and possible extensions (highlighted in yellow in Tables 5-1 through 5-4)

   They include (1) the once-through fuel cycle, which serves as the reference fuel cycle for all comparisons between fuel cycles; (2) the fuel cycle with a single recycling of plutonium in the form of a mixed uranium-plutonium oxide in LWRs; and (3) the fuel cycle with a single recycle of neptunium together with the plutonium in LWRs. In all cases, the spent fuel with or without mono-recycling is disposed of in a permanent geologic repository.

2. Schemes with partially closed fuel cycles (highlighted in green in Tables 5-1 through 5-3)

   Partially closed fuel cycles feature fuel cycles that are fully closed for plutonium, but neptunium is always transferred to waste, and treatments of americium and curium are variable.

3. Schemes involving fully closed fuel cycles (highlighted in blue in Tables 5-1, 5-2 and 5-4)

   Fully closed fuel cycles recycle all actinides continuously until they fission, and only actinide processing losses are transferred to waste.

Equilibrium vs. Dynamic Fuel Cycle Simulation

Generally, analyses are restricted to steady-state or equilibrium conditions (consumption = production of recycled elements). The steady-state approach does not take into account that the equilibrium phase of a nuclear scenario is preceded by a deployment phase and followed by a shutdown phase when nuclear power plants are replaced eventually by other types of energy system.

- The deployment phase takes many decades until the actinide inventory has built up and the fuel composition has reached equilibrium. Transmutation benefits are not impeded during the deployment phase, although the detailed isotopic composition of the waste may show significant differences from the values obtained for the cycle at equilibrium.
- During the shutdown phase, however, the actinide inventory could be come an important contributor to the waste legacy, even after a long operation of the reactors, if the inventory is not eliminated over time in dedicated burner reactors, for example.

Fewer dynamic simulations have been performed and have been generally limited to a time period of one or two centuries.

Results from equilibrium analyses have to be carefully reviewed because they can be misleading in terms of their apparent benefits to waste management, as will be discussed later.

Figure-of-Merits

Figure of merits for nuclear fuel cycles typically include the following elements:

- Uranium consumption
- Yearly fission product and TRU inventories going to geologic disposal

Fission product production and TRU going to geologic disposal are often further described by their:

- Decay heat power after specified cooling time(s) after reactor discharge
- Potential radiotoxicity after specified cooling time(s) after reactor discharge. Potential radiotoxicity is generally chosen to be the “ingestion radiotoxicity” calculated by dividing the mass of a given isotope by its maximum permissible concentration in water.

An additional figure-of-merit of somewhat lesser technical merit includes waste volumes either as generated; for examples, volume occupied by spent fuel assemblies or HLW-containing canisters; or as conditioned for long-term storage or final disposal. Waste volume is related to the extent of storage space or excavation for geologic disposal. Since they are many variables in defining the types of wastes requiring storage/geologic disposal and different criteria specifically associated with the chosen repository and waste package design, waste package parameters need to be provided in sufficient details for making meaningful comparisons.

Equilibrium System Simulation

The OECD/NEA report considers nine fuel cycle schemes and four variants for a total of 13 different fuel cycle scenarios. The CEA report focuses on six of them. Under equilibrium conditions, the generation capacity is assumed to remain constant over time.

Natural Uranium Utilization

Table 5-1 shows natural uranium utilization for seven representative fuel cycle schemes. In all cases, the LWRs consist of evolutionary PWRs (AREVA's EPR type).

Table 5-1
Utilization of Natural Uranium Resources [Adapted from OECD/NEA Report]

Fuel Cycle Scheme	Power from Pressurized Water Reactors (PWRs)	Power from Fast Reactors (FRs)	Natural Uranium Utilization**	Recovered Reprocessed Uranium (REPU)**
Once through	100%	0%	100	
Mono-recycling of Pu in PWRs	100%	0%	89.0%	8.12%
Mono-recycling of Pu + Np in PWRs	100%	0%	89.5%	8.30%
Multi-recycling of Pu in PWRs	100%	0%	86.6%	8.90%
Multi-recycling of Pu + Am in PWRs	100%	0%	99.4%	8.86%
Multi-recycling of Pu in FRs (CR* = 1.0, i.e., "breeder")	44%	56%	44.1%	5.26%
TRU Burning in FRs (CR* = 1.0, i.e., "breeder")	0%	100%	N/A***	N/A***
TRU Burning in FRs (CR* = 0.5, i.e., "burner")	63.2%	36.8%	62.7%	6.82%

* CR = Conversion Ratio
** Relative to the natural utilization factor of 100 for the once-through fuel cycle
*** Use of existing stockpiles of depleted uranium

As can be seen in Table 5-1, mono-recycling of Pu (or Pu + Np) in PWRs leads to savings of ~11% in natural uranium resources and, at least as a first approximation, to additional savings of ~8% by recycling reprocessed uranium (REPU). Such recycling is technically and economically

feasible in LWRs that are currently operating, as it has already been implemented on an industrial scale in several countries. Additional details can be found in OECD NEA Report No. 6017 "Management of Recyclable Fissile and Fertile Materials" [OECD 2007]. Experience gained by the KKG utility in Switzerland is documented in Appendix D of this OECD/NEA report.

Multi-recycling of Pu in PWRs leads to some incremental gains, while multi-recycling of Am together with Pu does not yield any benefits in terms of natural uranium utilization, except through re-use of reprocessed uranium.

If Pu is recycled in FRs, instead of in LWRs, the savings are approximately equal to the fraction of power generated by fast reactors.

Fission Products and TRU Going to Geologic Disposal [Adapted from OECD/NEA Report]

Tables 5-2 and 5-3 provide mass flows going to direct geologic disposal on an annual basis assuming cooling times of 5 years and 50 years.

Table 5-2
Yearly TRU and Fission Product Inventories Going to Final Disposal [Assumes 0.1% loss for separation processes and 5-Year Cooling Time]

Fuel Cycle Scheme	Pu in kg/TWhe	Np in kg/TWhe	Am in kg/TWhe	Cm in kg/TWhe	TRU in kg/TWhe	FP in kg/TWhe
Once through	26	1.9	1.6	0.28	29.8	130
Mono-recycling of Pu in PWRs	15.2	1.74	2.8	0.58	20.3	131
Mono-recycling of Pu + Np in PWRs	16.8	0.84	2.83	0.54	21.0	130
Multi-recycling of Pu in PWRs	0.07*	1.6	5.9	1.3	8.9	128
Multi-recycling of Pu + Am in PWRs	0.07*	1.7	0.008*	2.825	4.6	129
Multi-recycling of Pu in FRs (CR = 1.0)	0.08*	1.0	2.55	0.3	3.9	101
TRU Burning in FRs (CR = 1.0)	0.14*	0.0007*	0.0062*	0.0015*	0.15*	98.4
TRU Burning in FRs (CR = 0.5)	0.08*	0.0027*	0.0060*	0.0026*	0.095*	117.5

* Assuming a 1% (instead of 0.1%) loss for the separation processes would result in a mass ten times greater than those shown in the table for those transuranics that are multi-recycled (or burned).

The effect of cooling on TRU masses is shown in Table 5-3 in which the TRU inventories are shown for both 5 and 50 years of cooling time.

Table 5-3
Yearly TRU Inventories Going to Final Disposal after 5- and 50-Year Cooling Time [Assumes 0.1% loss for separation processes]

Fuel Cycle Scheme	Pu in kg/TWhe		Np in kg/TWhe		Am in kg/TWhe		Cm in kg/TWhe	
	5 yr	50 yr	5 yr	50 yr	5 yr	50 yr	5 yr	50 yr
Once through	26	23	1.9	2.1	1.6	4.2	0.28	0.07
Mono-recycling of Pu in PWRs	15.2	13.5	1.74	1.93	2.8	4.6	0.58	0.17
Multi-recycling of Pu in PWRs	0.07	1.03	1.6	1.84	5.9	5.7	1.3	0.26

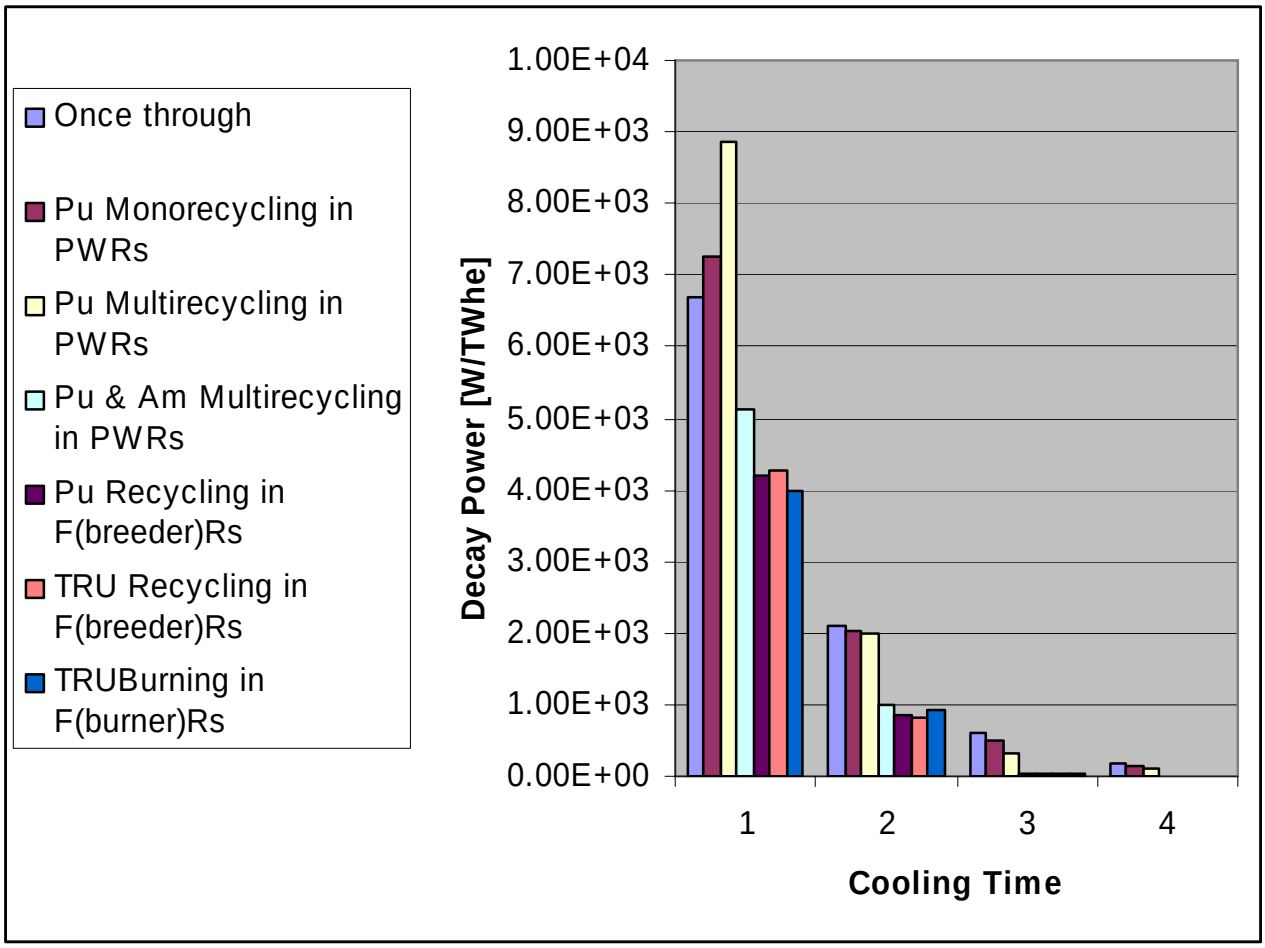
As can be seen, benefits to waste disposal are realized only when multi-recycling of specific transuranics (or its equivalent denoted as “burning”) is implemented. Mono- or multi-recycling of only Pu leads to increased quantities of higher actinides, Am and Cm, especially when recycling in done in PWRs. Based on equilibrium conditions, the advantages of fully closing the fuel cycle (schemes highlighted in blue) are also apparent by looking at the transuranics mass flows, which are lower by two or three orders of magnitude compared to the once-through fuel cycle and its variants (schemes highlighted in yellow).

Also, given the higher efficiencies of fast reactors, it should be noted that the shift from an all-PWR to an all-FR reactor system reduces the fission-product mass flow by ~30%.

Decay Heat

An important effect of partially closing or fully closing the fuel cycle is to reduce the total decay heat. Decay heat power of annual high-level waste (including spent fuel) masses going to direct geologic disposal is shown in Figure 5-1.

Figure 5-1
Decay Power of Spent Fuel and HLW as a Function of Cooling Time: 1 = 5 years; 2 = 50 years; 3 = 200 years; 4 = 1000 years



To achieve very low residual decay powers after a cooling time of 200 years, multi-recycling of Pu + Am is needed in PWRs while multi-recycling of only Pu in FRs is sufficient.

Radiotoxicity

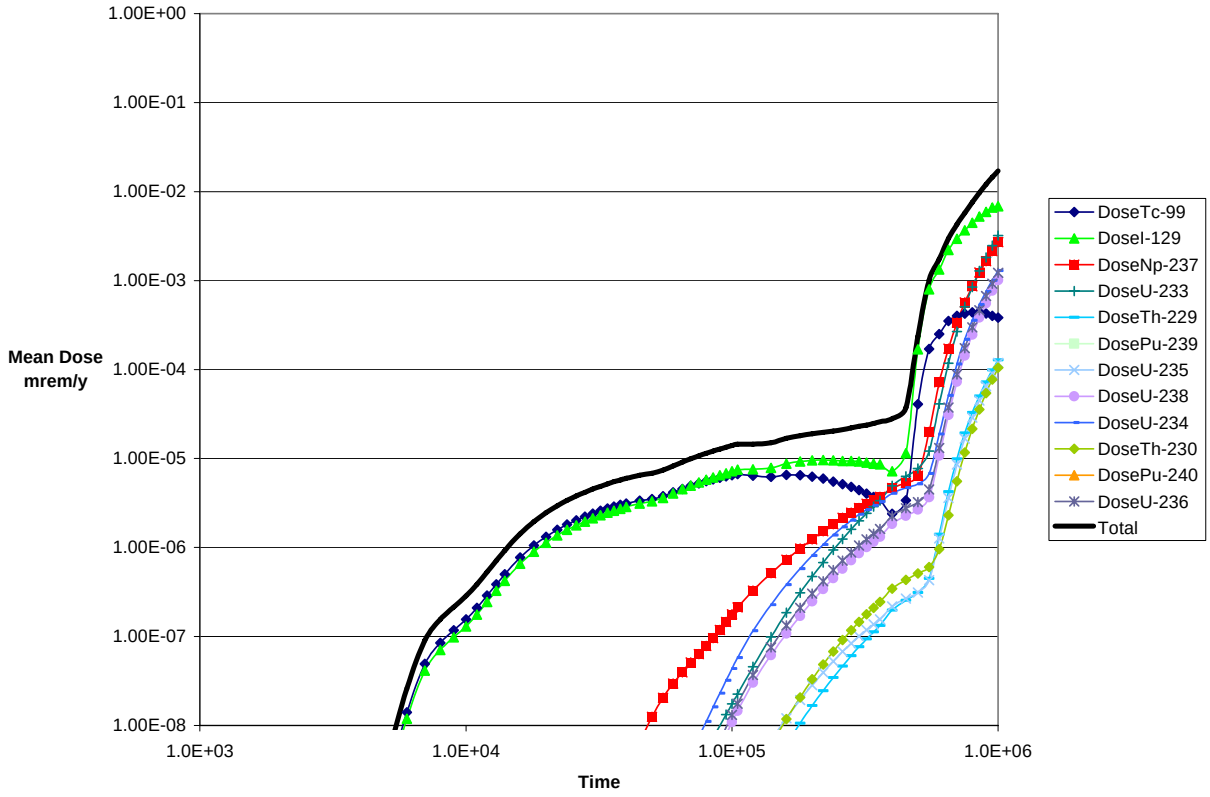
Potential radiotoxicity is often used as an indicator of waste management effectiveness for comparative assessment purpose. This is, however, an incomplete indicator as the long term environmental impact of the disposed HLW depends on:

- Its inventory as a result of the nuclear power plants fleet composition (reactor types) and selected fuel cycle strategy, and
- The solubility and migration of the elements in the selected geological site.

As a result, the relative radiological impact of each of the nuclides contained in the disposed HLW varies depending on the repository concept and the type of host rock.

This is illustrated in Figure 5-2, which illustrates that the dominant dose contributions for the Yucca Mountain site are from Tc-99 and I-129 up to several hundred thousand years, and I-129 beyond 1,000,000 years. It is interesting to note that, in present-day reprocessing plants, a substantial fraction (Tc-99) or the entire inventory (I-129) of these two nuclides are being managed by release and dispersal into the environment. This requires that the present generation of reprocessing plants be located on sites with favorable dispersion characteristics.

Fig 5-2
Mean dose as a function of time [Calculated with EPRI's TSPA Tool, IMARC]



Inventory Buildup

As previously noted, fuel cycle scenarios that belong in the Family 2 (full closure for Pu, but only partial, if any, closure for the minor actinides) and 3 (full closure for all transuranics) leads to high in-pile and out-of-pile TRU inventories.

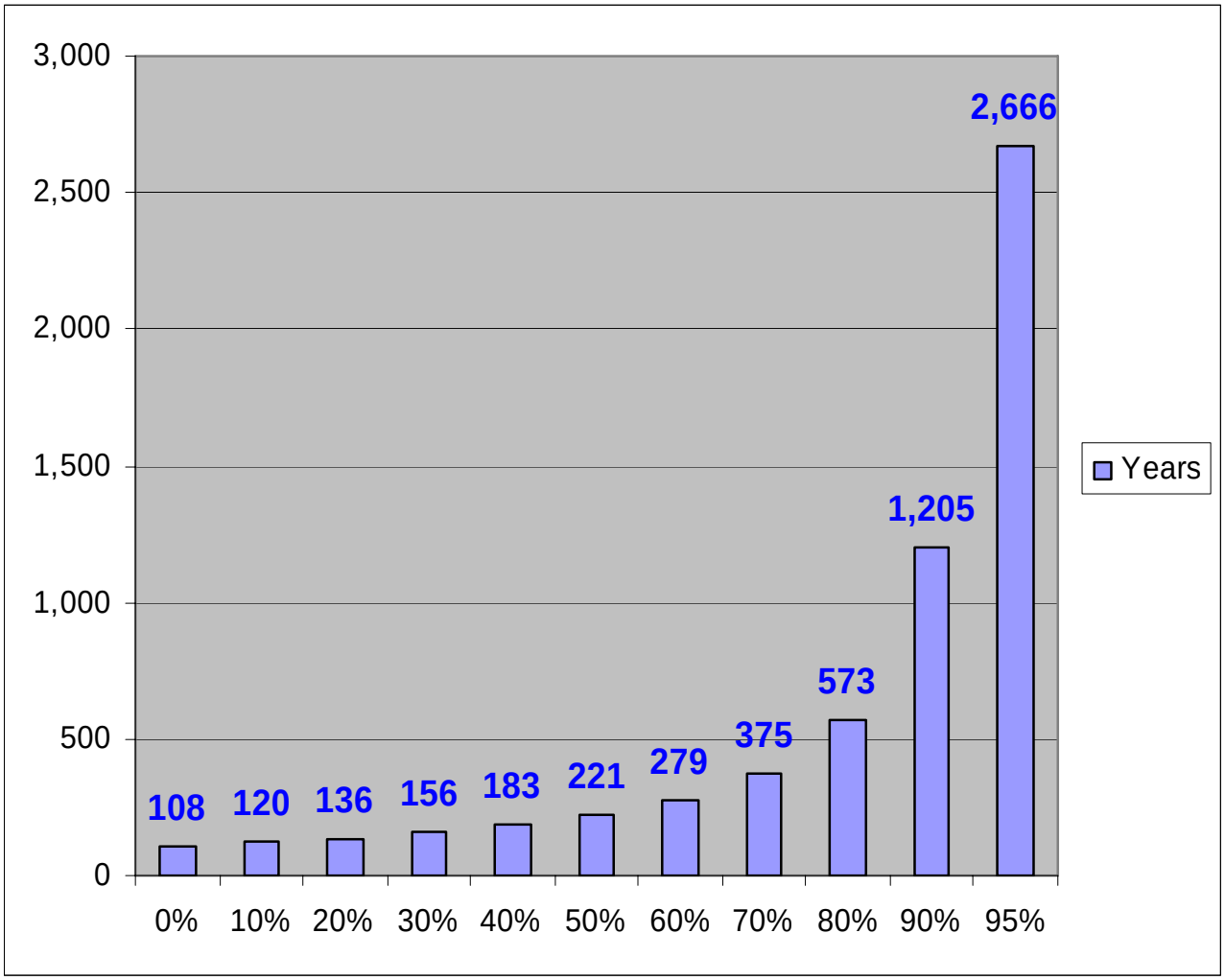
Calculated TRU inventories in various fuel cycles and annual TRU inventories in the wastes are shown in Table 5-4.

Table 5-4
Fuel Cycle TRU Inventories and Annual TRU Inventories Going to Direct Waste Disposal [Adapted from CEA Report on "Synthèses des Résultats des Recherches sur les Axes 1 et 3," 2005] – Amounts Normalized to 8.76 TWhe

Fuel Cycle →	Once-through in PWRs	Mono-recycling of Pu in PWRs	Multi-recycling of Pu in PWRs	TRU Burning in F breeder Rs
TRU Content Going to HLW Repository Assuming 0.1% Loss in Separation Processes [kg/year]				
Pu	230	153	0.37	1.25
Np	16.2	16.6	14.45	0.0066
Am	***6.35***	16.2	39.4	***0.055***
Cm	3.3	8.1	19.7	0.013
Cycle Inventory (Reactors + fabrication + reprocessing) [kg]				
Pu	767	3,285	4,818	17,520
Np	53	131	116	88
Am	***22***	88	307	***701***
Cm	11	44	158	175

The adoption of multi-recycling leads to a big reduction in the mass of TRU wastes, but this reduction is counterbalanced by the large increase in inventory in the fuel cycle (fuel facilities, reactors, storage, transport). As an example, comparing the once-through fuel cycle to TRU burning in fast breeder reactor cycle, the amount in americium-bearing waste is reduced by a factor of 6.35/0.055, i.e., greater than 100. However, assuming shutdown of the technology, the americium-bearing waste inventory would be 22 and 701 kg for the once-through and TRU-burning fuel cycle, respectively. To balance for this accumulation of 701 – 22 = 679 kg of Am wastes, equilibrium conditions would have to have been maintained for 108 years, obtained by dividing 679 by (6.35 – 0.055); the latter term represents the net annual mass flow of Am-bearing wastes going to the repository when compared once-through to multi-recycling of TRUs in fast breeder reactors. Figure 5-3 shows the number of years required to achieve parity and different levels of reduction factor on Am-bearing waste mass. In conclusion, the benefits of minor actinide multi-recycling are relevant only in the context of long-lasting, i.e., several hundreds or thousands of years, reliance on the technology.

Figure 5-3
Years Required for Parity (0%) and Achieving Various Reduction Factors (from 10% to 95%) for Americium-bearing Wastes



Dynamic System Simulation

Dynamic system simulations have been recently performed and published by Electricité de France. Of specific interest is the study by S. Massara et al. ["*Fast Breeder Reactor Scenarios of Nuclear Energy Evolution over the World Scale*" by S. Massara, P. Tetart, D. Lecarpentier, C. Garzenne, 15th International Conference on Nuclear Engineering, Nagoya, Japan, April 22-26, 2007]. Among the conclusions reached in this study, the following one is worth mentioning with regard to minor actinide recycling in fast breeder reactors (FBRs):

- Adoption of a multi-recycling strategy allows deploying 7% additional FBR capacity
- Multi-recycling allows a stabilization of TRU waste to be stored in a geologic formation
- This reduction is counterbalanced by an increased minor actinide inventory in the fuel cycle. Thus, higher doses are associated with both the fresh and spent fuels because of the presence of minor actinides (See Table 5-5 for an illustrative example of the impact

of adding 1% in minor actinide on heat load, gamma dose and neutron source term in fresh fast reactor fuel).

- The reduction factor on TRU mass if minor actinides are multi-recycled is very low (~5% by 2100 for a high-growth scenario resulting in ~5,700 GWe worldwide in 2100)
- The benefits of multi-recycling vs. direct disposal are relevant only in the prospective of a long-lasting nuclear era based upon operation of FBRs during several hundreds (or thousands) of years.
- Advantages and drawbacks of minor actinide multi-recycling have to be weighted in the framework of a cost-benefit analysis, integrating the impact of the presence of minor actinides on the unit costs for each of the fuel cycle operations.

Table 5-5
Impact of Adding 1% of Minor Actinides in Fresh Fast Reactor Assembly

Minor Actinide Content		+1% Np	+1% Am	+1% Cm
Fabrication	Heat Release	x 1	+ 30%	x 10
	γ Dose	x 2	x 30	x 200
	Neutron Source Term	x 1	+ 15%	x 700

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CONCLUSIONS

Potential benefits and drawbacks of reprocessing/recycling of spent light-water reactor (LWR) fuel are presently being debated in the U.S. as a result of several international and domestic developments including (a) international efforts to reduce global proliferation risks through a number of international initiatives, such as the Global Nuclear Energy Partnership (GNEP); (b) continuing delays with the licensing of the proposed Yucca Mountain geologic repository; and (c) DOE's mandate for making a recommendation for a second U.S. repository by 2010.

Adopting a slightly modified version of OECD NEA's approach, nuclear fuel cycles can be divided into three main families. The first family includes the current once-through fuel cycle and schemes with only one fuel recycling (mono-recycling of plutonium or plutonium + neptunium) in light-water reactors. These fuel cycles represent current industrial technology and readily implementable extensions. The second family, consisting of schemes with partially closed fuel cycles, includes multi-recycling of plutonium, possibly in different types of reactors (light-water reactors, fast reactors, and possibly others), but with different schemes in the treatment of minor actinides. The third family, consisting of fully closed fuel cycles, includes schemes in which all transuranics (plutonium, neptunium, americium, and curium) are multi-recycled until they eventually fission. This can be pursued in different types of reactors.

Equilibrium system simulation of nuclear energy systems show that it is possible to envision a strategic progression towards maximal use of uranium resources and maximal reduction of the waste source term; for example, by moving from the once-through fuel cycle to multiple recycling of plutonium in fast reactors to multiple recycling of all transuranics in fast reactors. However, multi-recycling leads to high in-pile and out-of-pile transuranics inventories impacting generation operations and costs. When reactors are eventually phased out, transuranics inventories may become an important contributor to the waste legacy. This may require recycling unwanted long-lived species in dedicated "burner" reactors, accelerator-driven systems, or some other suitable systems, during the phase-out phase.

Integrated process models dynamically simulating nuclear energy systems from uranium mining to final disposal of the wastes are needed to properly conduct comprehensive assessments of nuclear energy system strategies and to select the most promising development paths, taking into account that each country may be facing a different situation with regards to:

- Global energy mix and energy policy
- Availability of fissile materials resources
- Nuclear power fleet and inventory of radioactive materials (including legacy waste) resulting from past and present waste management practices
- Choice and capacity of candidate geologic formations chosen for ultimate disposal, and
- Public (and political) support for nuclear energy.

The objective of the EPRI program is to develop a sound, technically based strategy for the future of a sustainable nuclear energy fuel cycle. In 2007, two projects have been initiated with Electricité de France and the Massachusetts Institute of Technology to achieve this objective.

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