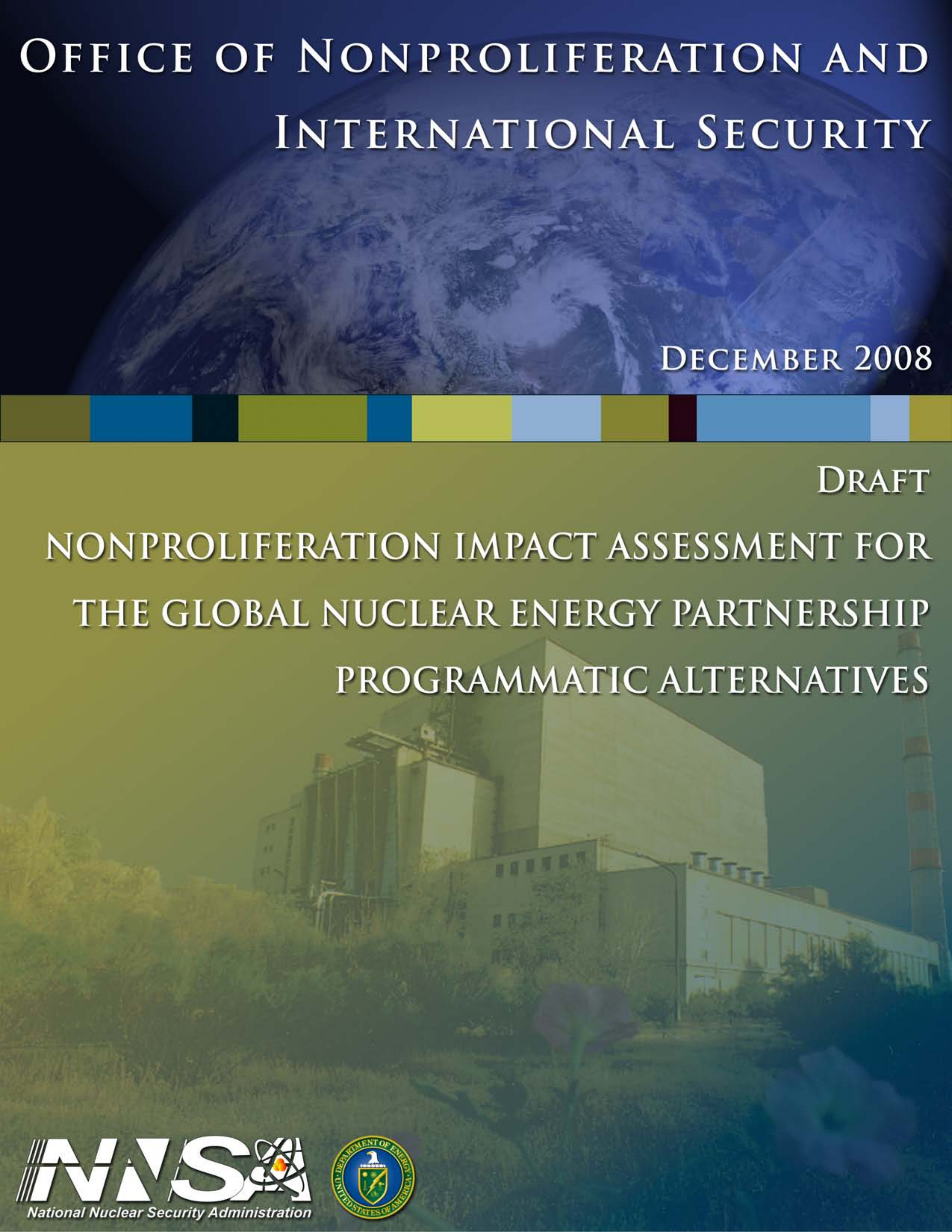

OFFICE OF NONPROLIFERATION AND INTERNATIONAL SECURITY

DECEMBER 2008

DRAFT

NONPROLIFERATION IMPACT ASSESSMENT FOR THE GLOBAL NUCLEAR ENERGY PARTNERSHIP PROGRAMMATIC ALTERNATIVES

National Nuclear Security Administration

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EXECUTIVE SUMMARY

Draft Nonproliferation Impact Assessment:

Companion to the Global Nuclear Energy Partnership Programmatic Environmental Impact Statement

1. Introduction

Secretary of Energy Bodman announced the Global Nuclear Energy Partnership (GNEP) in February 2006 as part of President Bush's Advanced Energy Initiative. GNEP aims to support the expansion of nuclear energy while reducing the associated nuclear waste impacts and risks of nuclear proliferation.

In parallel to the Department of Energy's GNEP Programmatic Environmental Impact Statement (PEIS), which analyzes the environmental impacts of a range of nuclear fuel cycle alternatives, this Nonproliferation Impact Assessment (NPIA) analyzes the same alternatives based on their potential impacts on the risk of nuclear proliferation and the ability to advance U.S. nonproliferation goals.

Although the completion of an NPIA is not a legal requirement, both the PEIS and NPIA documents, along with other information, will support a decision on the future course of the GNEP program. Similar assessments of proliferation impact have been conducted previously by the Department of Energy in connection with other major nuclear projects.

2. Scope

This draft NPIA is a comparative assessment of a range of alternatives. Its purpose is to establish a framework for evaluating the nonproliferation characteristics of the nuclear energy technologies evaluated as part of fuel cycle alternatives in the GNEP PEIS. It is not an evaluation of the purpose and need of the GNEP concept or program.

Further, this draft NPIA is prepared for information and evaluation purposes only, and does not represent any decision, plan or proposal by the Department of Energy with regard to any of the actions or possible alternatives addressed in the draft NPIA. Any such actions or potential actions by the Department of Energy or the U.S. Government as expressed in the draft NPIA are subject to further evaluation and decision-making in compliance with applicable laws, regulations, and policies of the U.S. Government.

This framework addresses two primary analytical variables: (1) the ability of alternative nuclear fuel cycles to support established nuclear nonproliferation policy objectives, and (2) a technical evaluation of the nonproliferation features of the alternative processes and technologies.

The programmatic alternatives for the domestic nuclear fuel cycle identified in the PEIS vary widely in reactor type, fuel type, and processing of spent fuel. For the purposes of this assessment, these alternatives fall into three broad categories:[1]

- **<u>Once Through</u>**: In these alternatives, fuel is used once in reactors, after which spent fuel[2] is treated as waste, and is stored and eventually disposed of in a geologic repository. The alternatives under consideration use uranium-based or uranium/thorium-based fuel in thermal-neutron reactors. The alternatives in this category are:

  (1) No action alternative – existing once-through uranium fuel cycle;
  (2) Thorium alternative;
  (3) Heavy water reactor (HWR) (HWR/HTGR Alternative Option 1); and
  (4) High-temperature gas-cooled reactor (HTGR) (HWR/HTGR Alternative Option 2).

- **<u>Full Actinide Recycle</u>**: In these alternatives, spent fuel from light-water reactors is reprocessed, and transuranic elements are removed from the waste stream and recycled. The ability to minimize long-term waste hazards and treat spent fuel as a resource by consuming transuranics in fast neutron reactors may alter proliferation risk. The alternatives in this category are:

  (1) Fast reactor recycle alternative; and
  (2) Thermal/fast reactor recycle alternative.[3]

- **<u>Partial Actinide Recycle</u>**: In these alternatives, spent fuel from light-water reactors is recycled in thermal-neutron reactors. Some of the transuranic elements are removed from the waste stream and recycled, but a significant portion remains in the waste stream. The ability to treat spent fuel as a resource may alter proliferation risk. The alternatives in this category are:

  (1) LWR recycle of reprocessed plutonium (Thermal Reactor Recycle Alternative Option 1);
  (2) Deep Burn HTGR recycle of reprocessed transuranic elements (Thermal Reactor Recycle Alternative Option 3); and
  (3) DUPIC[4] – HWR recycle of LWR spent fuel without separation of plutonium (Thermal Reactor Recycle Alternative Option 2).

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[1] This draft NPIA considers the same set of options and alternatives as the draft PEIS. Whereas the draft PEIS identifies “Options” under two of the “Alternatives,” the draft NPIA treats them all equally as “alternatives.” The correspondence of the draft NPIA alternatives to draft PEIS options is identified below.

[2] Spent fuel and spent nuclear fuel are used interchangeably in this assessment.

[3] In this assessment, thermal and fast reactor recycle is evaluated under the assumption that the transition to full actinide recycle is successful. The possibility of not accomplishing this transition is also discussed in Chapter 6.

3. Proliferation Risk

The risk of nuclear proliferation is inherent in the use of nuclear energy. The same underlying fission process that is used in nuclear power plants to produce electricity can also be used in nuclear weapons to produce explosions. The principal risks of nuclear proliferation come from the technical characteristics of the nuclear fuel cycle and how the fuel cycle is organized internationally. Fuel for the U.S. fleet of 104 LWRs must be enriched to a uranium-235 (U-235) concentration of 3-5%, which is far too low for use in a nuclear weapon. However, the *enrichment* processes used in LWR fuel production can also be used to produce high-enriched uranium for use in weapons.

Use of nuclear fuel in a reactor generates plutonium, which also can be used both in reactor fuel and in nuclear weapons. However, both of these uses require *reprocessing* of the spent reactor fuel.[5] Thus, recycling plutonium at the back end of the fuel cycle carries similar proliferation risks to enrichment of uranium at the front end.

Proliferation challenges arise in the context of both states seeking nuclear weapons and non-state actors that harbor similar aims or seek to exploit vulnerabilities in the security of nuclear facilities or materials to carry out acts of nuclear terrorism or to traffic in materials and technology on the international black market. These challenges make clear that improved mechanisms for impeding the spread of enrichment and reprocessing capabilities and for detecting and deterring proliferation or nuclear terrorism are needed.[6]

4. Proliferation Risk Assessment

One approach for reducing proliferation risk is to seek to build "proliferation resistance" into both nuclear facilities and the structure of the international nuclear fuel cycle. It is important to recognize that it is not possible to make any system completely "proliferation proof." Rather, the term "proliferation resistance" should be understood, and is used in this assessment, as a systems approach to reduction of risk through a combination of intrinsic features (*e.g.,* physical and engineering features of a nuclear energy technology) and extrinsic measures (*e.g.,* safeguards and physical barriers) that make it harder to divert or misuse nuclear materials or facilities without detection. Proliferation resistance includes institutional arrangements that may deter states from proliferation if they consider the political or strategic costs to exceed the potential benefit. This definition draws from that adopted in 2002 by the Generation IV Working Group on Proliferation Resistance and Physical Protection (PR/PP)[7] and is discussed in Chapter 3.

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[4] DUPIC stands for the Direct Use of spent PWR (pressurized water reactor) fuel in CANDU (Canada Deuterium Uranium) reactors.

[5] Reprocessing normally separates all or most of the uranium and plutonium from one another and from other constituents of spent fuel. Chapter 5 discusses partial separation processes in more detail. The term "recycling" encompasses both separation ("reprocessing") and the reuse of the separated product.

[6] The existing international framework of agreements, guidelines and norms for nuclear nonproliferation are discussed in Section 2.1.

[7] http://www.gen-4.org/Technology/horizontal/proliferation.htm and "Framework for Proliferation Resistance and Physical Protection for Nonproliferation Impact Assessments," Robert Bari, BNL-80083, Brookhaven National Laboratory Formal Report, March 2008.

This draft NPIA draws on U.S. Government nonproliferation objectives as the basis for a *policy evaluation* of proliferation risk, and on the PR/PP methodology as the basis for a *technical evaluation* of proliferation risk. However, because of its broad, programmatic nature, the GNEP PEIS does not include all the technical detail necessary to evaluate fully the potential nonproliferation impacts of the identified alternatives. Those details include the specific technologies to be deployed, the timing and scale of that deployment, and other important technical details, such as the form and quantity of fuel recycled, the location of facilities, and transport of nuclear materials, including spent and recycled fuel. Future assessments of nonproliferation impact may be prepared to inform decisions on implementing any of the GNEP PEIS programmatic alternatives and as both research and development programs and the PR/PP methodology evolve.

5. Nonproliferation Objectives

Advancing nonproliferation and nuclear security interests requires a combination of policy and technological innovation. Analysis limited to policy alone may make unrealistic assumptions of what is technically feasible, whereas analysis limited to technology alone may overlook opportunities for institutional arrangements that reduce proliferation risks. This draft NPIA attempts to blend those elements through what is termed a "policy effects" analysis. It evaluates objectives that may have significant nonproliferation impact and compares technical proliferation risks and nonproliferation benefits in the GNEP PEIS alternatives.

Specific nonproliferation policy objectives include:

1. *Limiting the further spread of enrichment and reprocessing*. In support of this objective, the United States is considering concepts for comprehensive fuel services arrangements as an alternative for countries that might otherwise consider developing their own uranium enrichment or spent fuel reprocessing facilities.[8] The comprehensive fuel services concept would include assured supply of fresh fuel, but the key innovation is that it also contemplates return of the spent fuel from the recipient country, though not necessarily to the same country that supplied the fresh fuel.

2. *Halting the build-up and eventually drawing down stocks of separated plutonium.* Current stocks of separated civil plutonium total roughly 250 metric tons worldwide, largely as a result of an imbalance between the reprocessing and reuse of such materials in reactors. The extent to which a fuel cycle alternative avoids accumulating separated plutonium or other weapons-usable material and whether it facilitates the drawdown of existing stocks of separated plutonium are considered.

3. *Developing and promoting reactors and fuel cycles with reduced proliferation and security risks*. Mitigating this risk depends on both the technologies and materials used and arrangements for their use or transport. The anticipated expansion of

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[8] The draft PEIS describes one potential concept for comprehensive fuel services, referred to as the Reliable Fuel Services Program.

nuclear energy offers the opportunity to develop and deploy innovative nuclear reactors, fuels, and related technologies with increased proliferation resistance.

4. *Improving international safeguards approaches to verify that countries are not misusing nuclear energy for weapons purposes.* GNEP safeguards activities focus on the new types of reactors and spent fuel recycling facilities contemplated under the GNEP program, as well as improving the effectiveness and efficiency of the application of safeguards, export controls, and physical protection.

Because the nonproliferation objectives of GNEP are inherently international in scope and intended impact, this draft NPIA considers additional policy factors, including U.S. leadership and our ability to impact the decisions of other countries with respect to the nuclear fuel cycle and the extent to which international safeguards are strengthened and robust nuclear infrastructures are implemented by states beginning or expanding nuclear energy development.

Choices the United States makes with respect to domestic nuclear energy are also important. Because of the pivotal role the United States plays in leading international efforts to prevent proliferation and setting high standards for safety and security, the manner in which the United States manages its fuel cycle will inevitably influence the decisions and actions of others. Over the last six decades, the United States has led every significant effort to erect, refine and strengthen the current system of interlocking, international obligations and national commitments that make up the global nonproliferation system. This includes:

- International treaties, particularly the Nuclear Non-Proliferation Treaty (NPT);
- International organizations, particularly the International Atomic Energy Agency (IAEA);
- Domestic laws, particularly the Atomic Energy Act of 1954 and the Nuclear Non-Proliferation Act of 1978;
- Export control measures, enforced through national laws, regulations, and the policies articulated in Nuclear Suppliers Group Guidelines;
- International safeguards, implemented by the IAEA in cooperation with its member states, to verify that nuclear material is not diverted from peaceful uses; and
- Physical protection, particularly the Convention on the Physical Protection of Nuclear Materials and Facilities and international guidelines adopted by the IAEA, as well as national measures to secure nuclear material and facilities from threats posed by non-state actors.

A key aim of U.S. nonproliferation policy looking forward will be to limit the further spread of enrichment and reprocessing technologies. In support of this objective, the United States is considering concepts for comprehensive fuel services arrangements, such as the Reliable Fuel Services Program described in the GNEP draft PEIS. This type of arrangement would offer countries a viable alternative to the development of indigenous nuclear fuel cycle programs. The U.S. ability to participate in and influence the development of such comprehensive fuel services would be stronger if the United States were active internationally in the spent fuel services market. Comprehensive fuel service arrangements that include the removal of spent fuel from a recipient country could be a significant incentive for that country to refrain from developing enrichment capabilities, which is currently the greatest proliferation concern. However, this benefit would need to be balanced against possible negative outcomes, as summarized below.

6. Comparison of Alternatives

Table 1 presents a side-by-side descriptive comparison of the three categories of fuel cycle alternatives, based on the policy factors outlined above. The assessments are based on a combination of technical analysis and expert judgment. A more detailed assessment of the nonproliferation impacts of the GNEP programmatic alternatives is presented in Chapter 6.

Nonproliferation Impacts	**Once-Through Fuel Cycle**	**Full Actinide Recycle**	**Partial Actinide Recycle**
Fuel Cycle *Direct influence on international comprehensive fuel services and incentives to refrain from enrichment and reprocessing*	*Lowest* influence: *Greatest* barrier to U.S. participation in comprehensive fuel services. Spent fuel has the highest long-term radiotoxicity. *Higher* demand for enrichment services, particularly for thorium and HTGR options.	*Highest* influence: *Lowest* barrier to U.S. participation in comprehensive fuel services. Minimizes long-term radiotoxicity and treats spent fuel as energy resource. *Lower* demand for enrichment services.	*Intermediate* influence: *Intermediate* barrier to U.S. participation in comprehensive fuel services. Treats spent fuel as energy resource, but offers limited reduction in long-term radiotoxicity. *Lower* demand for enrichment services.
Fuel Cycle *International fuel cycle policy*	*Mixed*: Could reinforce efforts to discourage reprocessing, but unlikely to influence countries that are already pursuing reprocessing.	*Mixed*: Could encourage a major transformation in how commercial reprocessing is carried out, but could reduce ability to argue that reprocessing is unnecessary.	*Lower*: Could encourage an incremental change in commercial reprocessing practices, but could reduce ability to argue that reprocessing is unnecessary. *Mixed* for DUPIC.
Fuel Cycle *Inherent proliferation risk of technology*	*Lowest* risk: Does not create technical basis for separating weapons-usable material from spent fuel.	*Highest* risk: Capable of separating weapons-usable material, though some modification may be needed depending on the	*Highest* risk: Capable of separating weapons-usable material, though some modification may be needed depending on the

	HWRs have *higher* risk of misuse.	separations technology used.	separations technology used. DUPIC has *low* risk because it involves limited separation, although HWRs have *higher* risk of misuse.
Plutonium Stocks	*No improvement*: Reactors could use existing plutonium stocks in MOX fuel, but are not currently licensed to do so.	*Potential significant reduction*: Recycling creates a market for plutonium-bearing fuel. Fast reactor startup would require large quantities of plutonium.	*Potential reduction*: Recycling separated plutonium creates a market for plutonium-bearing fuel. DUPIC alternative is *no improvement* since it would not reduce separated plutonium stocks.
Material Attractiveness	*Lowest*: Spent fuel is bulky and highly radioactive, though radioactivity decays over many decades. HWR spent fuel bundles are smaller and radioactivity decreases more quickly. HTGR spent fuel is difficult to reprocess. Enrichment of fresh fuel varies, but all is LEU.	*Highest*: Removal of fission products and separation of actinides greatly reduces barriers to theft, misuse, or further processing, even without separation of pure plutonium. Fast reactor fuels have higher concentration of weapons-usable materials.	*Highest*: Removal of fission products and separation of actinides greatly reduces barriers to theft, misuse, or further processing, even without separation of pure plutonium. Thermal reactor fuels have lower concentration of weapons-usable materials. *Low* for DUPIC, which has limited removal of fission products.
Safeguards	*Lowest* cost and difficulty: Spent fuel assemblies can be tracked as items. Costs are significantly *higher* for HWRs. *Low to medium* cost and difficulty for thorium or HTGR, which require new safeguards approach.	*Highest* cost and difficulty: Separation processes require continuous monitoring against diversion and novel bulk materials present new measurement challenges. Novel processes may provide new opportunities to detect misuse.	*High* cost and difficulty: Separation processes require continuous monitoring against diversion; bulk material measurement presents familiar challenges. A safeguards approach has been developed for DUPIC.

TABLE 1 Policy Assessment of GNEP Programmatic Alternatives

6.1 Direct Impact on Fuel Cycle: This factor addresses the ability of the United States to affect other countries' fuel cycle practices, particularly by participating in comprehensive fuel services arrangements to discourage the spread of enrichment and reprocessing. Having the capability to participate in such arrangements by accepting other countries' spent fuel for reprocessing and disposal, i.e., back-end fuel services, would offer two significant nonproliferation benefits: (1) it would provide the basis for comprehensive fuel services as an incentive for countries to refrain from sensitive fuel cycle activities, and (2) it would reduce the latent proliferation risk of spent fuel by drawing down and consolidating accumulations worldwide.

By this measure, the full actinide recycle alternatives have the advantage that they would provide the strongest basis for U.S. participation in back-end fuel services. Specifically, these alternatives would reduce technical barriers – and so could also reduce political barriers – to offering back-end fuel services by reducing long-term waste hazards dramatically. Removing plutonium and the other transuranic elements of spent fuel (except for minor process losses) from the waste stream would drop the radiotoxicity of the resulting waste to the level of natural uranium in ore within about 500 years, compared to over 250,000 years for the no action alternative.

Partial actinide recycle alternatives would not achieve as dramatic long-term radiotoxicity reductions but could provide a basis for treating foreign spent fuel as an energy resource. This could help reduce barriers to U.S. participation in back-end fuel services, particularly if accompanied by acceptable arrangements to store and/or dispose of high-level waste from reprocessing outside the United States.

Conceptually, a once-through fuel cycle could also permit acceptance of foreign nations' spent fuel, but only for geologic disposal or storage pending availability of a disposal facility. That approach would be feasible technically but would be limited by policy and legal constraints and may face challenges in gaining public acceptance.

Compared to either the full or partial actinide recycle alternatives, a once-through fuel cycle would also create the greatest demand for uranium enrichment services, which could create incentives for countries to develop indigenous enrichment capabilities. One way to reduce this risk would be to promote a major expansion of enrichment capability in the United States or other countries that currently provide international enrichment services.

6.2 Policy Impact on Fuel Cycle: This factor addresses the ability of the United States to influence other countries' fuel cycle policies.

The once-through fuel cycle aims to achieve this by demonstrating that reprocessing is not a necessary part of the civilian fuel cycle. A DUPIC fuel cycle, which recycles with only limited separation of fission products, may offer the same benefit. Proponents point out that since the United States adopted a once-through fuel cycle policy in the 1970s, no additional countries have started reprocessing programs for civilian purposes, and several countries have ended their reprocessing programs. However, U.S. opposition has not slowed large-scale reprocessing programs in Europe, Japan, and Russia and has limited U.S. opportunities to influence how those programs are carried out.

Economics has also played a role in limiting the spread of reprocessing capability. The historically low price of uranium and high capital cost of large-scale reprocessing make recycle non-competitive. If the price of uranium remains high, or if other factors such as energy security or waste management are seen as justifying the cost, then economics may no longer be sufficient to discourage the spread of reprocessing. In this circumstance, the continuing concerns in the United States regarding spent fuel management and disposition may raise questions internationally about whether a once-through fuel cycle is sustainable.

Existing spent fuel reprocessing programs in other countries (e.g., France and Japan) are based on partial actinide recycling processes that offer relatively limited energy security or long-term radiotoxicity reduction benefits to offset other attributes such as proliferation risk. By pursuing full actinide recycle, the United States could set a higher standard for international reprocessing services. Undertaking a partial recycle alternative in the United States would not set this higher standard, although it would avoid separation of pure plutonium.

6.3 Inherent Proliferation Risk of Fuel Cycle Technology: This factor addresses the risk that technologies used in the civil nuclear fuel cycle could be used, either directly or with modifications, to support production of weapons-usable materials.

The greatest proliferation risks associated with proposed technologies are those related to chemical separation of spent fuel through reprocessing. All the recycle alternatives aside from DUPIC have this inherent risk, although the cost, difficulty and detectability of any needed process modifications vary. Some of the reactor types involved also pose risks of misuse, including the misuse of heavy water reactors or potential modification of fast reactors into breeders to produce weapons-grade plutonium in their blanket fuel materials.

6.4 Plutonium Stocks: This factor addresses the ability to avoid accumulations of separated plutonium and to draw down existing stocks worldwide. Any reprocessing of spent fuel can result in an accumulation of separated plutonium or other relatively attractive weapons-usable materials. This is particularly true if the economic incentives continue to favor use of fresh uranium fuel.

The full actinide recycle alternatives all involve the use of fast reactors, which require large quantities of plutonium or other fissile material for their initial core loads. The deployment of even modest numbers of fast reactors offers the possibility of converting large quantities of separated plutonium into irradiated fuel and the greatest potential for reducing stocks of plutonium. Thermal neutron reactors can also use plutonium in mixed oxide (MOX) fuel, but most U.S. reactors are not currently licensed to use MOX.

A partial actinide recycle alternative could overcome this hurdle and facilitate the drawdown of existing plutonium stocks by creating a market for MOX fuel. The once-through and DUPIC fuel cycles would neither help nor hinder the drawdown of existing plutonium stocks.

6.5 Material Attractiveness: This factor addresses how attractive the materials used in the fuel cycle would be for use in nuclear weapons.[9] In this case the judgment is based on the most attractive materials in the fuel cycle alternative, since those are the most likely targets for theft or diversion.

For once-through fuel cycles, the weapons-usable fissionable materials in spent fuel are intermingled with uranium and highly radioactive fission products in large, bulky fuel assemblies. However, over a period of many decades the radioactivity decays and the attractiveness increases, so that an accumulation of spent fuel in a growing number of countries represents a latent proliferation risk that grows over long periods of time. If spent fuel is reprocessed the resulting plutonium-bearing product (whether pure plutonium or a blend of plutonium with other transuranics) is much more attractive. When recycled as reactor fuel, this material is typically diluted with uranium (or possibly an inert material such as zirconium), which can reduce its attractiveness significantly, depending on the relative concentrations and ease of separation of these materials.

Fast reactor fuels require a higher concentration of fissile isotopes than thermal reactor fuels and so are typically more attractive. The DUPIC fuel cycle does retain a relatively high fraction of the fission products with the actinides, leaving the material highly unattractive, but it does convert it from large fuel assemblies to a bulk powder that, while still highly radioactive, is somewhat easier to handle.

6.6 Safeguards: This factor considers how difficult it is for international safeguards to verify that nuclear materials are not diverted and that facilities are not misused.

Safeguards approaches for the once-through fuel cycle are well known and generally considered effective; enrichment plants pose a significant challenge, but are a common feature of all the alternatives. By contrast, safeguarding spent fuel reprocessing facilities is expensive and very challenging technically. Compared to the standard plutonium and uranium solvent extraction process in widespread use, many of the advanced separation processes under consideration pose new technical challenges for safeguards, but also new opportunities for detecting facility misuse. A safeguards approach for DUPIC has been developed and demonstrated, but only on a very small scale.

7. Summary

It is evident from Table 1 that the once-through and closed fuel cycle alternatives have complementary advantages and drawbacks, i.e. the strengths of one correspond to the weaknesses of the other. Once-through fuel cycle alternatives avoid production of materials that can be used in a nuclear explosive device without significant further processing, and are therefore preferable on purely technical grounds. However, this fuel

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[9] We use "material attractiveness" in the same sense it is used in "An Assessment of the Proliferation Resistance of Materials in Advanced Nuclear Fuel Cycles," C.G. Bathke et al. 8th International Conference on Facility-Operations – Safeguards Interface, March 30 – April 4, 2008, Portland OR. The term is also used in Department of Energy directives and Nuclear Regulatory Commission regulations to define physical protection requirements for facilities based on the quantity and type of material they contain.

cycle approach has proven challenging for the United States to implement, at least in the area of long-term sustainable waste management, and seriously limits the U.S. ability to participate in offering comprehensive fuel services to other countries as a tool to limit the spread of proliferation-sensitive fuel cycle technologies. Options available for strengthening this approach are, at the front end, to expand the capacity of current providers of international enrichment services, and at the back end, to pursue international, regional,[10] or possibly domestic arrangements for spent fuel storage or disposal.

Full actinide recycle alternatives produce materials with much higher intrinsic proliferation and security risk than a once-through fuel cycle, but offer opportunities to extend U.S. influence to address international fuel cycle challenges. The key to that influence is the ability to reduce dramatically long-term radiotoxicity hazards, which could help overcome political and public acceptance obstacles and make it possible for fuel suppliers collectively to offer comprehensive fuel services that include assured arrangements for acceptance and disposition of spent fuel. Such comprehensive fuel services offer a potentially transformative means to discourage the spread of both enrichment and reprocessing capabilities. The partial recycle alternatives may offer some of the benefits in this regard, but also suffer from most of the drawbacks of the closed fuel cycle alternatives.

Because the alternatives present complementary risks and benefits, this assessment does not identify a preferred alternative or alternatives. Such conclusions would depend on the relative importance policy makers would attach to each of the factors and the relative costs of each of the alternatives. Rather, this assessment aims to support a well-informed decision that recognizes the broad range of impacts that decision entails. Future decisions will likely involve specific technical choices for implementing the preferred alternative. For this purpose, it is important to continue efforts to develop, refine, and validate methods for proliferation risk assessment.

Going beyond current approaches to proliferation risk assessment, it would be valuable to convert the risk *assessment* methodology, which compares a specified set of technologies and processes, into a risk *reduction* methodology, which would provide design criteria to reduce proliferation risks. Such a methodology could be based on engineering and systems concepts developed to limit the known sources of proliferation risk.

Because of the importance of economic factors in determining the practicality of approaches to nuclear energy and fuel cycle systems, another important addition to existing proliferation risk assessment would be to address economic considerations in nonproliferation analyses. Such analyses would be designed to determine where economic pressures and nonproliferation interests may be aligned, for example, in structuring fuel service arrangements to be both viable business arrangements and attractive incentives to restrain the spread of enrichment and reprocessing.

Under any of the alternatives, it will be important to continue efforts to develop effective safeguards and international security measures, for both domestic and international use. Each of these alternatives in the GNEP PEIS, including the “no action” alternative,

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[10] In this context, “regional” refers to an international geographic region, such as East Asia.

assumes that the Department of Energy's research and development program on spent fuel recycling technologies, known as the Advanced Fuel Cycle Initiative, would continue. This program provides critical new opportunities to develop and test advanced security measures and advanced safeguards technologies and approaches. International collaborations undertaken by the Department under AFCI could also provide expanded opportunities to develop such measures, technologies, and approaches in cooperation with other countries.

1. GNEP-NPIA OVERVIEW

1.1 INTRODUCTION

Since the beginning of the atomic era at the end of World War II, the dual nature of nuclear energy has been clear. Nuclear power now accounts for roughly 15% of all electricity generation worldwide, and nuclear techniques are pervasive in medicine, agriculture, science, and industry. But nuclear energy can also lead to extraordinarily destructive weapons, and the United States has devoted considerable effort to preventing their spread. Nuclear nonproliferation – preventing the spread of nuclear weapons or other nuclear explosive devices[11] and the capability to produce them – has been a consistent theme of U.S. and international policy. In recent years, growing concerns over possible acts of nuclear terrorism have led to an expansion of nuclear security efforts to protect against the theft or unauthorized use of weapons-usable nuclear materials and sabotage of nuclear facilities and activities. Widespread expectations of a "nuclear renaissance" promise a major expansion in the use of nuclear power worldwide to meet increasing demands for electricity while limiting the future risks of climate change. This poses the challenge of minimizing the risk that such an expansion could contribute to further nuclear proliferation.

1.2 NUCLEAR ENERGY AND FUEL CYCLE

The principal proliferation risk associated with nuclear energy use comes from nuclear fuel cycle capabilities – particularly enrichment and reprocessing. Most nuclear power plants are light-water reactors that use low-enriched uranium as fuel. But the same technology used to enrich uranium for power reactors can also be used to produce high-enriched uranium for use in nuclear weapons. In addition to these risks at the front end of the fuel cycle, there are risks at the back end, after spent fuel is removed from a reactor. Spent fuel can either be disposed of as waste or reprocessed to recycle the plutonium and other fissionable materials contained in spent fuel to generate more electricity. But this same material can also be used directly in nuclear weapons. Therefore, nuclear nonproliferation efforts place a high priority on limiting the further spread of sensitive nuclear fuel cycle capabilities and the weapons-usable materials they can produce.

Currently, 30 countries operate nuclear power plants, but far fewer countries operate commercial uranium enrichment or reprocessing plants. Eight countries dominate the international market for enrichment and four of those dominate the international market for reprocessing.[12] Of these eight countries, five are nuclear weapon states. As worldwide demand for electricity grows, nuclear power is expected to spread to additional countries, and the demand for nuclear fuel cycle services is expected to grow. Two thirds of countries

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[11] In this assessment the terms "nuclear weapon" and "nuclear explosive device" are used interchangeably. A nuclear explosive device could include a deployed weapon, a test or demonstration device, a terrorist's improvised nuclear device, or an ostensibly "peaceful" nuclear explosive.

[12] The countries that operate large-scale commercial enrichment facilities are China, France, Germany, Japan, the Netherlands, Russia, the United States and the United Kingdom. Argentina and Brazil operate smaller enrichment plants. France, Japan, Russia and the United Kingdom operate commercial reprocessing plants. Enrichment and reprocessing plants in Japan and China are intended primarily to meet domestic needs.

with nuclear power plants currently rely on international markets in whole or in part to meet their nuclear fuel requirements. One goal of U.S. nonproliferation policy is to encourage countries that have or are starting nuclear power programs to continue to rely on those markets.

The current commercial market functions well to provide front-end enrichment services, providing a choice among several commercial suppliers. In addition, there are a number of uranium suppliers and fuel fabricators. The challenge looking forward is not lack of choice or availability of supply, but confidence that supply of all the components at the front end of the fuel cycle – uranium mining, conversion, enrichment, and fabrication – will keep pace with demand as the use of nuclear power surges. Historically, the lead time for expanding fuel production capacity has been shorter than that for reactor construction. Nonetheless, the perception that fuel supply may not keep pace can be an argument to build or reserve the option to build indigenous enrichment plants.

At the back end, countries have adopted a variety of strategies to approach the challenges of spent fuel management. Many countries, including the United States, have chosen a once-through fuel cycle, in which spent fuel is treated as waste destined for a geologic repository. In practice, none of these countries has an operating repository, so spent fuel remains in interim storage. Other countries have chosen to reprocess their spent fuel, relying either on their own capabilities or on reprocessing services provided by a third party. France, Russia, and the United Kingdom (UK) operate large, commercial-scale reprocessing facilities that provide reprocessing services to other countries. All these services use the Plutonium Uranium Reduction and EXtraction (PUREX) process, initially developed to produce plutonium for weapons, to produce a pure plutonium oxide product.[13] Because of a longstanding imbalance between the separation and re-use of plutonium in reactor fuel, roughly 250 metric tons of separated plutonium have accumulated worldwide, mostly at reprocessing plants in France, Russia, and the UK; these countries also have significant excess reprocessing capacity available for the international market. The Japanese commercial-scale Rokkasho Reprocessing Plant, which is expected to begin operation in 2008, will be dedicated to reprocessing domestic spent fuel.

1.3 PURPOSE OF THIS ASSESSMENT

In February 2006, President Bush announced the Global Nuclear Energy Partnership (GNEP) as part of his Advanced Energy Initiative. GNEP is intended to support a safe, secure, and sustainable expansion of nuclear power domestically and internationally. To do this, the GNEP program would promote technologies that support economic, sustained production of nuclear-generated electricity, while reducing the impacts associated with spent nuclear fuel disposal and reducing proliferation risks. Internationally, the GNEP program would support development of grid-appropriate power reactors for developing countries. In support of international nonproliferation goals, the United States is also cooperating with international partners to develop a comprehensive reliable fuel services concept, which, in its most comprehensive form would involve both assured supply of fresh fuel and "take-

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[13] Japan's Rokkasho Reprocessing Plant uses the PUREX process but blends uranium and plutonium nitrate before conversion to produce a 50:50 blend of uranium and plutonium oxide.

back" of spent fuel, i.e. the return of spent fuel from the recipient country – not necessarily the same country that supplied the fresh fuel – for reprocessing or disposal. GNEP seeks to organize a partnership of countries that agree on principles governing the global expansion of nuclear power in a safe and secure manner that reduces the risk of nuclear proliferation.

The Secretary of Energy is considering key decisions about the course of the domestic GNEP program. To support potential decisions and meet the requirements of the National Environmental Policy Act (NEPA), the Department of Energy (DOE) is preparing a Programmatic Environmental Impact Statement (PEIS) for the GNEP program. This PEIS assesses the potential environmental impacts of the range of reasonable alternatives for implementing the GNEP program within the United States, as well how certain international initiatives could result in environmental impacts within the United States and the global commons.

To complement the PEIS, the National Nuclear Security Administration (NNSA), a separately organized agency within DOE, is preparing this Nonproliferation Impact Assessment (NPIA) for the GNEP program as DOE has done in parallel with other environmental impact statements.[14, 15, 16, 17, 18] This draft NPIA is prepared for information and evaluation purposes only, and does not represent any decision, plan or proposal by DOE in regard to any of the actions or possible alternatives addressed in the draft NPIA. Any such actions or potential actions by DOE or the U.S. Government as expressed in the draft NPIA are subject to further evaluation and decision-making in compliance with applicable laws, regulations, and policies of the U.S. Government.

Understanding the nonproliferation impacts of GNEP and other programs that influence the international fuel cycle is critical. This is particularly true in the case of GNEP, which identifies nonproliferation as a primary objective. In particular, the GNEP program aims to advance the following nonproliferation and international security policy objectives:

- Limit the further spread of indigenous enrichment and reprocessing programs, by providing reliable fuel services as a viable alternative to such programs;
- Halt the build-up and eventually draw down stocks of separated plutonium;
- Develop and promote reactors and fuel cycles with reduced proliferation and security risks; and

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[14] The DOE Office of Arms Control and Nonproliferation "Nuclear Infrastructure Nonproliferation Impact Assessment" DOE/NE-0119, September 2000

[15] The DOE Office of Arms Control and Nonproliferation "Nonproliferation Impacts Assessment for the Management of the Savannah River Site Aluminum-Based Spent Nuclear Fuel," December 1998

[16] The DOE Office of Arms Control and Nonproliferation "Nonproliferation Impacts Assessment for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel," July 1999

[17] DOE, "Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives," January 1997

[18] The DOE Office of Arms Control and Nonproliferation, "The National Ignition Facility (NIF) and the Issue of Nonproliferation," December 1995

- Improve international safeguards approaches to verify that countries are not misusing nuclear energy for weapons purposes.

This assessment compares proliferation risks and nonproliferation benefits in projected alternative futures for the GNEP program architecture. It discusses whether and how well these alternatives support U.S. nonproliferation goals. By illustrating how U.S. nonproliferation objectives can be achieved in a world where peaceful use of nuclear power is growing, this assessment aims to inform decisions on how to develop the fuel cycle and strengthen the international nuclear nonproliferation regime.

1.4 SCOPE OF THIS ASSESSMENT

Consistent with the NEPA requirements, the GNEP PEIS considers the potential environmental impacts of the range of reasonable alternatives for achieving the purpose and need for agency action. One element of that purpose and need is to reduce proliferation risks associated with the global expansion of nuclear power. Although not required by NEPA, this nonproliferation impact assessment considers the same range of domestic programmatic alternatives as the GNEP PEIS, along with other information necessary for this assessment. Since a major part of the nonproliferation impact relates to international fuel services, this assessment considers factors not required or specified fully in the domestic programmatic alternatives in the PEIS, such as enrichment, back-end fuel services, safeguards, and physical protection. As a consequence, the scope and emphasis of this NPIA differ from those of the PEIS in that the NPIA addresses nonproliferation-related aspects of the broad fuel cycle alternatives that are not specified in the PEIS.

As mentioned above, the focus of this document is on nonproliferation policy issues. More specific technical nonproliferation assessments may be undertaken as decisions are made on the future course of the GNEP program. However, a number of related technical assessments have already been done. A list of relevant documents may be found in the bibliography.

1.5 STRUCTURE OF THIS ASSESSMENT

The GNEP program is in part an extension of longstanding work in the U.S. Government on both advanced nuclear energy systems and efforts to strengthen the nuclear nonproliferation regime. Chapter 2 of this assessment outlines the key elements of the international nuclear nonproliferation regime and U.S. nonproliferation policy history as context for the assessment. It also describes major policy considerations and initiatives.

Chapter 3 describes the policy and technical factors used in the assessment. It begins with policy factors, based on the GNEP policy objectives listed above and other longstanding U.S. policy objectives. Next, it outlines the proliferation risk assessment methodology that will be used to support more detailed decisions on implementing specific fuel cycle alternatives once selected. This methodology is based on the internationally recognized Proliferation Resistance and Physical Protection (PR/PP) methodology developed by a Working Group of the Generation IV International Forum. Since the technology details are not yet defined fully for any of the GNEP programmatic alternatives, the current assessment will focus on evaluating the relevant nonproliferation features of those alternatives against established nuclear nonproliferation and international security policy objectives rather than against the detailed PR/PP methodology.

Since the reliable fuel services concept is a key element of GNEP's international component and would offer its central nonproliferation benefit, Chapter 4 outlines a range of possible international fuel services concepts and alternatives. This chapter identifies and compares the characteristics of these proposed alternatives that affect proliferation risk. Some of these concepts are still being developed, so the assessment of nonproliferation impacts can be expected to evolve as the concepts mature.

Chapter 5 describes the technical characteristics of the GNEP domestic programmatic alternatives. It begins by describing these alternatives, using the descriptions from the GNEP PEIS. The chapter sets out key technical characteristics of the facilities and processes involved in these alternatives, describing different types of reactors, different types of recycling processes, spent fuel treatment, and transportation with their potential nonproliferation considerations.

Finally, Chapter 6 provides overall assessments of the GNEP programmatic alternatives. These assessments will emphasize policy factors and focus on the ability of each of the domestic programmatic alternatives to support the international nonproliferation and security objectives of the U.S. Government. The assessments also address technical factors where relevant information is available, both to identify where clear distinctions exist among the alternatives and to outline some of the issues that may arise in future decisions. As decisions are made regarding the GNEP program, more detailed technical assessments using this framework may be carried out.

Following Chapter 6 are appendices listing the primary safeguards, security, and export control regulations, a bibliography with relevant background material, and a glossary of the acronyms used in this document.

2. NONPROLIFERATION POLICY BACKGROUND AND CONTEXT

2.1 EXISTING FRAMEWORK FOR NUCLEAR NONPROLIFERATION

Nuclear energy and nuclear materials can be used both for peaceful and destructive purposes. For decades, the United States and the international community have pursued policies to promote the benefits of the peaceful uses of nuclear material while controlling against the risk of nuclear proliferation. President Eisenhower's "Atoms for Peace" speech in December 1953 led to enactment of the Atomic Energy Act of 1954, which provides for international cooperation on the peaceful uses of nuclear energy, under conditions designed to avoid contributing to nuclear proliferation. Internationally, Eisenhower's proposal led in 1957 to the establishment of the International Atomic Energy Agency (IAEA), with the twin objectives "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" and to "ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose."[19] The Nuclear Nonproliferation Treaty (NPT) of 1970 provides a legal framework for preventing the spread of nuclear weapons while promoting peaceful nuclear cooperation and facilitating disarmament.

Within this framework, U.S. and international nonproliferation policies have consistently pursued the following objectives:

- Limit the spread of the most sensitive nuclear fuel cycle technologies (enrichment and reprocessing) through a combination of technology controls and measures that provide assured access to nuclear fuel cycle services.
- Control the use of the most sensitive weapons-usable materials (plutonium and high enriched uranium[20]) in peaceful nuclear programs.
- Apply safeguards and physical protection measures to detect, deter, and prevent the diversion or theft of nuclear material and the misuse, attack, or sabotage of nuclear facilities.
- Design nuclear facilities to reduce the opportunities for misuse, diversion, or theft of nuclear materials or attack on nuclear facilities.

To assess how the Global Nuclear Energy Partnership (GNEP) program may contribute to each of these objectives, it is useful to understand the history and context of how these policies have been pursued more broadly over the history of the nuclear era.

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[19] See Article II of the IAEA Statute, available at http://www.iaea.org/About/statute_text.html.

[20] High enriched uranium (sometimes referred to as highly enriched uranium) is uranium whose concentration of the fissile isotope U-235 is 20% or more of all uranium.

2.1.1 Nuclear Nonproliferation Treaty

The NPT is an international treaty to limit the spread of nuclear weapons. The treaty, which entered into force in 1970, is a legal cornerstone of the international nuclear nonproliferation regime. There are currently 189 states party to the treaty: the five nuclear weapon states (NWS) and 184 non-nuclear weapon states (NNWS). The treaty is commonly described as having three pillars: nonproliferation, peaceful use, and disarmament. Articles I and II contain legal obligations for NWS not to assist NNWS in acquiring nuclear weapons and for NNWS not to acquire them. Article III requires NNWS to accept IAEA safeguards on all nuclear material, to verify that nuclear energy is not diverted from peaceful uses. Article IV recognizes the right to peaceful use of nuclear energy (in accordance with Articles I and II) and calls for nuclear cooperation. Article VI calls for good faith negotiations on disarmament.[21]

2.1.2 Safeguards and Security

Effective safeguards and security are key to responsible management of the anticipated future expansion of nuclear power and mitigation of the associated nuclear proliferation and terrorism risks posed by state and non-state actors.[22] Policy discussions related to the nonproliferation component of GNEP tend to group together terms such as “safeguards and security” in a way that generates confusion. In reality, “safeguards” and “security” are complex and overlapping mission areas consisting of distinct activities for which different entities have primary responsibility.

The term “safeguards” is used to describe both domestic and international safeguards measures, and it may mean different things in those contexts. Domestic safeguards are measures taken by the state to detect and deter loss, theft, or diversion of accountable nuclear materials by non-state actors, including insiders. By contrast, international safeguards refer to the application of measures by the IAEA to enable it to detect state-level diversion of nuclear materials for military purposes. Under IAEA safeguards, the state operating the facility must be viewed as a potential proliferation risk. International safeguards require – and therefore depend on – reporting by the domestic state system of accounting and control –; IAEA material accountancy is based on verifying independently the declarations made by the state regarding nuclear facility operations and nuclear material inventories.

The NPT and the IAEA Statute[23] provide the legal foundation for international safeguards. Under the NPT, each NNWS must conclude a safeguards agreement with the IAEA

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[21] The text of the NPT, together with a more detailed description of its provisions, is available online at http://www.state.gov/t/isn/trty/16281.htm.

[22] This assessment uses the term “non-state” actors to refer to individuals or groups acting outside the authority of the state in question. Sometimes referred to as “sub-state” or “sub-national” groups, this category includes, *inter alia,* criminals and criminal organizations, insiders, terrorists, and insurgencies and may be organized within a state or across state lines.

[23] The IAEA Statute is the treaty establishing the IAEA, and is available online at http://www.iaea.org/About/statute.html.

covering all nuclear material and facilities in the state.[24] The overall purpose of IAEA safeguards is to verify that nuclear material is not diverted for nuclear weapons or other nuclear explosive devices. Given the comprehensive nature of these safeguards agreements, this includes verifying that all nuclear material has been declared. The technical objective of IAEA safeguards, particularly at declared facilities, is "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of weapons or other nuclear explosive devices or for purposes unknown." This objective is achieved by "the use of material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures."[25]

The United States has consistently lent strong support to the IAEA safeguards system, and has been its chief supplier of technical, human, and financial support through voluntary financial and in-kind contributions to the IAEA. Additionally, the United States has also worked tirelessly to strengthen the safeguards system by promoting universal adherence to safeguards agreements and to Additional Protocols and by pressing for the vigorous and effective implementation of inspections and other measures aimed at detecting undeclared nuclear activity. The Additional Protocol, adopted by the IAEA in 1997, requires expanded declarations to the IAEA of nuclear and nuclear-related activities and locations and provides expanded access rights for IAEA inspectors, and requires a separate agreement between the state and the IAEA – a modifying addition to an existing safeguards agreement. It is intended primarily to provide stronger tools to detect and deter undeclared nuclear activities and to respond to questions and inconsistencies that may arise in safeguards implementation[26,27]

In the United States, domestic safeguards (often referred to as "safeguards and security") include measures related to:

- <u>Domestic material control and accountancy</u> – measures taken by a state to detect the diversion or theft of nuclear materials by non-state actors;

- <u>Physical security</u> – measures, such as armed protective force personnel and physical barriers, designed to provide physical protection against theft, sabotage, or other malicious acts by non-state actors, and to protect nuclear materials and facilities from acts of terrorism, including theft or radiological sabotage;

- <u>Information security</u> – measures that focus on protecting sensitive and classified information related to security and technology;

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[24] See "The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," published by the IAEA as INFCIRC/153 (Corrected), http://www.iaea.org/Publications/Documents/Infcircs/Others/infcirc153.pdf.

[25] INFCIRC/153, paragraphs 28 and 29.

[26] See "Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards," published by the IAEA as INFCIRC/540 (Corrected), http://www.iaea.org/Publications/Documents/Infcircs/1997/infcirc540c.pdf.

[27] For more information on IAEA safeguards, see the fact sheet "IAEA Safeguards: Stemming the Spread of Nuclear Weapons," http://www.iaea.org/Publications/Factsheets/English/S1_Safeguards.pdf.

- Insider mitigation – background checks, fitness for duty, personnel reliability, behavioral observation, and other insider mitigation measures; and

- Recapture and recovery – intelligence, law enforcement, and technical measures designed to facilitate search, recovery, and interdiction of missing nuclear materials, or devices.

Any expansion of nuclear power will have implications both for IAEA safeguards and for domestic safeguards and security systems in many countries. The IAEA will likely need additional funding and staff as well as technical assistance to improve the effectiveness and efficiency of its safeguards system. It will need new safeguards approaches for new types of nuclear facilities, particularly for complex or large fuel cycle facilities. Many of the GNEP programmatic alternatives would involve new facilities with novel processes for reprocessing and recycling spent fuel. These facilities pose particular challenges for both domestic and international safeguards, for example:

- Quantitative measurements of spent nuclear fuel;

- Safeguards for electrochemical processing;

- Safeguards for new aqueous processing methods;

- Nondestructive measurements of mixed actinide materials;

- Process monitoring, including flows of non-nuclear materials;

- Continuity of knowledge for fast reactor fuels in liquid metal;

- Design information verification for larger flexible facilities; and

- Improved safeguards efficiency, monitoring more facilities with fewer resources.

The overall U.S. approach to safeguards and security includes measures and metrics intended to guide designers, operators, and inspectors towards an optimal balance among facility design and operational considerations including safeguards approaches, physical protection arrangements, safety, and economy of operations. Under the concept of Safeguards by Design, safeguards requirements would be incorporated directly and early into the design of facilities. This allows the inherent properties of materials, processes, and physical configurations to facilitate safeguards implementation and offers substantial efficiencies compared to treating safeguards as an add-on requirement after a facility is designed or built.

2.1.3 Nuclear Cooperation and Export Control

For the United States, the Atomic Energy Act of 1954, as amended, provides the principal statutory basis for the United States to engage in international nuclear cooperation. Major nuclear exports from the United States require an agreement for cooperation in the peaceful uses of nuclear energy between the United States and the recipient country.[28] The United States maintains 20 agreements with individual countries and groups of countries (including the European Union) that permit U.S. exports of major items of nuclear equipment and material to 46 NPT Parties. The United States also has a separate agreement with the IAEA that permits similar transfers to IAEA member states that are prepared to meet U.S. legal and policy requirements for such cooperation, as well as an agreement governing cooperation with Taiwan.

In addition, exports of nuclear material and equipment also require export licenses, with a similar list of conditions. There are also controls on nuclear-related dual-use equipment and on technology related to both. The key nonproliferation conditions required under U.S. law for exports to NNWS include, but are not limited to, the following:

- Comprehensive domestic safeguards on nuclear materials;
- Peaceful use assurances;
- No enrichment or reprocessing of nuclear material without prior U.S. consent;
- No alteration in the form or content of material containing plutonium, uranium-233 (U-233) or highly enriched uranium[29] without prior consent;
- No enrichment of transferred uranium to 20% or above without prior consent;
- Right of return of any transferred material, equipment, components, technology, and produced material in the event of a nuclear detonation;
- Implementation of a safeguards agreement between the IAEA and the NNWS;
- Physical protection of nuclear facilities and nuclear materials;
- Consent rights for re-export of nuclear materials, equipment, components, and technology; and
- Controls on sensitive nuclear technology (SNT).

The NPT itself has an export control requirement, in Article III.2, which requires that IAEA safeguards be applied for exports of nuclear material to non-nuclear weapons states and on nuclear material used in, or produced through the use of, "material and equipment especially designed or prepared" for nuclear use. The list of items whose export triggers this safeguards requirement is known as the Trigger List.[30] In the mid-1970s, the United States led an effort to join with other nuclear suppliers to establish stronger guidelines for nuclear

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[28] Section 123 of the Atomic Energy Act of 1954 (as amended), sets forth requirements for agreements for peaceful nuclear cooperation between the United States and other countries. Most major nuclear exports can only take place under such agreements.

[29] Highly enriched uranium is uranium enriched to 20% or more in the isotope uranium-235 (U-235).

[30] http://www.zanggercommittee.org/Zangger/default.htm.

exports. This led to the establishment of the Nuclear Suppliers Group (NSG), which has agreed on guidelines for both "Trigger List" and dual-use exports, as well as for related technologies. These guidelines include provisions that correspond to each of the U.S. legal criteria listed above.[31] One purpose of these guidelines is to ensure a common framework for nuclear export policy so that suppliers will not seek a commercial advantage by undercutting each other's nonproliferation policies.

2.1.4 Proliferation Resistance

Another approach to reducing proliferation risks is by incorporating the concept of proliferation resistance into nuclear facilities and fuel cycles and international fuel cycle architectures. Proliferation resistance (or proliferation risk reduction) must be understood as a systems approach to reducing the risk of proliferation or of nuclear material diversion, both through intrinsic measures (such as making it harder to divert and misuse materials or to misuse facilities, particularly without detection) and extrinsic measures (such as more effective international safeguards and assured fuel services to discourage the spread of enrichment and reprocessing). The GNEP program, in concert with the Generation IV International Forum (GIF), is exploring new reactor designs that would incorporate intrinsic proliferation resistance measures through enhanced safeguardability, more robust physical barriers to impede unauthorized access to nuclear material, and, in some cases, ultra-long-life fuels and such concepts as small "cartridge reactors," in which the fuel is supplied in the form of a complete sealed core that would be returned to the supplier after use in exchange for a fresh cartridge.

It is important to recognize that it is not possible to make any system completely "proliferation proof" (the term proliferation resistance should not be misused or misunderstood to imply that a system is proliferation proof). Rather, it is very important in considering whether and how intrinsic or extrinsic measures improve proliferation resistance with respect to a range of specified threats and scenarios or pathways to see where gains and trade-offs are encountered for each.

2.2 HISTORY OF U.S. POLICY ON FUEL CYCLE CONTROLS

The United States has long led global efforts to strengthen the nuclear nonproliferation regime. These efforts have employed actions taken by the United States itself, and actions taken together with others through bilateral, regional, multilateral, and international arrangements and agreements. In response to changing circumstances, the United States and others have recognized the need to strengthen existing tools and mechanisms and deploy new ones to deal with emerging threats.

The GNEP program is intended to advance U.S. nuclear nonproliferation goals. It draws on decades of policy initiatives to control the most sensitive parts of the nuclear fuel cycle, i.e., enrichment and reprocessing. With respect to enrichment, although the United States has maintained a domestic enrichment capacity, it has exercised and recommended restraint with respect to the transfer of technology and concern about the emergence of new enrichment

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[31] http://www.nuclearsuppliersgroup.org/default.htm.

programs. The United States has also pursued similar policies with respect to the transfer of reprocessing technology. However, unlike enrichment, which is essential for a nuclear power program that relies on light-water reactors, the United States has not engaged in commercial reprocessing since the mid-1970s. U.S. policy on whether to pursue a domestic civil reprocessing capability has varied significantly over time. Major legal and policy milestones that bear on the U.S. approach to these two technologies are listed below.

- 1954 – The Atomic Energy Act (AEA) of 1954, as amended, in particular by the Nuclear Nonproliferation Act of 1978 (NNPA), defines U.S. policy for the development, use, and control of atomic energy. The Act authorizes the U.S. Government to regulate the export of nuclear materials, facilities, equipment and technology in accordance with bilateral and international cooperation agreements negotiated by the Department of State with technical assistance from the Department of Energy (DOE). The Act defines the nature and requirements of those cooperative agreements and the procedure by which Congress reviews them. The Act also provides export licensing criteria for nuclear materials, facilities, equipment, and technology.

- 1976 – President Ford, "Statement on Nuclear Policy," 28 October 1976: "I have concluded that the ***reprocessing and recycling of plutonium*** should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation."

- 1976 – Symington Amendment

  - Adopted 1976. Section 101 of the Arms Export Control Act, formerly section 669 of the Foreign Assistance Act of 1961 as amended.
  - Prohibits most U.S. assistance to any country found trafficking in ***nuclear enrichment equipment or technology*** outside of international safeguards. President Jimmy Carter found Pakistan in violation of the Symington Amendment in 1979 because of Pakistan's clandestine construction of a uranium enrichment plant. U.S. aid to Pakistan was possible between 1982 and 1990 only through the use of presidential waivers.

- 1977 – President Carter, "Nuclear Power Policy," 7 April 1977: "[W]e will defer, indefinitely, the ***commercial reprocessing and recycling of the plutonium*** produced in the U.S. nuclear power programs. From our own experience, we have concluded that a viable and economic nuclear power program can be sustained without such reprocessing and recycling."

  As part of the Carter administration's policy to discourage the spread of reprocessing facilities, the United States made preliminary studies of the possibility of establishing a facility for storing spent nuclear fuel in the Pacific Basin area and persuaded Japan to conduct a joint feasibility study for an interim fuel storage facility in Palmyra Island in the Pacific. In addition, in the late 1970s, DOE announced a program in which the U.S. Government would contract with U.S. utilities to take title to and store the utilities' spent fuel. Under the program, the

U.S. Government would compensate the utilities for the energy content of the spent fuel. DOE indicated that it would make available to foreign countries on a limited basis the option of returning spent fuel to the United States when doing so would contribute to meeting U.S. nonproliferation goals, and announced it was initiating a study on this issue. However, these offers were never implemented in part because the Nuclear Non-Proliferation Act (NNPA) of 1978 and other legislation placed important restrictions on the importation of foreign power reactor spent fuel into the United States.

- 1977 – Glenn Amendment

  - Adopted 1977. Section 102(b) of the Arms Export Control Act, formerly section 670 of the Foreign Assistance Act of 1961 as amended.
  - Prohibits U.S. foreign assistance to any NNWS (as defined by the Nuclear Non-Proliferation Treaty) that, among other things, detonates a nuclear explosive device.
  - Extended the Symington Amendment prohibitions and penalties to the import or export of ***reprocessing technology, materials, or equipment*** (with some exceptions) by a non-nuclear-weapon state regardless of whether safeguards are attached.

- 1978 – Nuclear Non-Proliferation Act (NNPA)

  - Includes the following provisions, which amend the Atomic Energy Act of 1954:
    - Requirements for full-scope IAEA safeguards as a condition of supply for nuclear materials and facilities to NNWS, and enhanced requirements for new and renegotiated agreements for cooperation.
    - New law and policy for the active U.S. pursuit of more effective controls over the nuclear fuel cycle, especially enrichment and reprocessing. The NNPA included initiatives to restrain the spread of both enrichment and reprocessing through assurance of supply and spent-fuel storage. This included maintaining adequate enrichment capacity on a long-term basis, and prompt discussions to develop international approaches for meeting future worldwide nuclear fuel needs, including: an international nuclear fuel authority; facilities operated under international auspices for the provision of nuclear fuel services; spent fuel storage facilities under international auspices, including the possibility of compensation for the energy content of such fuel; and creating a low-enriched uranium (LEU) stockpile to assure continuity of supply. The benefits of such arrangements were to be states that did not establish any new enrichment or reprocessing facilities. The NNPA also provides for a report to Congress that would address the options for and desirability of foreign participation, including investment, in new U.S. enrichment capacity.
  - In other elements addressing enrichment and reprocessing, the NNPA:
    - Incorporated more explicit consent rights on enrichment and reprocessing as a condition of U.S. supply under agreements for cooperation in:

  - ° Section 402 of the NNPA. Additional Requirements: (a) Except as specifically provided in any agreement for cooperation, no source or special nuclear material hereafter exported from the United States may be ***enriched*** after export without the prior approval of the United States for such enrichment; and in
  - ° Section 123(7) of the AEA. With certain exceptions, U.S.-origin nuclear material[32] may not be enriched or reprocessed without the prior approval of the United States. Furthermore, U.S.-origin plutonium, U-233, or high-enriched uranium (HEU) may not be altered in form or content without the prior approval of the United States.
- Defined sensitive nuclear technology as "any information (including information incorporated in a production or utilization facility or important component part thereof) which is not available to the public which is important to the design, construction, fabrication, operation, or maintenance of a ***uranium enrichment or nuclear fuel reprocessing facility or a facility for the production of heavy water*** ….". It also placed restraints and requirements on transfers of sensitive nuclear technology.
- Added section 129 of the Atomic Energy Act to prohibit the transfer of nuclear materials, equipment, or sensitive technology from the United States to any NNWS that the President finds to have detonated a nuclear explosive device, terminated or abrogated safeguards of the IAEA, materially violated an IAEA safeguards agreement, or engaged in manufacture or acquisition of nuclear explosive devices. The section similarly prohibits transfers to any country, or group of countries, that the President finds to have violated a nuclear cooperation agreement with the United States, assisted, encouraged, or induced a NNWS to engage in certain activities related to nuclear explosive devices, or ***agreed to transfer reprocessing equipment, materials, or technology to a NNWS, except under certain conditions***.

- 1978 – Nuclear Suppliers Group Guidelines, INFCIRC/254:

  - Special controls on sensitive exports

    Suppliers should exercise restraint in the transfer of sensitive facilities, technology and *weapons-usable materials.*[33] If ***enrichment or reprocessing facilities, equipment or technology*** are to be transferred, suppliers should encourage recipients to accept, as an alternative to national plants, supplier involvement and/or other appropriate multinational participation in resulting facilities. Suppliers should also promote international (including IAEA) activities concerned with multinational regional fuel cycle centers.
  - Special controls on export *of* ***enrichment facilities, equipment and technology***

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[32] For the purposes of this discussion, U.S.-origin nuclear material includes material supplied by the United States as well as material for which U.S. consent is required for other reasons, in particular because it is produced through the use of U.S.-origin material, equipment, facilities and technology.

[33] The phrase in italics has been replaced since 1978 by the term "*material usable for nuclear weapons or other nuclear explosive devices.*"

> For a transfer of an ***enrichment facility***, or technology therefor, the recipient nation should agree that neither the transferred facility, nor any facility based on such technology, will be designed or operated for the production of HEU without the consent of the supplier nation, of which the IAEA should be advised.

- 1981 – President Reagan
  - 16 July 1981, "Statement on United States Nuclear Nonproliferation Policy":

    "The United States will continue to inhibit the transfer of ***sensitive nuclear material, equipment and technology***, particularly where the danger of proliferation demands."

    "The Administration will also not inhibit or set back ***civil reprocessing*** and breeder reactor development abroad in nations with advanced nuclear programs where it does not constitute a proliferation risk."
  - 8 October 1981, "Statement Announcing a Series of Policy Initiatives on Nuclear Energy":

    "I am lifting the indefinite ban which previous administrations placed on ***commercial reprocessing activities*** in the United States."
- 1993 – President Clinton issued a policy statement on 27 September 1993 on ***reprocessing***:

  "The United States does not encourage the civil use of plutonium and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes. The United States, however, will maintain its existing commitments regarding the use of plutonium in civil nuclear programs in Western Europe and Japan."
- 1997 – Guidelines for the Management of Plutonium adopted by Belgium, China, France, Germany, Japan, the Russian Federation, Switzerland, the UK, and the United States (INFCIRC/549).

  These "guidelines for the responsible management by Governments of plutonium in all peaceful nuclear activities" state that materials, "which can be used for the manufacture of nuclear explosive components without transmutation or further enrichment are particularly sensitive and require special precaution."
  - The Guidelines apply to plutonium in the following forms:
    - separated plutonium;
    - plutonium contained in unirradiated mixed oxide fuel elements;

    - plutonium contained in other unirradiated fabricated goods; and
    - plutonium in the course of manufacture or fabrication or contained in unirradiated goods in the course of manufacture or fabrication.

  - In addition to guidelines for physical protection, nuclear material accountancy and control, and international transfers, the Guidelines set forth Policies for Management of Plutonium, which include "the importance of balancing supply and demand, including demand for reasonable stocks for nuclear operations, as soon as practical."

- 1999 – The Board of Governors of the IAEA adopted recommendations of the nuclear weapon states and the IAEA Secretariat that it commence monitoring of neptunium and americium as Alternate Nuclear Materials (ANM). Some important aspects of the adopted recommendations include:

  - ANM is not statutorily considered Special Fissionable Material (SFM) at this time and is not covered by IAEA Safeguards Agreements.
  - Although the technical utility of ANM in nuclear explosives is recognized, ANM is currently not considered to be as great a proliferation concern as SFM because there is a very limited supply of ANM worldwide, and the vast majority of separated ANM stocks are currently found in the five NWS.
  - NNWS agree to report separated inventories and transfers (or export denials) of ANM to the IAEA. NWS (except for China, which opted for "observer" status) agree to report to the IAEA exports of ANM to NNWS.
  - Reprocessing plants currently under IAEA safeguards will be subject to Flow Sheet Verification, including material sampling to verify neptunium flows.
  - The IAEA will reconsider the need to require accounting for separation of ANM should accumulations in NNWS (either through import or separations) warrant this action.

- 2002 – National Security Presidential Directive 17: Controls on Nuclear Materials. In addition to programs with former Soviet Union states to reduce fissile material and improve the security of that which remains, the United States will continue to discourage the worldwide accumulation of separated plutonium and to minimize the use of HEU.

  > "As outlined in the National Energy Policy, the United States will work in collaboration with international partners to develop recycle and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant."

- 2004 – President Bush: National Defense University speech of 11 February 2004 proposed strict controls on enrichment and reprocessing technologies. Noting that,

  > "Currently, the Nuclear Nonproliferation Treaty allows states like Iran to develop the capability to produce weapons material under the cover of peaceful programs

> by pursuing a nuclear enrichment and reprocessing capability. The world must create a safe orderly system to fuel civilian nuclear reactors without adding to the danger of nuclear proliferation."

President Bush proposed that:

- "The world's leading nuclear exporters should ensure that states have reliable access at reasonable cost to fuel for civilian reactors, so long as those states renounce ***enrichment and reprocessing***…."
- The NSG members should "refuse to sell ***uranium enrichment or reprocessing equipment or technology*** to any state that does not already possess full-scale, functioning enrichment or reprocessing plants."

- The appendix lists current applicable regulations for safeguards, physical security, transportation, and export control of nuclear materials.

2.3 NONPROLIFERATION CHALLENGES OF NUCLEAR POWER GROWTH

2.3.1 Challenges from States

The international community faces the threat posed by states attempting to develop nuclear weapons, some despite solemn international obligations under the NPT to refrain from proliferation. In addressing the risk posed by these proliferant states, the NPT has long provided an essential framework. Successes include helping to ensure that only one state with nuclear weapons, Russia, rather than four, emerged from the break-up of the Soviet Union. South Africa, Argentina, and Brazil also entered the nonproliferation regime as non-nuclear-weapon states, ending their status as NPT hold-outs with suspect nuclear programs. It was also a success in resolving potential threats in Iraq and Libya. However, these successes are tempered by the continuing challenges posed to the international community and the NPT by North Korea's pursuit of nuclear weapons and Iran's drive to acquire a nuclear weapons capability. Other states as well could be contemplating developing an unauthorized nuclear program. And forty years after the NPT opened for signature, India, Israel and Pakistan all remain non-parties. It is clear that improved mechanisms for detecting and deterring such ambitions are not only desirable but necessary for improving international stability.

2.3.2 Challenges from Non-State Actors

In recent years, a new threat of nuclear proliferation has emerged as a result of the rapid rise in non-state actors' involvement in the proliferation of nuclear and other weapons of mass destruction (WMD). Such non-state actors may reside within a state or cross state boundaries. They can consist of individuals of several nationalities. They may act alone, or in groups, but they act without explicit state authority. As exemplified by the secret A.Q. Khan supply network, this involvement includes illicit trafficking in nuclear-related technology, weapons design, and equipment. It also includes non-state actors' efforts to acquire and use nuclear or other WMD. It is made more dangerous by potential cooperation between these groups and states that have violated their NPT nonproliferation obligations.

2.3.3 Enrichment Technology

The proliferation risk from enrichment services arises because there is little or no distinction between the technology needed for production of low-enriched fuel for power reactors and the technology needed to produce HEU for use in nuclear weapons. Enrichment plants can be converted – or the technology used – to produce HEU, which can be used directly in nuclear weapons. Uranium enrichment plants remain an essential element in the international fuel cycle since many reactor types require LEU fuel. The United States has sought to reduce the proliferation risk associated with uranium enrichment by being a reliable supplier of enrichment services, through the classification of enrichment technology information, and the rigorous implementation of export controls on the technologies.

The United States is not alone in this approach. It is exemplified, for example, by the "Special controls on sensitive exports" section of the NSG Guidelines for Nuclear Transfers (INFCIRC/254,Part 1[34]), which states "suppliers should exercise restraint in the transfer of sensitive facilities, technology and material usable for nuclear weapons or other nuclear explosive devices. If enrichment or reprocessing facilities, equipment or technology are to be transferred, suppliers should encourage recipients to accept, as an alternative to national plants, supplier involvement and/or other appropriate multinational participation in resulting facilities. Suppliers should also promote international (including IAEA) activities concerned with multinational regional fuel cycle centers."

2.3.4 Reprocessing Technology

Reprocessing and recycling of plutonium creates direct and indirect proliferation risks. The direct proliferation risk from reprocessing arises from the separation, processing, and transport of plutonium that is directly usable for nuclear weapons. The indirect risk results from setting a precedent in the United States that could encourage or support a global industry and technical community for reprocessing.

U.S. policy has changed from time to time with respect to the salience of the indirect risk of reprocessing. As a result of these policy changes and market forces, a commercial reprocessing industry has not emerged in the United States. However, as noted above, President Bush has decided that "the United States will work in collaboration with international partners to develop recycle and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant," and DOE is considering alternatives for recycling spent fuel.[35]

Regardless of changing policies regarding domestic deployment of reprocessing facilities for civil purposes, the United States has continued and will continue its policy not to interfere with civilian nuclear programs that involve the reprocessing and recycling of plutonium in

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[34] http://www.nuclearsuppliersgroup.org/guide.htm

[35] DOE has supported studies by four commercial consortia related to commercial spent fuel recycling in the United States. Summaries of these studies are available at http://www.gnep.energy.gov/afciparticipants/industryinvolvement.html.

Western Europe and Japan. In regions of the world of proliferation concern, however, the United States actively opposes plutonium reprocessing and recycling.

The United States will continue to discourage the worldwide accumulation of separated plutonium and to minimize the use of HEU in civil nuclear programs. Among other initiatives, the United States participated in the effort to develop an internationally agreed set of guidelines on the management of civil plutonium. In 1997, the United States reached agreement with Belgium, China, France, Germany, Japan, Russia, Switzerland, and the United Kingdom on International Guidelines for the Management of Civil Plutonium,[36] which, *inter alia*, provide that each state will take into account the need to avoid contributing to the risks of proliferation and the importance of balancing plutonium supply and demand as soon as practical.

Some have asserted that any effort to restrict access to sensitive nuclear technologies is inconsistent with the NPT. However, the Treaty allows for discretion on the part of supplier states regarding the nature of their cooperation with other states. Indeed, during the debates of the United Nations committee that drafted the NPT, multiple proposals were made that would have (1) created a legal duty for suppliers to contribute to the development of nuclear industry in the territories of NNWS, (2) affirmed an "inalienable" right of NNWS to develop nuclear explosive devices for civil or "peaceful purposes," and (3) extended Article IV nuclear cooperation explicitly to "the entire technology of reactors and fuels."[37] These efforts were considered and rejected.

Since enrichment and reprocessing technologies entail an inherent capability to produce fissile material that can be used in nuclear weapons, the nonproliferation obligations of supplier states call for special restraint in any transfers of these technologies. For this reason, the IAEA Director General has referred to enrichment and reprocessing as the "Achilles heel" of the nuclear nonproliferation regime.[38] The United States continues to believe that the best approach is for the commercial market to provide a reliable supply of nuclear fuel at reasonable cost from competing vendors in order to eliminate any need for additional countries to develop enrichment or reprocessing capabilities of their own.

2.4 PRESIDENTIAL INITIATIVES

In a major speech at the National Defense University on February 11, 2004, President Bush articulated an ambitious agenda to strengthen existing tools and develop new ones in the prevention of nuclear proliferation. Key elements of that agenda are:

- Placing a strong emphasis on compliance with NPT nonproliferation obligations;

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[36] Published by the IAEA as INFCIRC/549
http://www.iaea.org/Publications/Documents/Infcircs/1998/infcirc549.pdf.

[37] Department of State, Bureau of International Security and Nonproliferation, "Promoting Expanded and Responsible Peaceful Uses of Nuclear Energy," April 16, 2007 (available at http://www.state.gov/t/isn/rls/other/83210.htm).

[38] Mohamed ElBaradei, Introductory Statement to the Board of Governors, March 8, 2004 (available at http://www.iaea.org/NewsCenter/Statements/2004/ebsp2004n002.html).

- Strengthening the IAEA safeguards system by universalizing the more demanding Additional Protocol, making implementation of the Protocol one of the conditions countries must meet to be eligible for nuclear supply;
- Creating a Committee on Safeguards and Verification at the IAEA, which was established by the Board of Governors in June 2005 and met six times before making its final report in May 2007; and
- Adopting a United Nations Security Council Resolution to criminalize WMD proliferation, and in April 2004, the Council adopted Resolution 1540, which established for the first time binding, mandatory, obligations on all UN member states to criminalize WMD proliferation, to enforce effective export controls, and to secure nuclear materials.

To strengthen controls on the nuclear fuel cycle, President Bush proposed (1) that a complete ban be placed on the export of sensitive uranium enrichment and plutonium reprocessing technology to all countries not now having full-scale plants and (2) that those countries that forego these fuel cycle programs have access to a reliable supply of nuclear fuel at prevailing market prices. Under this proposal, members of the NSG would ensure that states that renounce enrichment and reprocessing technologies have reliable access, at reasonable cost, to fuel for civilian reactors. The United States is also working with the other nuclear fuel suppliers and the IAEA to develop a mechanism for alternative nuclear supply arrangements in the event of problems with the commercial market (See Chapter 6 for a more detailed discussion).

2.5 NONPROLIFERATION INFRASTRUCTURE FOR NUCLEAR POWER

A fundamental aim of the GNEP program is to reduce the barriers developing countries face in seeking to develop nuclear power. The United States is working with the IAEA to identify the infrastructure that countries need in order to manage peaceful nuclear power programs safely and securely. Financing nuclear power can also be a challenge for many countries, and the United States is working to facilitate financing mechanisms that could be used by developing countries, and strongly supports IAEA efforts to that same end. Altogether, GNEP offers the prospect of expanding the benefits available through international nuclear cooperation and expanded nuclear power generation around the world. The challenge facing the world community is to assemble comprehensive, cost-effective nuclear fuel services in a way that credibly protects customers from political discrimination and removes incentives to pursue enrichment or reprocessing. This is particularly challenging given the current fragmentation of fuel services into separate markets with separate suppliers for each step of the fuel cycle.

In pursuing these capacity building steps, the United States will work closely with the IAEA and others – states, multilateral groups, and industry – to ensure that the infrastructure put in place to support and manage peaceful nuclear power programs includes both the elements needed to operate nuclear power plants safely and efficiently and the elements needed to advance nuclear nonproliferation goals. This includes putting in place the legal and regulatory infrastructure – and making available the human and financial resources – needed in many nonproliferation areas, for example:

- the accounting, control, and reporting required by IAEA comprehensive safeguards agreements and Additional Protocols;
- effective physical protection arrangements on nuclear facilities and nuclear and other radioactive material; and
- export control systems that satisfy the requirements of the NPT, AEA, NNPA, IAEA safeguards agreements, and UN Security Council Resolution 1540.

Building up this requisite infrastructure for safe and secure use of civil nuclear power before it expands is consistent with longstanding U.S. policy. Section 202 of the NNPA calls for international training programs on safeguards and physical protection. U.S. assistance programs in these areas as well as export control and border security expanded significantly after the breakup of the Soviet Union and intensified worldwide after the terrorist attacks of September 11, 2001. These arrangements aim not only to buttress the nonproliferation regime, but also to help mitigate the risks posed by non-state actors.

3. ASSESSMENT FRAMEWORK AND FACTORS

The assessment framework for this Nonproliferation Impact Assessment (NPIA) is based on two major components:

- The degree to which the proposed architecture and its alternatives support U.S. nuclear nonproliferation policy objectives; and
- A review of the nonproliferation features of the proposed processes and technologies.

The nonproliferation policy goals of the GNEP program focus on supporting longstanding U.S. policy objectives that involve limiting the spread of sensitive enrichment and reprocessing/separations technologies and strengthening safeguards, physical protection, and other controls on nuclear materials and facilities. Any proposed processes and technologies warrant a more detailed analysis through the Proliferation Resistance and Physical Protection (PR/PP) evaluation methodology[39] that was developed as part of the Generation IV International Forum (GIF) technical evaluation once those processes and technologies become more clearly defined. This methodology will be described later in this chapter. The NNSA has an ongoing program to provide these detailed technical assessments.[40, 41, 42, 43]

3.1 POLICY FACTORS

The approach for assessing the degree to which the GNEP alternatives support U.S. nonproliferation policy flows from the discussion in Chapter 2 of U.S. nonproliferation objectives and U.S. policies to achieve those objectives. Section 3.1.1 describes a number of policy-related evaluation factors that guide this policy effects assessment. Although the GNEP program as discussed in the Programmatic Environmental Impact Statement (PEIS) and in this assessment focuses on domestic actions, there is an international component to the GNEP Program, and as a U.S. nonproliferation initiative, it is inherently international in scope and intended impact. Realizing the GNEP vision will require resolve on the part of policy makers, the establishment of new institutions, and technological innovation. Analysis limited to technology alone can neither capture this interplay of policy, institutional, and technological elements in GNEP, nor capture those international nonproliferation benefits of GNEP that will depend heavily on diplomatic and institutional initiatives as much as on domestic fuel cycle choices. The policy effects analysis focuses on how GNEP seeks to

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[39] http://www.gen-4.org/Technology/horizontal/proliferation.htm and "Framework for Proliferation Resistance and Physical Protection for Nonproliferation Impact Assessments," Robert Bari, BNL-80083, Brookhaven National Laboratory Formal Report, March 2008.

[40] "Nuclear Infrastructure Nonproliferation Impact Assessment," U.S. Department of Energy, DOE/NE-0019, September 2000.

[41] "Advanced Safeguards Approaches for New Reprocessing Facilities," P.C. Durst, I. Therios, R. Bean, A. Dougan, B.D. Boyer, R. Wallace, M. Ehinger, D. Kovacic, K. Tolk, PNNL-16674, June 2007.

[42] "Advanced Safeguards Approaches for New TRU Fuel Fabrication Facilities," P.C. Durst, M. Ehinger, B.D. Boyer, I. Therios, R. Bean, A. Dougan, K. Tolk, PNNL-17151, November 2007.

[43] "Advanced Safeguards Approaches for New Fast Reactors," P.C. Durst, I. Therios, R. Bean, A. Dougan, B.D. Boyer, R. Wallace, M. Ehinger, D. Kovacic, K. Tolk, PNNL-17168, December 2007.

achieve U.S. international nonproliferation objectives. This discussion, in turn, provides the necessary context within which to examine the domestic alternatives considered in the GNEP PEIS and the technologies and facilities employed in each of the domestic alternatives. In summary, the following analysis is intended to shed light on where and how those domestic alternatives support or negatively impact U.S. nonproliferation policy objectives.

The domestic fuel cycle alternatives addressed in the PEIS need to be considered and compared at two different levels of analysis. At one level is the question of how well each alternative would support the achievement of broader U.S. international nonproliferation goals, as well as energy and environmental objectives, in comparison to other alternatives. For example, does one of the alternatives better enable the United States to implement policy initiatives in GNEP, such as comprehensive fuel assurances, that support key U.S. nonproliferation objectives? At a second level are the comparative proliferation risks associated with the technologies deployed in each domestic alternative. It is difficult to make such comparisons at this stage, since those alternatives are defined in broad programmatic terms. There might be alternative technologies that could be deployed to implement the different alternatives. In the event that the Record of Decision following the final PEIS selects a programmatic alternative, future decisions will still be needed on the technology and strategy for implementing that alternative. At that stage, a more technically based analysis may be needed to determine whether there is a set of technologies and strategies that would present fewer proliferation risks than other options.

3.1.1 Policy Factors

The policy factors below provide qualitative nonproliferation benchmarks for the various architectures and domestic fuel cycle alternatives analyzed in the GNEP PEIS. They combine the four high-level nonproliferation and international security policy objectives of GNEP presented in Chapter 1 and the longstanding nonproliferation goals identified in Chapter 2, as follows:

- ***Restrain the spread of enrichment and reprocessing technology* –** Restraining the further spread of enrichment and reprocessing technology is a fundamental element of the President's nonproliferation policy and has long been a key element of U.S. nonproliferation policy. In support of this objective, the United States is considering concepts for comprehensive fuel services arrangements as an alternative for countries that might otherwise consider developing their own uranium enrichment or spent fuel reprocessing facilities.[44]. The comprehensive fuel services concept would include assured supply of fresh fuel, but the key innovation is that it also contemplates return of the spent fuel from the recipient country, though not necessarily to the same country that supplied the fresh fuel.

- ***Minimize and avoid accumulation of stocks of separated weapons usable material*** – This factor assesses whether and how fuel cycle alternatives under consideration

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[44] The draft PEIS describes one potential concept for comprehensive fuel services, referred to as the Reliable Fuel Services Program.

contribute to minimizing separated stocks of weapons-usable nuclear materials such as separated plutonium or its near equivalent, beyond the working stocks needed to implement the fuel cycle strategy, and to draw down existing excess stockpiles of separated plutonium.

- ***Promote improvements in the effectiveness and efficiency of international safeguards*** – One of GNEP's principal nonproliferation program elements is to support improvements in the effectiveness of international safeguards that would apply to fuel cycle facilities and reactors deployed under GNEP. A related objective is to improve the efficiency (cost-effectiveness) of such safeguards as applied worldwide

- ***Enhance U.S. influence to promote nonproliferation in the structure of the international fuel cycle, through direct control and policy leadership*** – This factor assesses whether GNEP program alternatives contribute to the enhancement of U.S. influence, directly or indirectly. An increase in the U.S. market share of nuclear fuel and other exports would contribute to direct and tangible U.S. influence through the system of legal obligations set forth in bilateral peaceful nuclear cooperation agreements. Historically, U.S. nuclear exports have been a key mechanism for applying nonproliferation requirements to specific materials and facilities in other countries, pursuant to bilateral Agreements for Cooperation with those countries. Indirect effects can also have value, for example by setting an example of a successful fuel cycle strategy for other countries to emulate, but these effects may be less durable since they impose no tangible constraints. In this regard, the longstanding U.S. example of refraining from reprocessing may be of less significance than the general decline of U.S. preeminence in international nuclear commerce in general and in the fuel supply market in particular.

- ***Reduce proliferation risk by building international agreement on technology strategies to reduce proliferation and security risks in nuclear energy and fuel cycle systems*** – GNEP aims to foster international collaboration to identify, demonstrate and promote commercial deployment of technologies that reduce these risks. This may include deployment of grid-appropriate reactors and fuel cycle technologies that have increased proliferation resistance and reduced security risk. Potential strategies include refinement and application of the PR/PP assessment methodology and the development of design criteria based on this methodology.

- ***Strengthen nuclear nonproliferation and nuclear security by encouraging the adoption and implementation of robust nuclear infrastructures*** – This factor assesses whether GNEP approaches lead others to adhere to and effectively implement international standards and best practices, including effective state systems of accounting and control; Additional Protocols; the Convention on Physical Protection of Nuclear Material and its amendment; implementation of the NSG Guidelines for export control; and implementation of UNSCR/1540. In practice, this factor is largely independent of domestic fuel cycle alternatives and therefore does not distinguish among those alternatives.

3.2 PROLIFERATION RESISTANCE AND PHYSICAL PROTECTION METHODOLOGY

3.2.1 Definition of Proliferation Resistance and Physical Protection

A clear definition of proliferation resistance establishes a firm foundation for analysis and assessment in the Proliferation Resistance and Physical Protection (PR/PP) framework. The definition given below has been used in the work of the Generation IV International Forum (GIF) and agrees with the definition established at the international workshop sponsored by the IAEA in Como, Italy, in 2002.[45]

Proliferation resistance is that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by the host state seeking to acquire nuclear weapons or other nuclear explosive devices.[46] This concept focuses attention on whether and how the intrinsic features (*e.g.*, physical and engineering characteristics of a nuclear technology) and extrinsic measures (*e.g.,* safeguards and physical barriers) of the nuclear energy system impede diversion or misuse by the state by making such actions more difficult or more detectable, in comparison to some other technology or facility under consideration. Given the dual nature of nuclear technology, no system can completely eliminate proliferation risks. Therefore, the term "proliferation resistance" should be applied as a comparative measure and not misused to describe particular systems as "proliferation resistant" or "proliferation proof."

For the purpose of this analysis, the nuclear energy system concepts for GNEP include the facilities that would comprise them, their safeguards, their physical security, the fuel services arrangements among its participants, and the transportation of nuclear materials.

While the PR/PP definitions provide a foundation for evaluating the relative proliferation risks of GNEP alternatives, there can be other factors that influence the nonproliferation impact of those alternatives. For example, the nuclear fuel cycle decisions of other countries also need to be considered. Furthermore, the anticipated political, strategic or economic consequences of responses to proliferation actions, if detected by safeguards or undertaken overtly, can be effective in deterring such actions.

Physical protection (effectiveness) is that characteristic of a nuclear energy system that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices and the sabotage of facilities and transportation by non-state actors.[47]

These definitions are given further specificity in terms of the measures for evaluating PR/PP, below. Both PR and PP are discussed here for completeness and to document the process by which the technologies will be evaluated as they become better defined.

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[45] http://www.jaea.go.jp/jnc/kaihatu/hukaku/database/2/h16/documents/04_Hurt_2.pdf

[46] While proliferation resistance refers to host state adversaries, it is understood that many proliferation resistant characteristics are effective against both state and non-state adversaries.

[47] This definition of physical protection is one element of the concept of "safeguards and security" as used historically in the domestic U.S. safeguards program.

3.2.2 Analytical Approach

In the standard PR/PP methodological approach, analysts define a set of challenges for a given system, analyze the system response to these challenges, and assess outcomes. The challenges to the GNEP system are the threats posed by potential proliferant states and by non-state adversaries. The technical and institutional characteristics of the nuclear energy system are used to evaluate the response of the system and determine its resistance to proliferation threats and effectiveness against adversary seizure of nuclear material or sabotage of nuclear material or facilities. The outcomes of the system response are expressed in terms of PR/PP measures and assessed. For PP, the outcomes of the system response are the results from assessing the effectiveness of the PP measures against the threats.

The evaluation methodology accounts for both the intrinsic and extrinsic protective features of the GNEP system. Intrinsic features include the physical and engineering aspects of the GNEP system; extrinsic features include institutional aspects such as safeguards and physical barriers. This methodology distinguishes between the state and non-state adversaries. However, protective features and system responses to state or non-state actors often overlap. Therefore, responses and outcomes can be similar for both types of adversaries.

Figure 3.1 provides an expanded outline of the methodological approach. The first step is threat definition. For both PR and PP, the threat definition describes the challenges that the system may face and includes characteristics of both the actor and the actor’s strategy. For PR, the actor is the state itself, and the threat definition includes both the proliferation objectives and the capabilities and strategy of the state. For PP threats, the adversary is a non-state actor acting without explicit state authority. The PP actors’ characteristics are defined by their objective, which may be either theft or sabotage, and their capabilities and strategies.

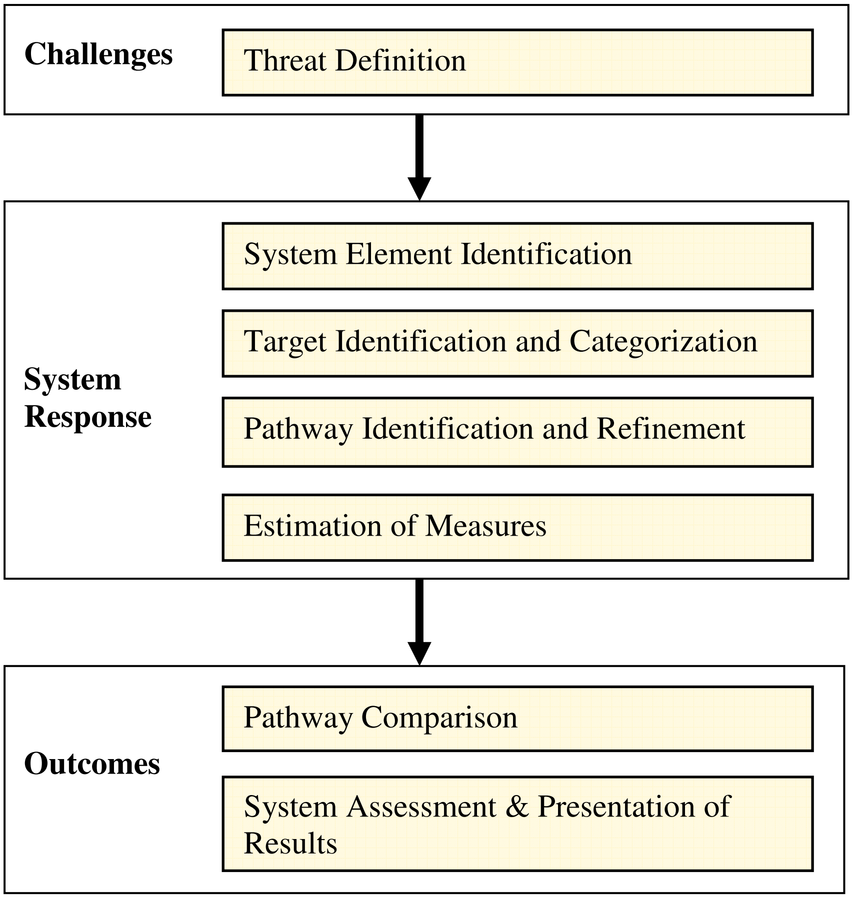

FIGURE 3.1 Detailed Framework for the PR/PP Evaluation Methodology

The challenges to the nuclear energy system are defined in terms of a standard set of reference threats, covering the anticipated range of actors, capabilities, and strategies.

For PR, the potential threats include:

- Concealed diversion of declared materials;
- Concealed misuse of declared facilities;
- Overt misuse of facilities or diversion of declared materials; and
- Clandestine dedicated facilities.

For PP, the potential threats include:

- Radiological sabotage;
- Material theft; and
- Information theft.

The selection of which potential threats to include is performed at the beginning of a PR/PP evaluation. The uncertainty in the system response to a given threat is then evaluated independently of the probability that the system would ever actually be challenged by the threat. In other words, PR/PP evaluations are not contingent on the threat occurring.

After the threats have been sufficiently detailed for the PR/PP evaluation, the system response step is performed and has four components:

System Element Identification. The nuclear energy system is decomposed into smaller elements or subsystems amenable to further analysis. The elements can comprise a facility (in the systems engineering sense), part of a facility, a collection of facilities, or a transportation system within the identified nuclear energy system element where acquisition (diversion) or processing (PR) or theft/sabotage (PP) could take place.

Target Identification and Categorization. Target identification is conducted by systematically examining the nuclear energy system for the role that materials, equipment, and processes in each element could play in each of the strategies identified in the threat definition. PR targets are nuclear material, equipment, and processes to be protected from threats of diversion and misuse. PP targets are nuclear material, equipment, or information to be protected from threats of theft and sabotage. Targets are categorized to create representative or bounding sets (scenarios) for further analysis.

Pathway Identification and Refinement. Pathways are potential sequences of events and actions followed by the actor to achieve objectives. For each target, individual pathways are divided into segments through a systematic process and analyzed at a high level. Segments are then connected into full pathways and analyzed in detail. Selection of appropriate pathways will depend on the scenarios themselves, the state of design information, the quality and applicability of available information, and the analyst's expert knowledge.

Estimation of Measures. The results of the system response are expressed in terms of PR/PP measures. Measures are the high-level characteristics of a pathway that affect the likely decisions and actions of an actor and therefore are used to evaluate the actor’s likely behavior and the outcomes. For each measure, the results for each pathway segment are aggregated as appropriate to compare pathways and assess the system so that significant pathways can be identified and highlighted for further assessment and decision making.

For PR, the measures are:

- *Proliferation Technical Difficulty* (TD) – The inherent difficulty, arising from the need for technical sophistication and materials handling capabilities, required to overcome the multiple barriers to proliferation.

- *Proliferation Cost* (PC) – The economic and staffing resources required to overcome the multiple technical barriers to proliferation including the use of existing or new facilities.

- *Proliferation Time* (PT) – The minimum time required to overcome the multiple barriers to proliferation (i.e., the total time required by the state for the project).

- *Fissile Material Type* (MT) – A categorization of material based on its utility for use in nuclear explosives.

- *Detection Probability* (DP) – The cumulative probability of detecting a proliferation segment or pathway.

- *Detection Resource Efficiency* (DE) – The efficiency in the use of staffing, equipment, and funding to apply international safeguards to the nuclear energy system.

For PP, the measures are:

- *Probability of Adversary Success* – The probability that an adversary will successfully complete the actions described by a pathway and generate a consequence.

- *Consequences* – The effects resulting from the successful completion of the adversary's action described by a pathway.

- *Physical Protection Resources* – The staffing, capabilities, and costs required to provide PP, such as background screening, detection, interruption, and neutralization, and the sensitivity of these resources to changes in the threat sophistication and capability.

The final steps in PR/PP evaluations are to integrate the findings of the analysis and interpret the results. Evaluation results include best estimates for quantitative and qualitative descriptors that characterize the results, the uncertainty associated with those estimates, and appropriate displays to communicate results and uncertainties.

3.2.3 Technical Factors and Metrics

The link between technical factors, PR/PP measures, and their underlying metrics can be summarized by the following:

1. The measures are the fundamental constituents of proliferation resistance;

2. The metrics are the scales or units in which they are expressed; and

3. The technical factors are a higher level expression of proliferation resistance that are more readily usable by the decision maker. They are supported by the measures.

Proliferation Resistance

Three high-level technical factors will be evaluated once specific technologies and/or sites are selected. They are:

- T1: Avoiding proliferator success
- T2: Facilitating cost effective international monitoring
- T3: Resulting in less attractive material types and forms

These technical factors are determined by the PR/PP measures through the following association.

Technical Factors	Associated PR/PP Measures
Avoiding Proliferator Success (T1)	• Technical Difficulty • Proliferation Cost • Proliferation Time • Detection Probability
Facilitating Cost Effective International Monitoring (T2)	• Detection Resource Efficiency • Detection Probability
Resulting in Less Attractive Material Types and Forms (T3)	• Material Type

Grading Structure for Technical Factors

A grading structure will be used for the three technical factors:

- Immediate and substantial impact;
- Delayed but substantial impact; and
- Significantly delayed and/or minimal impact.

Both negative (i.e., acquisition and/or use by the adversary of a dangerous capability) and positive impacts (the denial of that capability) can be considered. Immediate, Delayed, and Significantly Delayed are typically similar to the IAEA safeguards timeliness criterion: immediate is typically on the order of a day; delayed is typically on the order of a month; and significantly delayed is typically on the order of a year, although different definitions are sometimes more appropriate.

After measures have been estimated for pathways, pathways are compared and ranked to identify the significant pathways. To facilitate pathway comparison, quantitative metrics are applied to the TD, PC, PT, MT, and DP measures to relate them to descriptive values, from very low to very high, that would suggest the likely decision-making by a proliferant state. Likewise, for the DE measure, a quantitative metric is applied to reflect the magnitude of required resources, relative to the resources that the IAEA commonly applies to safeguard facilities. The analyst may select other quantitative metrics appropriate for comparing pathways for the specific threat being considered. Each of the PR measures is discussed in greater detail below.[48]

Proliferation Technical Difficulty (TD) Measure

The TD measure is estimated using a metric scale. Technical difficulty arises from inherent characteristics of the pathway that create difficulty and thus a potential for failure or significant delay due to technical problems. This measure may be adjusted to reflect the capabilities of a particular state.

Estimation of TD uses expert judgment to identify the sources of intrinsic difficulty in completing a pathway segment, such as difficulties associated with criticality hazards, radiation, lack of design information, lack of access, or inability to fabricate or produce equipment or materials covered by export controls. Estimation of TD for a complete pathway uses the combined sources of difficulty for all segments.

Proliferation Cost (PC) Measure

The PC measure is estimated in dollars and can be compared with the total resources available to a proliferant state for military expenditures. Alternatively, this measure can be estimated as a fraction of the state's gross domestic product. This measure expresses the economic and staffing investment required to overcome the multiple barriers that impede completion of the action associated with the segment.

The PC measure is aggregated over a pathway by summing the value of the measure for each segment in the pathway. In many cases, this measure will be dominated by one segment. This measure does not include the cost of the declared nuclear energy system but does include the cost of undeclared modifications made to that system to complete the diversion pathway. These modifications may include process modifications as well as modifications intended to defeat safeguards verification activities. This measure does not include the political, strategic or economic costs of potential responses to implementing a diversion or breakout strategy. Those issues are addressed in Chapter 4 as part of the fuel cycle and fuel assurances analysis.

Proliferation Time (PT) Measure

The PT measure is estimated in units of time and ranges from very low (< 3 months) to very high (> 30 years). The proliferation time is the minimum time required to overcome the multiple barriers that impede completion of the action associated with the acquisition and processing segments. Typically, PT is measured from the time that the proliferant state initiates its first detectable activity (e.g., its first action to divert material or misuse a declared facility). However, the analyst may select other initiation times, such as the time when the proliferant state's planning starts if the analyst judges this to be important in

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[48] More details and discussion of the metrics can be found in "Framework for Proliferation Resistance and Physical Protection for Nonproliferation Impact Assessments," Robert Bari, BNL-80083, Brookhaven National Laboratory Report, March 2008.

affecting the state's preferences between pathways. The analyst should state explicitly, the basis used for selecting an initiation time and use it consistently. Typically PT is estimated at the end of the processing segment and does not include the weapon fabrication time (which is subsumed in the MT measure). In practice, though, weapon fabrication time is assumed to be short compared to the PT, so this distinction is not important.

For example, abrupt diversion of spent fuel from a storage facility might require less than one week. Extraction of plutonium from irradiated targets might require 3 to 12 months, assuming that the extraction facility (whether clandestine or obtained through misuse of a declared facility) is already available.

For a pathway, the PT measure is aggregated by summing serial activities and taking into account parallel activities. Parallel and serial activities depend on the details of each pathway.

Fissile Material Type (MT) Measure

The MT measure ranks types of fissile material produced by the processing segment – typically metal – based on their utility for use in fabrication of a nuclear explosive and the relative preference of a proliferant state. As such, the MT measure is only estimated for pathways; it is not estimated for segments. In producing those pathway estimates, it is useful to understand the MT at the end of major stages. The MT measure is not expected to be an important discriminator between the GNEP alternatives.

The specific design tradeoffs that arise from fissile material properties will affect several areas that would be important to the objectives of a proliferant state, such as technical performance (e.g., explosive yield and reliability of that yield), the ability to stockpile the material, and deliverability.

Because detailed information on the relationship between MT and weapons design is sensitive, the PR methodology applies an approximate ranking of nuclear material types. This ranking reflects relative PR based on the preferences of a proliferant state in attempting to acquire its first few weapons. The ranking ranges from material like high-enriched uranium (HEU), for which design and fabrication of nuclear explosives has low difficulty (low PR ranking), to low-enriched uranium (LEU), for which fabrication of a workable nuclear explosive is essentially impossible (very high PR ranking). The basic range is:

- lower PR – HEU or weapons-grade plutonium (WG-Pu);
- medium PR – reactor-grade plutonium (RG-Pu);
- higher PR – "deep-burn" plutonium (DB-Pu); and
- highest PR – LEU.

For plutonium, a very wide range of isotopic compositions can be generated depending on the conditions of reactor operation and recycle of spent fuel. The basis for categorizing the attractiveness of different plutonium compositions is complex. Here the MT PR ranking for plutonium compositions is based on the study of the U.S. National Research Council on the spent-fuel standard.[49] More recent work suggests that these MT measures may need to be reconsidered and may not discriminate among the GNEP programmatic alternatives that involve spent fuel reprocessing.[50] In the continuum that ranges from ordinary rock (which contains uranium) and uranium ore to purified uranium products, fresh LEU fuel, spent fuel, and pure plutonium; the plutonium-bearing materials of interest in the GNEP alternatives are clustered at the high end of the proliferation risk spectrum.

Detection Probability (DP) Measure

The DP measure expresses the probability that the action described by a pathway segment is detected. DP results from measurements to detect and resolve anomalies that may be generated along that segment. DP is generally expressed as a cumulative probability function. If a defined safeguards approach is not available, however, DP can only be expressed by a very wide uncertainty band.

In addition, a variety of concealment strategies may affect DP. The effects of a concealment strategy are determined by analyzing pathways that include the strategy, not by assigning an arbitrary DP uncertainty for assumed effects of concealment methods.

Safeguards involve continuously evolving technology. A number of system attributes can affect both the optimal approach for the application of safeguards and the effectiveness of that approach in providing high DP.

A significant tool for enhancing the detection of undeclared segments is the Additional Protocol (AP). As noted in Chapter 2, the AP requires expanded declarations and grants broader inspection rights that are designed to increase the ability to detect undeclared nuclear activities, particularly enrichment and reprocessing. Implementation of the AP could therefore provide some assurance that a state was not pursuing enrichment or reprocessing capabilities. It could also provide assurance that the state was meeting commitments it might have undertaken to forgo sensitive fuel cycle development in exchange for assured fuel services.

Under modern integrated safeguards, safeguards detection resources, such as the frequency of inspections are increased progressively as anomalies are detected. This provides a higher cumulative confidence of detection with lower detection resources. Likewise, safeguards approaches that provide multiple and diverse measurements capable of detecting the actions described by a pathway segment increase the DP.

For internal pathway segments, the reference metric scale for the DP measure is based on a comparison with the applicable IAEA safeguards detection goals contained in the IAEA

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[49] "*Nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition alternatives*" (U.S. Department of Energy, DOE/NN-0007, 1997) pp. 38-39.

[50] "An Assessment of the Proliferation Resistance of Materials in Advanced Nuclear Fuel Cycles," C.G. Bathke et al. 8th International Conference on Facility-Operations – Safeguards Interface, March 30 – April 4, 2008, Portland OR

safeguards criteria. A “medium” DP meets the IAEA safeguards detection goals for spent fuel and irradiated materials. A “high” DP meets IAEA goals for HEU and separated plutonium, and a “low” DP meets IAEA goals for depleted uranium, natural uranium, and LEU.

For external pathway segments, DP may have large uncertainty unless the segment generates obvious visual, thermal, or other signatures. If detection uncertainty is large, it may be useful to provide decision makers with a qualitative, general description of the methods available to detect the external segment, particularly if the actual DP cannot be readily evaluated and presented.

Detection Resource Efficiency (DE) Measure

The DE measure is estimated for each pathway segment by summing estimates of the manpower (e.g., Person Days of Inspection, PDI) and/or the cost (in $) required to implement the detection methods for the segment. Safeguards resources are then aggregated for all segments of a pathway. Estimates of time or cost will necessarily be based on currently accepted safeguards approaches but anticipated changes to safeguards approaches and safeguards technology should be considered that could occur over the multi-decade life cycle for most nuclear facilities. The DE measure is normalized by a variable such as the energy production supported by the system element and is presented as the ratio of that normalization variable divided by the inspection time or cost.

Physical Protection

Each of the previously cited PP measures is discussed in greater detail below.

Probability of Adversary Success. This measure assesses the probability that an adversary will successfully complete the actions described by a pathway and generate a consequence. If the actions required to complete the pathway are within the resources and capability of the adversary, then the probability of adversary success depends on the capability of the physical protection system to detect the actions, delay the adversary, and neutralize the adversary before the actions can be completed. This measure is commonly used in the design and analysis of physical protection systems, and various tools are available to quantitatively evaluate the measure. For some pathways, this measure may be affected by a small number of segments, such as the physical difficulty in obtaining access to safety equipment in attempting to sabotage passively safe nuclear reactors and the difficulty of accessing and removing fresh or spent fuel.

Consequences. Consequences are defined as the adverse effects resulting from the successful completion of the adversary's intended action described by a pathway. Theft consequences can be expressed in terms of the type and quantity of the material removed. Sabotage consequences can be measured by the amount of radionuclide released, quantities of radionuclide per unit area, etc. Perhaps the most meaningful measurement of sabotage consequences at the coarse pathway level is whether a release is contained at facility site or released offsite.

Physical Protection Resources. This measure reflects the resources devoted to reducing probability of adversary success. It quantifies the capabilities and costs (both infrastructure and operation) required to provide a level of PP that reduces that probability and associated consequences to an acceptable level of risk. (No PP system can *guarantee* 100% effectiveness.) PP as used in this context includes detection, assessment, delay, and response components as well as personnel, operational, and other procedures for material control, as well as nuclear material accountability and insider mitigation measures. The physical protection resources measure for a given pathway is evaluated for each pathway segment and then aggregated appropriately, noting that some PP system elements can provide responses to multiple segments. This measure can be evaluated by aggregating resources for all pathways associated with a particular target. The physical protection resources measure can also be expressed as a cost per unit of energy produced.

The three measures for physical protection are consistent with those commonly used by national programs to make efficient investments to protect critical infrastructure and key assets. PP is a national responsibility and thus involves national policies. The goal is to optimally allocate resources to limit risk (the product of the probability of adversary success and cost) to a uniform level across both nuclear and non-nuclear critical infrastructure and key assets. Quantitative analysis for these three measures would also be required to support licensing and deployment decisions for any new nuclear infrastructure.

4. INTERNATIONAL FUEL CYCLE AND FUEL ASSURANCE CONCEPTS

4.1 GNEP INTERNATIONAL OBJECTIVES

In support of international nonproliferation objectives, the United States is cooperating with international partners to develop a comprehensive fuel services concept. The concept envisions establishing international fuel supply (front-end) and spent fuel management (back-end) mechanisms as incentives for countries to refrain from pursuing investments in costly and sensitive indigenous enrichment and reprocessing programs. Given that the spread of enrichment and reprocessing technology to additional nations would represent a significant latent proliferation risk, efforts to restrict the spread of these sensitive technologies are essential. These concerns must take into account the right of states to use nuclear energy for peaceful purposes, which is recognized explicitly in Article IV of the Nuclear Nonproliferation Treaty (NPT). A system of fuel supply and service mechanisms that helps shape the global nuclear trade market in a manner that restricts the spread of enrichment and reprocessing would be fully consistent with the purpose of the NPT in avoiding additional latent risk of proliferation while encouraging the peaceful use of nuclear energy.

If properly structured, assurance of fuel supply could make acquisition of national enrichment capabilities unnecessary and financially unattractive. Similarly, assurance of spent fuel disposition would make acquisition of reprocessing capabilities unnecessary and financially unattractive.

For the most part, the commercial market offers fuel services in a highly specialized manner, with separate suppliers for uranium, enrichment, fuel fabrication and, for those who choose it, reprocessing. The GNEP comprehensive fuel services concept, however, envisions assured access to consolidated packages of cradle-to-grave fuel services, including both the supply of fresh fuel and the disposition of spent fuel.

The credibility of these assurances is critical. To be effective in reducing proliferation risk, states would need to find fuel supply and disposition assurances credible, economical, and not detrimental to long-term energy security. Conversely, another way to reduce proliferation risk would be to ensure that states find the costs of international responses to proliferation to be formidable.

There have been several previous studies of proposed Fuel Banks and other cooperative fuel cycle mechanisms. In 1978, the Nuclear Nonproliferation Act required the President to submit to Congress proposals regarding “initial fuel assurances, including creation of an interim stockpile” of low-enriched uranium (LEU) “to be available for transfer pursuant to a sales arrangement to nations which adhere to strict policies designed to prevent proliferation when and if necessary to ensure continuity of nuclear fuel supply to such nations” [Section 104(b)]. The Carter Administration’s reports to Congress indicated only modest interest in such proposals and such negotiations were not pursued. Among other more visible efforts in the 1970s and 1980s were the IAEA study on Regional Nuclear Fuel Cycle Centers

(1975-77); the International Nuclear Fuel Cycle Evaluation program (INFCE, 1977-80); the Expert Group on International Plutonium Storage (IPS, 1978-82); and the IAEA Committee on Assurances of Supply (CAS, 1980-87). These studies concluded that most of the proposed arrangements were technically feasible and that, based on the projections of energy demand, economies of scale rendered them economically attractive. However, the political obstacles to such arrangements, including disagreement on the appropriate nonproliferation criteria, prevented their adoption.

4.2 FRONT-END APPROACHES

Conservative projections of global nuclear power expect roughly 2% annual growth over the next 25 years, slightly below the expected growth in global electricity production.[51] In China, annual growth rates above 7% are expected.[52] Combined with concerns over climate change and the need for energy security, this growing demand for electricity could lead to proportionately higher growth for nuclear power.[53] Keeping pace with nuclear power growth, global enrichment capacity will grow in proportion, but assurances of fuel supply could provide alternatives to the spread of enrichment technology to additional nations.

The health of the normal market and the preponderance of credible and complementary proposals for supply assurance mechanisms may make it easier to achieve the GNEP objective of providing nuclear fuel supply assurances on the front end. In principle, credible front-end supply assurances should ameliorate energy security concerns and create confidence that countries can safely forgo development of indigenous enrichment capabilities. However, it may prove difficult to assure customers that these back-up assurances would be insulated from political influence exercised through state export controls or other means that limit the credibility of those assurances. Another potential obstacle arises from the lack of fungibility of fabricated fuel. An assured supply of LEU does not automatically equate to an assured supply of fabricated fuel for a particular reactor, since most fuel designs are not interchangeable between reactors.[54]

4.2.1 IAEA Proposal

A recent IAEA report, "Options for Assurance of Supply of Nuclear Fuel,"[55] signals considerable interest in developing multilateral and multinational approaches to assured fuel supply. The report enumerates and summarizes 12 such proposals (see Section 4.5)

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[51] http://www.eia.doe.gov/oiaf/ieo/highlights.html

[52] EIA 2007 Outlook, http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2007).pdf

[53] "Energy Market and Economic Impacts of S. 280, the Climate Stewardship and Innovation Act of 2007," July 2007, EIA, SR/OIAF/2007-04.

[54] "The fuel assembly to be inserted in the reactor is a highly technologically specific product …; its design takes into account the fuel assemblies that are already in the reactor and its operating history. Moreover, …each fuel type requires extensive licensing. … A change of supplier is …connected with an extensive licensing effort, sometimes requiring the insertion of lead test assemblies. Such a changeover will typically take between 2 and 5 years, …. These changes would also presuppose the market availability of several manufacturers for the particular type of fuel required." - GOV/INF/2007/11

[55] GOV/INF/2007/11 of 13 June 2007.

received by the IAEA Secretariat and develops a proposed Framework based on common themes running through the proposals. This framework comprises three levels of assurance.

- Level 1: utilizes market arrangements between suppliers and reactor operators and is based on normal market forces, which are deemed to be efficient, with healthy levels of competition and functioning market mechanisms.
- Level 2: entails back-up commitments from suppliers underpinned by commitments from their respective governments to authorize such supply in response to a market disruption.
- Level 3: based on a fall-back physical reserve (or fuel bank) of LEU to be used as a supply source of last resort.

While the current nuclear fuel market has been seen by some as fully adequate, there certainly is room for improved transparency, particularly on price statistics and price fluctuations. To realize the promise of a credibly assured fuel supply beyond that afforded by Level 1 or normal market forces, the IAEA notes that suppliers would need to insulate Levels 2 and 3 from political intervention. This would entail pre-negotiated commercial agreements and pre-negotiated export and transit licensing guarantees in accordance with supplier states' laws and regulations. Level 3 assurances would further require adequate reserve inventories and/or production capacities, as well as agreed criteria under which such material would be released in the event of a supply disruption. As with earlier proposals, the supply criteria remain an area of political disagreement.

4.2.2 Fuel Leasing

Fuel leasing is one of the models under consideration for addressing both the front and back ends of the fuel cycle. While the details of fuel leasing would be negotiated in specific contracts between the specific parties, there are some general common features worth noting. For example, the "leasing" concept implies that, the supplier of fresh fuel would retain ownership of – or at least some fiduciary responsibility for – the supplied fuel even after it is used or "spent." Historically, until the Atomic Energy Act was amended in 1964 to allow private ownership of nuclear material, the Atomic Energy Commission leased nuclear material and fuel to both domestic and foreign customers. After legislation was enacted in 1964 to authorize private ownership of nuclear material in the United States, leasing as a means of acquiring reactor fuel became an exception rather than the rule. The U.S. Government retained its monopoly control over domestic uranium enrichment operations until 1992, when the Atomic Energy Act was further amended to enable a transition to private ownership of the Government enrichment facilities and to enable privately owned enrichment facilities to be built in the United States. The private ownership model played a significant role in expanding the economic diversity in the U.S. fuel marketplace, which was previously dominated by a U.S. Government-owned enterprise administered through the DOE. Currently, the U.S. front-end nuclear fuel industry is fully privatized though subject to significant government regulation.

Leasing by itself would not necessarily create any new nonproliferation obligations on the part of customers, though it might affect the perceived credibility of back-end fuel services measures since the spent fuel would continue to belong to the supplier. In practice, implementing leasing could prove complicated in a marketplace where multiple commercial suppliers (licensed by multiple governments) provide specialized services ranging from uranium supply through conversion, enrichment, and fabrication.

In the current system of bilateral nuclear cooperation agreements, nonproliferation obligations follow exports of nuclear material, non-nuclear material, equipment, and components to other countries; in some cases obligations apply to nuclear materials produced by or through the use of such exports. These obligations create a "cradle-to-grave" set of legal commitments enforceable under international law and are imposed regardless of the ownership of the nuclear material. By the time fabricated fuel arrives at a reactor, it is often carrying obligations owed to several supplier states that place legal requirements that include peaceful use assurances, limits on retransfers and changes in form or content, limits on end use, and physical protection and safeguards requirements. It is also important for these commitments to be enforceable, so that violations carry significant costs.

4.2.3 Commitments on Enrichment Services

Another proposal that describes a specific financial instrument as a guarantee of fuel supply and/or services is one from the United Kingdom (UK). The UK has suggested issuing "enrichment bonds" as a means of guaranteeing enrichment services. These bonds would be legal arrangements among the various parties – the supplier and customer firms, the supplier and recipient states and the IAEA – that "would guarantee that, subject to compliance with international law and to meeting the nonproliferation commitments to be assessed by the IAEA, national enrichment providers will not be prevented from supplying the recipient state with enrichment services in the event the guarantee is invoked."[56] Such an arrangement might involve granting consent rights in advance. The thrust of the proposal is to increase confidence that export approvals will be given by placing the final judgment on the export of LEU in the hands of the IAEA, thereby assuring that other issues or purely political considerations will not stand in the way of nuclear trade. According to notes on the UK's policy that British officials distributed for a special IAEA meeting in 2006, such an approach would "significantly limit the criteria upon which export approvals are normally based to include only nonproliferation considerations." The proposal argues that "governments must ultimately be prepared to relinquish some rights in exchange for a broader nonproliferation gain."[57]

4.2.4 Fuel Reserves

The United States has set aside 17.4 metric tons of high-enriched uranium (HEU) to be down blended to LEU and held in reserve to back up supply assurances. This LEU would be made available for qualifying nations in the event of nuclear fuel supply disruptions that cannot be corrected through normal commercial means and that are not related to

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[56] GOV/INF/2007/11 of 13 June 2007.

[57] Ibid.

proliferation activities. The qualifications for access to the reserve would include satisfying export control obligations and other U.S. legal requirements, having the necessary safeguards in place, and being in good standing with the IAEA.

The United States is also supporting the establishment of an international fuel bank under the auspices of the IAEA. In 2006, the Nuclear Threat Initiative (NTI) pledged $50 million toward the establishment of such a fuel bank, contingent upon similar donations by others equaling $100 million or the equivalent in LEU. The United States has pledged nearly $50 million, Norway $5 million, and the United Arab Emirates $10 million toward the establishment of this fuel bank. Other countries have also expressed interest in contributing.

In order to credibly implement a fuel bank concept, supplier states would have to address the issue of prior consent for the transfer of supplier-obligated fresh fuel by the operator of the fuel bank. Of the many legal issues surrounding fuel banks, consent rights may pose a particular challenge. Countries participating as recipients in the fuel bank may well request prior consent to the transfer of fresh fuel to their utilities, as well as transfers of spent fuel to an international facility on a long-term, predictable and reliable basis, as a condition of agreeing not to pursue indigenous enrichment or reprocessing. However, in accordance with their laws and regulations, suppliers might well insist on case-by-case approvals if they wished to exercise more leverage over the structure and direction of the fuel bank and management of spent fuel.

LEU in the U.S. reserve or in a fuel bank will be in the form of uranium hexafluoride (UF_6) at a specific assay and available for delivery. While the United States would provide enriched uranium, the buyer or the buyer's agent would have to work out arrangements for possible conversion or blending of the LEU into an appropriate form and delivery. As this is essentially a commercial transaction, the buyer would be responsible for transportation, insurance, safety, and liability issues associated with the LEU once title is transferred, as well as other contract terms as mutually agreed.

As mentioned above, fuel fabrication is an additional link in the supply chain and another potential choke point for assurance-of-supply purposes, even with an adequate and assured supply of LEU feed material. In the case of countries that do not possess their own fuel fabrication capacity, fuel fabrication services might also have to be assured to make the notion of a fuel reserve or bank a credible assurance mechanism.

4.2.5 International Nuclear Fuel Centers

The establishment of new international nuclear fuel centers (INFCs) has been suggested as a possible framework to promote access to nuclear power and to strengthen nuclear nonproliferation. In the first instance, such centers are likely to focus on the provision of uranium enrichment services and the "assured supply" of LEU feed material. They would thus provide additional sources of supply of enrichment services and/or LEU and may contribute to a physical fuel bank. INFCs would place the physical plant, whether enrichment or reprocessing, within the borders of a current technology holding state, thereby limiting the spread of sensitive technology and infrastructure to additional nations.

The proposals that have been made to date concerning the possible establishment of INFCs have been based either on the use of a national facility (e.g. as proposed by Russia at Angarsk) or on the concept of an IAEA Center, which would involve an IAEA role in the construction, operation, and monitoring of a uranium enrichment plant (as has been proposed by Germany). However, the latter proposal raises serious questions concerning whether the international inspectorate for nuclear safeguards, the recognized authority and clearing house for international nuclear regulatory standards and promoter and provider of technical assistance for emerging peaceful nuclear energy programs, could engage the marketplace as a commercial supplier without significant conflicts of interest.

In the past, a multinational consortium approach has been taken including the EURODIF enrichment plant in France and URENCO's plants in the UK, Germany, and the Netherlands. Though URENCO is a multinational consortium, it has fully exclusive agreements that place restrictions on partnership and technology transfer. Currently, in addition to purely national facilities, a URENCO-owned enrichment plant, an Areva-owned enrichment plant using URENCO technology, and a General Electric/Cameco (Canada)-owned enrichment plant using Australian technology are all being planned or built in the United States, and an Areva-owned plant using URENCO technology is being built in France. Multinational arrangements such as INFCs could develop objective criteria regarding expansion of membership, and such matters as investment, member voting rights in corporate decision-making, sharing in profits, and guaranteed production shares for non-technology holding partners as an assured supply measure. For example, a credible profit sharing mechanism might increase the economic attractiveness of an assured supply concept in which participation in the center is an alternative to initiating domestic enrichment and/or reprocessing activities. Likewise, consideration should be given to how a center could facilitate expanding production capacity to meet new future demand for services.

A legal framework of partnership arrangements could also involve bilateral agreements between technology holding and non-technology holding partner states, including legal commitments by non-technology holding partners to refrain from acquisition or development of enrichment technology while the partnership agreement is in force. Such an arrangement could provide direct market incentives for non-technology holders to voluntarily limit the spread of sensitive technology in exchange for profit sharing in economically credible industrial capacity while creating an additional fuel assurance mechanism. Such arrangements may be particularly attractive to major uranium supplier nations that currently do not have enrichment, since it would enable them both to rely on the center for the most proliferation-sensitive step in the front end of the fuel cycle and to earn profits through a business strategy of offering a wider range of higher value-added front-end products (e.g., fabricated assemblies).

4.3 BACK-END APPROACHES

A more complex problem is presented by the back end of the fuel cycle, i.e., storage and disposition of spent nuclear fuel. Under a comprehensive fuel services program, back-end fuel services could include return or "take-back" of the recipient country's spent fuel to another country, though not necessarily to the same country that supplied the fresh fuel, either for recycling or for disposal. All of the GNEP programmatic alternatives discussed below would generate significant amounts of radioactive waste, but they may differ significantly in terms of type, quantity and long-term radiotoxicity of waste. To date, the disposition of spent nuclear fuel has been a persistent economic and policy challenge. That is, given the balance of fresh uranium fuel costs, spent fuel storage costs, and estimates of spent fuel disposal and recycling costs, the most common approach to spent fuel management has been storage of the spent nuclear fuel at sites where it was generated. Most countries are in a position to store their spent fuel for a considerable time very economically and would be willing to do so if given assurance that back-end fuel services would be offered at a later date when recycling and/or disposal methods mature and economics improve.

However, escalating inventories of spent nuclear fuel will eventually create market pressures for improved spent nuclear fuel management strategies. Over the next 25 years, conservative estimates indicate that worldwide generation of spent fuel will be roughly double the amount of spent fuel generated to date. Avoiding a long-term negative nonproliferation impact depends on limiting the number of technology holders engaged in spent fuel reprocessing. Arrangements for supplier countries to accept spent nuclear fuel from recipient countries would help relieve spent fuel management pressures and thereby help to ensure that plutonium bearing fresh fuels and reprocessing and fabrication facilities remain limited to countries that already have reprocessing capabilities. The recycling activities could also help reduce the growing stocks of separated civil plutonium that currently have no identified disposition path. Alternative back-end services might also include technical support to the recipient country for disposal or for interim spent fuel storage, or acceptance by the supplier for interim storage pending reprocessing or disposal, or interim storage in a third party state, pending final disposal or recycle. Currently, France, the UK, and Russia offer international reprocessing services, though France and the UK require that wastes from reprocessing be returned to the country where the fuel was used.

The ability to provide assured back-end services (long term spent fuel storage, recycling and/or disposal) to recipients will likely be extremely important to achieving the nonproliferation objectives of the comprehensive fuel services concept. The potential to avoid the burden of managing and disposing of spent fuel may prove to be the most attractive incentive in the long term to refrain from development or acquisition of reprocessing and enrichment capability. Relieving this spent fuel disposition burden could depend on whether front-end and back-end supply arrangements can be effectively linked in a cradle-to-grave fuel service arrangement.

In order to offer back-end services sustainably over the long term, countries providing those services will likely need to develop and implement more sophisticated approaches to spent fuel management, such as reduction in waste hazard and volume. Direct geological disposition of foreign spent fuel would be particularly problematic, as it would likely lead to public concerns about importing nuclear waste and possibly competition with domestic nuclear power users over access to repository or storage facilities. By contrast, spent fuel recycling treats spent nuclear fuel as an economic resource rather than an indefinite economic and safety liability and as a hedge against future scarcity of uranium, while reducing waste hazard. In either case, the impacts of arrangements for disposition of foreign spent fuel on repository capacity requirements would have to be considered. Eventually the rising costs of uranium and the accumulating inventories of spent fuel may make spent fuel recycling seem more attractive. If and when that time comes, if a back-end fuel service regime is not already established, then it may prove difficult to convince countries not to move forward with reprocessing programs to close their own fuel cycles.

4.3.1 Legal and Policy Constraints

Legal and policy constraints limit the ability of any country to participate in back-end fuel services. In the United States, such constraints could limit the ability of the U.S. to lead diplomatic efforts to design new institutional frameworks that advance U.S. nonproliferation objectives. There is currently no specific proposal for U.S. participation in a comprehensive fuel services program. This section highlights some (but not necessarily all) of the legal constraints that could impact U.S. participation in back-end fuel services.

Section 131.f of the Atomic Energy Act of 1954 sets forth requirements with which the Department of Energy must comply prior to entering into arrangements involving the direct or indirect commitment of the United States for the storage or other disposition, interim or permanent, of foreign spent fuel.. Section 107 of the 1978 DOE Authorization Act (codified at 22 USC 3224a) prohibits DOE from using any appropriated funds, directly or indirectly, for the repurchase, transportation, or other disposition, interim or permanent, in the United States of any foreign power reactor spent fuel, unless similar requirements are satisfied. The Nuclear Waste Policy Act of 1982 contains requirements regarding disposal of spent fuel and high-level radioactive waste that would impact U.S. acceptance of foreign spent fuel for reprocessing or disposal. Lastly, a proposed action by DOE to transfer foreign spent fuel from foreign countries to the U.S. for reprocessing or disposal, or to send back any resulting radioactive wastes from reprocessing to a foreign nation, would require appropriate review under the National Environmental Policy Act.

In addition, domestic political concerns could constrain U.S. participation in back-end fuel services. Owners and operators of U.S. nuclear power plants would likely object to proposals for acceptance of foreign reactor spent fuel for reprocessing or disposal if such acceptance were perceived as giving preference to foreign over domestic spent fuel, particularly if the Federal Government has not yet met its contractual obligations to dispose of domestic spent fuel. Any plan to accept foreign spent power reactor fuel would be subject to both legal requirements and political scrutiny that would dictate a through evaluation of all environmental, cost, safety, security, and nonproliferation impacts.

Finally, international constraints may affect any country’s ability to participate in back-end fuel services. Spent fuel is often subject to nonproliferation-related consent rights applied by multiple supplier governments whose firms may have provided uranium, enrichment and fabrication services, or the reactor itself. This could involve complex negotiations because of the large number of parties involved, but is a manageable problem. At present, most suppliers’ export licenses defer decisions on spent fuel disposition but subject that fuel to consent rights for reprocessing or other alteration in form and content. One alternative would be to develop international export control guidelines that encourage exporters to address spent fuel management at the time of export. This could provide an enabling step toward true cradle-to-grave fuel services.

4.3.2 Fuel Cycle Alternatives and Back-End Services

This section presents a discussion of options for structuring back-end fuel services for information and evaluation purposes only. At this time, there is no specific proposal for the international component of GNEP, and the options described below are not decisions, plans or proposals by DOE. This discussion goes beyond the scope of the GNEP PEIS because it is important to the nonproliferation discussion, and is framed in terms of options available to a generic supplier. The supplier could be a supplier government, an individual supplier company, or a consortium of several countries and/or companies. Options for back-end services include:

- As an initial step, the supplier could offer assistance with spent fuel management in the recipient country. This could include technical, financial or logistical assistance with interim storage, either at or near the reactor site or at a centralized national facility. One approach would be for suppliers and customers to cooperate to establish a regional[58] storage facility. Dry cask storage technologies have been well demonstrated and have been found to be safe and environmentally acceptable over a multi-decade operating period.

- A supplier could help establish a national disposal facility for spent fuel, in the recipient country. This would be an extended process, including surveying potential sites, planning, design, construction, licensing, and operation of such a repository, and obviously depends on geology.

- If at least one country were willing to accept spent fuel from other countries, the supplier could help that country establish such a disposal facility to operate on a regional or international basis and make arrangements with the recipients and with the disposal facility state for the use of that repository.

- A supplier could accept spent fuel from the recipient country recycle the recovered fissionable material in its own reactors, and return the resulting waste to that country for disposal.

- A supplier could accept spent fuel from the recipient country, recycle the recovered fissionable material in its own reactors, and dispose of the resulting waste.

The key factor in determining the nonproliferation value of any of these approaches to back-end services is whether the benefit is attractive enough to encourage the recipient to refrain from – or even make a commitment to forgo – pursuing its own sensitive fuel cycle capabilities. The list above is ranked in order of expected value to the recipient. The most attractive alternative – and therefore the service for which the recipient presumably would be willing to pay the most – is for a supplier to accept spent fuel from the recipient country

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[58] In this context, "regional" refers to an international geographic region, such as east Asia.

and to dispose of it or recycle the recovered fissionable material in its own reactors and dispose of the waste resulting from recycling.

However, the significance of the difference between the last two options above depends on the characteristics of the waste generated from the recycling process. Chapter 5 will discuss the GNEP programmatic environmental impact statement, which considers a set of alternative fuel cycle architectures to address the back end of the U.S. fuel cycle. These alternatives have the potential to generate a range of different waste forms. They range from once-through fuel cycles involving various reactor types and fuels, to full actinide recycle alternatives that rely on fast reactors to consume transuranic materials and remove them from the high level waste, to partial actinide recycle alternatives that may reduce the spent nuclear fuel or radioactive waste requiring geologic disposal but typically leave substantial quantities of long-lived transuranic material (plutonium and/or the minor actinides neptunium, americium and curium) in the waste stream. Under a partial actinide recycle alternative, the resulting high-level waste would be relatively long-lived[59], so proposals under which the suppliers retain such waste would have significant value to the recipient. Under a full actinide recycle alternative, the resulting long-term radiotoxicity of high-level waste would be substantially minimized and therefore relatively more manageable. Under this scenario, having a supplier retain the waste from recycling might be of less value to the recipient. But by the same token, the supplier might be more willing to retain the full actinide recycle waste.

Since the development of back-end fuel services as part of a comprehensive reliable fuel services arrangement would support a central nonproliferation objective of GNEP, the success or failure of each alternative in achieving that objective would depend on how well that alternative would support the development of comprehensive fuel services as an accepted market norm. In general, these three types of fuel cycles would have very different implications for the ability to implement such a concept. These are described in detail in Chapter 5 and their nonproliferation impacts assessed in Chapter 6.

4.3.3 Back End Supplier Business Models and Economics

Effective delivery of back-end services is critical to the comprehensive fuel services concept. The back end has historically been the most problematic part of the fuel cycle from an economic perspective. The problems include the ability to adequately and fairly fund the uncertain costs of safe radioactive waste disposal in any nuclear fuel cycle, the high degree of economic risk associated with the feasibility of reprocessing, and the inconstant nature of government policy, particularly on reprocessing and recycling of spent fuel. This section addresses some of the underlying economic issues that a supplier would face in implementing a comprehensive set of back-end services. These are potentially decisive issues for GNEP international fuel services and must be addressed in business plans and analyses.

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[59] For the purposes of this assessment, "long-lived" is a term used to describe the radiotoxicity of the waste and the length of time that will be required before the radiotoxicity of the waste is comparable to that of natural uranium. This includes radioisotopes with decay lifetimes, including daughters, of a thousand years or longer.

4.3.3.1 Public and private goods

Management of nuclear fuel generates both private and public benefits. To the extent that it contributes to power generation, the benefit is predominantly to the private sector and is reflected in the revenue generated in power production. In a once-through fuel cycle, nuclear fuel becomes a net commercial liability once it is discharged. Continued management of the fuel in this context does generate public benefits in the form of public safety and security, but is difficult to maintain indefinitely under private control and responsibility.

To the extent that spent fuel can be recycled, its private valuation is increased. If reprocessing and fuel fabrication costs were made low enough in comparison to the use of fresh LEU fuel in light water reactors (LWR), the energy generated with recycled spent fuel could make that spent fuel a commercial asset rather than a liability. The physical transformation of the constituents of spent fuel through recycling has the potential to reduce disposal costs, further increasing the net value of the spent fuel. The net economic value would depend on the details of the process and on the economic and regulatory context. Thus, depending on the process used, reprocessing and recycling could fundamentally affect the balance of public and private interests in the back end of the fuel cycle.

Historically, recycled fuel in LWRs has had a significantly higher cost than fresh LEU fuel. Based on the limited experience with construction and commercial operation of fast reactors, it is often assumed that use of recycled fuel in fast reactors would generate still higher costs. To some degree, these costs would depend on the capital cost structure of the nuclear industry in general, with high capital costs up front offset by anticipated future revenues spread over multiple decades. The cost models, therefore, depend heavily on the expected return on investments, which are high for private capital investors but lower for private lenders. Public intervention could reduce overall capital costs and could alter the balance of costs and benefits for a particular fuel cycle. For example, Federal loan guarantees could increase the ratio of debt to equity investments, could reduce significantly the necessary rate of return on private investment and could increase the net present value of recycling.

To the extent that fuel cycle technologies alter the economic feasibility of nuclear fuel recycling and the cost of spent fuel disposal, they can also change the incentives for spent fuel management and the business models appropriate for the conduct of spent fuel management. The details of how these incentives would be affected by different recycle alternatives would determine which business models are most appropriate.

4.3.3.2 Vertical integration of fuel cycle services

The issue of assured fuel supply and its role in facilitating the expansion of nuclear power was covered in a previous section. At least as important, and possibly more so, is the issue of assured fuel disposition (including arrangements to “take back” spent fuel from the recipient country, though not necessarily to the same country that supplied the fresh fuel). For a significant expansion of global nuclear power, the issue of uncertain and potentially very high spent fuel management and disposal costs is unattractive and possibly prohibitive for some new nuclear power states.

From a nonproliferation perspective, the value of integrating front- and back-end fuel services lies in increasing the disincentives for countries to pursue independent development of enrichment or reprocessing. The value of such services is both economic – decreasing the barriers to entry into the use of nuclear power – and political – building public confidence in the country's ability to manage the actual and perceived liabilities of nuclear power. Many countries have adopted interim storage as their de facto spent fuel management strategy. This strategy defers most costs for several decades and may reduce the net present cost of spent fuel management, but imposes a growing liability of spent fuel storage costs – and growing incentives over time to switch to a spent fuel strategy based on an independent reprocessing program. The value of integrated fuel services, therefore, may be greatest for countries embarking on nuclear power programs, since they face the largest barriers to entry into this market and are not yet facing legacy spent fuel management liabilities.

4.3.3.3 Issue - Timing

The timing of when to introduce spent fuel recycling is an economic issue as well as a technological one. Delaying recycling increases the stock of spent fuel that must be managed but also allows for further development of technology and options to deal with the spent fuel. To the extent that recycling generates significant public benefits, it may be desirable to initiate reprocessing before it is viable on purely commercial terms. One possibility is a "two-tier" recycling system involving the initially less expensive LWR mixed oxide (MOX) cycle. This LWR MOX cycle could be converted to a fast reactor cycle if and when the economics of that cycle become more competitive. In nonproliferation terms, this may avoid the opportunity cost of delay in offering back-end or comprehensive front- and back-end fuel services. In purely economic terms, it involves balancing the opportunity cost of using recycling methods that produce waste forms that may be relatively costly to manage with the avoided cost of continued spent fuel storage.

4.3.4 U.S. Engagement and Leadership – the Path to Success

Currently, about two thirds of total spent fuel discharged annually on a world-wide basis is generated in six countries that are commercial reprocessing technology holders, namely, the United States, the UK, France, Russia, China, and Japan. In addition, these six nations have by far the largest existing stocks of stored spent fuel since they have been engaged in the commercial nuclear power endeavor longer than most other countries. In addition, most of the spent fuel generated in Taiwan and South Korea is subject to U.S. prior consent rights based on the historic extent of U.S. nuclear fuel supply. Control over the fate of this material gives the United States considerable influence over global back-end services.

However, the overall share of U.S. companies in nuclear export markets (particularly fuel exports) has declined steadily. Considering that much of the anticipated growth in nuclear power is projected to take place in countries where the United States has not established nuclear supply relationships, this suggests that U.S. influence on fuel-cycle related nonproliferation outcomes (through the system of nuclear trade obligations and other market effects) could continue to decline. This might well be the case unless energy policies and economics shift in favor of increased provision of reliable front- and back-end services and use of nuclear power in the United States.

The first market opportunities appear to be in providing power reactors and front-end services, with opportunities in back-end services developing over time. One long term key to success in including provision of back-end services could be for the six recognized commercial reprocessing technology holding states to work together to address the issue of full fuel cycle assurances and services as a group, given that they currently operate most reactors and generate a large majority of the global spent fuel discharges. In addition, these technology holders may wish to engage with potential users of back-end fuel services to develop and assess back-end service arrangements that would be attractive to other countries. Such mechanisms were proposed under the GNEP Strategic Plan, which calls for supplier states to cooperate to provide "cradle-to-grave" fuel services worldwide.[60] If the United States does not become an active participant in providing back-end services, either directly or through partnership with other back-end service providers, it could limit the U.S. ability to influence how other states manage their nuclear fuel cycle requirements.

4.4 ROLE OF INTERIM STORAGE OF SPENT FUEL

To influence states' decisions regarding acquisition of reprocessing facilities, the assurance of back-end services would need to be credible in the near to medium term. Even if the United States decided to pursue changes to the back-end of the domestic fuel cycle, the need for this credibility could occur well before the infrastructure needed for commercial spent fuel reprocessing and recycle would be in place in the United States. Even with aggressive implementation of the GNEP vision, the time frame for substantial recycle capacities to come online would require a near-term transition period during which interim storage of spent nuclear fuel would play a vital role in the provision of back-end services. As noted earlier, such interim storage could take place in the recipient country (either at the reactor site or at an away-from reactor interim storage facility), in a supplier state, where the storage might be connected to operation of a reprocessing facility or on an interim basis pending further development of the fuel cycle, or in a third country, perhaps as part of a regional or international interim storage facility.

Determining which option, or combination of options, makes sense, will require a careful balancing of logistical, legal, and cost concerns, assurance of safety and environmental protection, any supplier commitments to take spent fuel, maintenance of effective physical protection and safeguards (including during transportation of spent fuel), and coordination with available downstream reprocessing and recycling options. Simply put, interim storage could be an important element of a transition to fuel cycles in which spent fuel storage gives way to reprocessing and recycling or to permanent disposal.

In general, it appears that expanded safe and secure interim storage of spent fuel could be a viable transition strategy to "buy time" until permanent, sustainable solutions for spent fuel management can be brought to commercial scale if public acceptance issues could be addressed satisfactorily. If carbon management policies end up stimulating the nuclear power sector, the amount of spent fuel generated could be substantially higher. A majority

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[60] Global Nuclear Energy Partnership Strategic Plan, Department of Energy, Office of Nuclear Energy, Office of Fuel Cycle Management, January 2007, http://www.gnep.energy.gov/pdfs/gnepStrategicPlanJanuary2007.pdf.

of that spent fuel will likely be stored prior to any other treatment. Expanded use of interim storage , either in the recipient country, a supplier state, or a third country, would be essential to near- and mid-term management of the back end of the fuel cycle regardless of which recycle technologies (if any) are ultimately deployed.

5. DESCRIPTION AND TECHNICAL ASSESSMENT OF GNEP PEIS FUEL CYCLE ALTERNATIVES AND TECHNOLOGIES

5.1 INTRODUCTION

This chapter describes programmatic alternatives and technologies under consideration by the GNEP program and summarizes their technical nonproliferation impacts. Until specific technology alternatives are identified more detailed analysis would be premature. Consequently, only the more important considerations will be mentioned here. More detailed and comprehensive assessments may be conducted to support future decisions regarding those specific alternatives. The GNEP programmatic environmental impact statement (PEIS) analyzes the range of reasonable alternatives (i.e., representative nuclear fuel cycle choices) for satisfying the purpose and need for agency action. The purpose and need includes to reduce the proliferation risk of using nuclear power and to reduce the impacts associated with the disposal of spent fuel. The alternatives fall in one of three general categories:

- **Once-Through**: Use of uranium-based or uranium/thorium-based fuel in thermal-neutron reactors. Variations in moderation or fuel type may alter the proliferation risk and environmental impacts by changing isotopic composition or physical integrity of spent fuel. The use of thorium may alter the proliferation risk and environmental impacts by changing the isotopic and elemental composition of spent fuel.

- **Partial Actinide Recycle**: One or more recycles in thermal-neutron reactors of actinide elements recovered from spent fuel. Reducing the quantities of one or more of the higher actinide elements from the wastes destined for disposal may alter the proliferation risk and environmental impacts.

- **Full Actinide Recycle**: One or more recycles in fast-neutron reactors of actinide elements recovered from spent fuel. Essentially eliminating, or at least reducing, the higher actinide elements from the wastes destined for disposal may alter the proliferation risk and environmental impacts.

For the purposes of the PEIS, the following specific alternatives have been selected as being representative of options in each of these categories.

5.2 FUEL CYCLE ALTERNATIVES

This section describes each of the domestic programmatic alternatives evaluated in the GNEP PEIS and outlines briefly some of the key technical characteristics related to proliferation and security risk, safeguards, and proliferation-relevant aspects of the fuel cycle. These technical characteristics, normalized for the generation of 100 GW[61] of electricity, are summarized for each of the 9 alternatives in Table 5.1. In particular, a major

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[61] The analysis in the GNEP PEIS is based on capacity to produce 200 GW of electricity per year. The GNEP PEIS also discusses impacts associated with 100 GW, 150 GW, and 400 GW production capacities.

reduction in waste management requirements would support the GNEP objective of developing a concept for comprehensive fuel services to limit the spread of sensitive fuel cycle capabilities – enrichment and reprocessing – beyond current technology holders. As noted in previous chapters, one must distinguish proliferation risks, where the risk is acquisition of nuclear weapons by a non-nuclear weapon state (NNWS), from physical security risks, where the proliferation threat is a non-state actor. These issues are addressed more comprehensively in the assessments in Chapter 6. The technical characteristics listed in the following table, are explained in detail in sections 5.2.1 through 5.2.9.

Alternative	**LEU feed MTIHM/yr**	**LEU Feed enrichment**	**TRU to waste MT/yr**
No-Action (LWR)	2170	4.4%	28
HWR	5300	2.1%	38
HTGR	770	14.0%	16
Thorium Alternative: Seed Pins Blankets	 410 80	 19.9% 12.2%	7.8
LWR/LWR (MOX-U-Pu) Alternative	1660	4.6%	8.3
LWR/HWR (DUPIC) Alternative	1800	3.5%	15
LWR/HTGR	Unknown	Unknown	Unknown
Fast Reactor Recycle (figures for fast reactor component alone)	1350	n/a	0.1
Thermal and Fast Recycle (figures for fast reactor component alone)	1400	n/a	0.11

Table 5.1 Parameters of interest for nonproliferation for the GNEP alternatives[62]

5.2.1 No-Action Alternative

The no-action alternative is a continuation of the present practice, which is represented as the "once-through" (i.e., no recycle) use of enriched uranium oxide (UO_2) fuel in light water reactors (LWRs), storage of discharged spent fuel for an extended period of time (typically 25 years or more to allow for cooling and radioactive decay[63]), followed by disposal of the spent fuel in an engineered repository in a geologic environment. This option would nominally use uranium enriched to 4.4% and would continue the current practice of uranium enrichment up to 5% for civilian use. Use in LWRs would continue to generate spent fuel at

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[62] "*Performance Summary of Advanced Nuclear Fuel Cycles*", R.A. Wigeland, GNEP-TIO-AI-AI-RT-2008-000268, Rev. 2, July 2008.

[63] The storage time of twenty-five years is a value used in this NPIA to facilitate the analysis and may not represent actual storage times. In addition, these storage times were not part of the GNEP PEIS.

a rate of 2170 Metric Tons Initial Heavy Metal (MTIHM) per year for 100 GW[64] of electricity generation. The assumed fuel burnup (irradiation level) at discharge is 51 GWd/MT.[65] At discharge about 5% of the initial heavy metal inventory has been converted to fission products, while about 1.3% of the initial heavy metal inventory has been converted to higher actinide elements such as plutonium. Under these assumptions, the plutonium typically is roughly 51% Pu-239 at discharge, increasing to roughly 54% Pu-239 after 10 years of storage due to the decay of the plutonium isotopes. Details on uranium usage and spent fuel production are listed in Table 4.8-4 in the GNEP PEIS. Spent fuel is not reprocessed in this alternative.

The no-action alternative presents well-understood proliferation and security risks. Well-established international safeguards measures are being applied by the International Atomic Energy Agency (IAEA) world-wide at thermal power reactors operating on a once-through fuel cycle, and physical protection guidelines and standards have been established. Storage of spent fuel assemblies in reactor cooling pools and in dry-cask storage facilities present well-understood safeguards requirements and challenges; the spent fuel assemblies can be subject to item-counting safeguards approaches. Although the IAEA has yet to safeguard a geologic repository of any sort, a general safeguards concept has been developed, so that clandestine removal of spent fuel assemblies from a geologic repository should be detectable.

The no action alternative does not reduce the waste management requirements to support the major expansion of worldwide nuclear power use and, therefore, offers no new technological approach that might better enable the implementation of comprehensive nuclear fuel service arrangements including back-end fuel services. It also provides no reduction in the need for uranium enrichment that will therefore drive an expansion of worldwide enrichment capacity, and could lead to the spread of centrifuge enrichment programs to additional countries.

5.2.2 HWR alternative

The HWR alternative involves the once-through use of natural or low-enriched UO_2 fuel in heavy-water-moderated reactors (HWRs), storage of the discharged spent fuel for an extended period of time (typically 25 years or more to allow for cooling and radioactive decay), followed by disposal of the spent fuel in an engineered repository in a geologic environment. The technology examined for this alternative was the ACR-700, an advanced CANDU[66] design that uses low-enriched uranium (LEU) with a U-235 enrichment of 2.1%, less than the current enrichment levels required for use in LWRs. This HWR alternative would continue the need for uranium enrichment, albeit at a lower level than present.

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[64] Unless otherwise stated, this Assessment uses gigawatts (GW) as a measure of electricity generation rather than a measure of thermal output from the nuclear reaction. Typical efficiencies are on the order of 33%, so one GW electric corresponds to roughly 3 GW thermal.

[65] Burnup is measured in terms of gigawatt-days of thermal output per metric ton of initial heavy metal. This measure involves thermal rather than electrical output since burnup is a measure of how much energy has been extracted from fuel.

[66] CANDU refers to CANada Deuterium Uranium reactor produced by Atomic Energy of Canada, Ltd.

Current CANDU reactors can operate on natural uranium, although the ACR-700 design uses enriched uranium in order to reduce the amount of spent HWR fuel per GW by increasing the fuel burnup at discharge to 20.5 GWd/MT. Usage in HWRs would generate spent fuel at a rate of about 5300 MTIHM per year per 100 GW. At discharge, for fuel irradiated to 20.5 GWd/MT burnup, about 2.1% of the initial heavy metal inventory has been converted to fission products, while about 0.7% has been converted to higher actinide elements such as plutonium. Due to the lower burnup for the HWR fuel compared to LWR fuel, the plutonium is about 59% Pu-239 at discharge and 62% Pu-239 after 10 years of storage. Although the amount of transuranic material per MT of uranium is lower as compared to spent LWR fuel, the uranium use per year is higher (5300 vs. 2170 MTIHM) so that the plutonium production and the total transuranic material produced per 100 GW is higher, as shown in Table 4.8-4 of the PEIS.

From a nonproliferation and security perspective, as with LWRs in a once-through fuel cycle, this alternative leaves plutonium in spent fuel assemblies. However, HWR assemblies are both more numerous and smaller than spent LWR assemblies, and the safeguards resource burden incurred by the IAEA in safeguarding HWR reactors is considerably higher than in safeguarding LWRs. This higher safeguards burden could become a serious concern in a fuel cycle in which HWRs replaced LWRs. This would be especially so if this occurred in non-nuclear weapon states where the requirement to apply safeguards would impact IAEA resources. In addition, CANDU reactors are designed for on-load refueling, which is designed to provide a higher capacity factor but also presents a proliferation issue. Specifically, fuel in these reactors can be irradiated to any desired burnup and removed without having to shut down and, therefore, could be used to produce plutonium high in Pu-239 content. Reprocessing methods for HWR spent fuel have been developed and used in some parts of the world, although in this GNEP alternative spent fuel would not be reprocessed. In contrast to LWRs, which must be shut down before discharging spent fuel (a highly detectable event), HWRs constantly discharge spent fuel.

HWRs operating on a once-through fuel cycle generate more spent nuclear fuel per GW than do LWRs, and a once-through HWR fuel cycle would pose similar repository challenges as does the LWR once-through fuel cycle. HWR assemblies also contain the same heat-generating transuranic elements that impact repository thermal loading and ultimately the design for additional repository capacity. A once-through HWR fuel cycle would offer no significant advantages over the LWR once-through fuel cycle in enabling the implementation of comprehensive fuel services.

5.2.3 HTGR Alternative

The HTGR alternative is the once-through use of enriched UO_2 fuel in high-temperature gas-cooled graphite-moderated reactors (HTGRs), storage of the discharged spent fuel for an extended period of time (typically 25 years or more to allow for cooling and radioactive decay), followed by disposal of the spent fuel in an engineered repository in a geologic environment. The alternative examined in the PEIS uses prismatic graphite blocks in the core region, with the fuel in kernels embedded in fuel compacts that are loaded in the fuel holes in the graphite blocks. The HTGR uses LEU with a U-235 enrichment of 14%, significantly higher than the current enrichment levels required for use in LWRs. This would not only continue the use of uranium enrichment, but would require enrichment to higher levels. The fuel burnup at discharge is 100 GWd/MT. Usage in HTGRs would generate spent fuel at a rate of about 770 MTIHM per year per 100 GW. At discharge, for fuel irradiated to 100 GWd/MT burnup, about 11% of the initial heavy metal inventory has been converted to fission products, while about 2.1% has been converted to higher actinide elements such as plutonium. The plutonium is about 46% Pu-239 at discharge and 51% Pu-239 after 10 years of storage, a result of the relatively high burnup for the HTGR fuel. Although the amount of transuranic material per MT of uranium is higher than for the LWR, the LEU use per year is lower (770 vs. 2170 MTIHM) so that the plutonium production and the total transuranic material production for 100 GW is lower (about 60% as much, as shown in Table 4.8-4 of the GNEP PEIS). This reduction is due in large part to the relatively high 47.7% thermal efficiency for electricity production of the HTGR, compared to 33% for the LWR. The spent HTGR fuel is not commonly reprocessed, although methods have been proposed for processing the silicon carbide fuel kernels in the graphite matrix of the compact. Reprocessing this spent fuel would also require removing the fuel compacts from the graphite blocks after discharge, and reprocessing of spent HTGR fuel is likely to be technically difficult and economically attractive.

From a nonproliferation perspective, HTGRs operated in a once-through fuel cycle offer a number of advantages compared to LWRs. However, the higher enrichment level required by HTGR fuel would mean that enrichment plants supporting an HTGR fuel cycle would normally be operating at enrichment levels a fraction below that needed to produce high-enriched uranium (HEU, defined as 20% U-235 or higher), which might place a greater burden on safeguards at such facilities to verify non-production of HEU or detect clandestine diversion of the 14% enriched product to a clandestine enrichment plant that could complete enrichment to higher levels. Nuclear material accountancy for some types of HTGRs would be more complicated, if they involve large numbers of very small fuel elements, and reverification of inventory in the event of loss of continuity of knowledge of the spent fuel for HTGRs would be a significantly greater challenge than it would be for an LWR. HTGRs produce about one-third as much spent fuel per GW as LWRs. Although the Pu-239 percentage in HTGR spent fuel is less than that for LWRs, the higher transuranic material per MT of uranium would continue to pose the same geologic disposal issues and constraints associated with other once-through alternatives that the GNEP program seeks to alleviate. Thus, it is not clear that the HTGR once-through fuel cycle offers any technical advantages in enabling the implementation of comprehensive fuel services.

5.2.4 Thorium Alternative

The thorium alternative is the once-through use of thorium and uranium oxide (ThO_2/UO_2) fuel in LWRs. Enriched uranium is included in the fuel to support the fission process. Discharged spent fuel would be stored for an extended period of time (typically 25 years or more to allow for cooling and radioactive decay) and eventually disposed of in an engineered repository in a geologic environment. Although Th-232 is included in the fuel for breeding U-233, there is a substantial amount of LEU in the fuel both for supporting the fission reaction and for providing U-238 to dilute the generated U-233, so that the percentage of U-233 in the discharged uranium remains low. Since standard-sized fuel assemblies are used, only the fuel composition is changed from typical LWR fuel. The alternative examined in the PEIS is an option in which two types of fuel pins are used, either in different assemblies or within each fuel assembly; "seed" pins that contain LEU at 19.9% U-235 enrichment and "blanket" pins that contain both LEU at 12.2% U-235 enrichment and natural thorium. The enrichment levels are significantly higher than the current enrichment levels required for use in LWRs. Consequently, this would not only continue the use of uranium enrichment, but would require enrichment to higher levels. The fuel burnup at discharge is 75 GWd/MT for the seed fuel pins and 149 GWd/MT for the blanket fuel pins. Usage of thorium-based fuel in LWRs would generate spent fuel at a rate of about 1025 MTIHM per year per 100 GW. At discharge, the Pu-239 fraction is 49%, slightly less than for the LWR in the no-action alternative. The amount of plutonium per 100 GW is 8.5 MT/yr, significantly less than the 24 MT/yr generated in the no-action alternative. Reprocessing methods have been developed for thorium-oxide fuel, so in many respects the thorium alternative has characteristics similar to the no-action alternative.[67]

From a nonproliferation perspective, the once-through thorium cycle is very similar to the no-action alternative and presents reasonably well-understood proliferation risks. Well-established international safeguards measures are being applied by the IAEA at thermal power reactors operating on a once-through fuel cycle that could reasonably be applied to the thorium once-through fuel cycle, although the introduction of "blankets" and U-233 add a minor increased level of complication to the safeguards approach. Safeguards requirements for storage and disposition of spent fuel would be essentially the same as for LWRs.

The higher enrichment level that the thorium fuel alternative requires would mean that enrichment plants supporting a thorium fuel cycle would normally be operating at enrichment levels a fraction below that needed to produce HEU. At some enrichment plants, this could complicate implementation of safeguards measures designed to detect production of HEU or to detect clandestine diversion to an enrichment plant that could complete enrichment to higher levels. This fuel cycle would create greater overall uranium enrichment requirements than the "no action" alternative. A once-through thorium fuel cycle would offer no significant advantages over the LWR once-through fuel cycle in enabling implementation of comprehensive fuel services.

5.2.5 LWR/LWR (MOX-U-Pu) Alternative

In this partial actinide recycle alternative, LWRs are used for the recycle of plutonium in mixed-oxide (MOX) fuel. In general, there would be multiple recycles of plutonium recovered from spent LWR fuel using mixed plutonium and uranium oxide (Pu-MOX) fuel in LWRs.[68] In the equilibrium case, all reactors are using MOX-U-Pu and the discharged spent fuel is reprocessed (typically by chemical means) to recover the uranium and

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[67] Y-12 document number Y/PTA-02013/Part 4/R1, presented by Duane Starr.

[68] In current practice, spent fuel is normally recycled only once. While multiple recycle is technically feasible, it has not been considered economically viable, largely because it leads to increasing concentrations of higher isotopes of transuranic elements, which pose fuel design and waste management challenges.

plutonium. The recovered plutonium and uranium are used for fabrication of new fuel for LWRs. The other transuranic elements and the fission products are placed in the processing waste. Uranium enrichment is required in order for the fuel to support the fission process in the reactors, with the LEU enriched to 4.6% in U-235, which is consistent with current LWR enrichment levels. Use of Pu-MOX in an indefinite recycle in LWRs would generate TRU in waste at the rate of 8.3 MT/yr. The reprocessing waste is stored for an extended period of time (the total time from discharge to disposal would typically be 25 years or more to allow for cooling and radioactive decay), followed by disposal in an engineered repository in a geologic environment.

The Pu-239 fraction in the spent fuel is 34%, substantially less than for the previous alternatives. This low fraction is the reason that a slightly higher 4.6% U-235 enrichment is needed for the corresponding MOX blend to maintain the fission reaction in the reactors using this Pu-MOX. Reprocessing of spent fuel is required in this case for the recovery of the plutonium, but could be performed with a process that does not separate pure plutonium and instead generates a plutonium-uranium product.

The LWR MOX partial recycle alternative, in which a U-Pu mixed-oxide fuel is used, presents a number of nonproliferation issues. Effective safeguards for the necessarily very large throughput reprocessing and MOX fuel fabrication facilities would demand significant resources and systems. Compared to the “no action” alternative, there would be a slight reduction in safeguards resources required for the smaller amount of enrichment services needed. While using a reprocessing technology that does not result in separation of pure plutonium would make clandestine efforts to misuse an aqueous reprocessing plant to produce separated plutonium readily detectable under IAEA safeguards, the COEX®, NUEX®, and UREX+ suite of aqueous alternatives to PUREX can be converted to separate pure plutonium. Following any withdrawal or breakout from nonproliferation and safeguards obligations, the time required to convert such plants to separating pure plutonium ranges from several days to a number of weeks, depending on the complexity of the process flow sheet.

The COEX®, NUEX®, and UREX+ suite alternatives to PUREX produce mixed products that would be considered Category I nuclear materials for physical protection purposes, the same as the product of PUREX. Likewise, following withdrawal or breakout, unauthorized separation of plutonium from the product of an alternative separation process by the state would be readily achievable using well understood technology. In addition, the product of a COEX® plant (a 50:50 uranium and plutonium mix) would be virtually identical to the product that would be produced in a PUREX plant that also includes blending of separate uranium and plutonium nitrate solutions prior to oxidation of the final product, such as that used in Japan’s Rokkasho Reprocessing Plant.

Although intermediate products might have different compositions, the ratio of uranium and plutonium in the fabricated MOX fuel product would be identical for fuel cycles that would employ PUREX or alternative aqueous processes to produce fuel for thermal reactors. A thermal recycle-only option would not alleviate the impact that inclusion of minor actinides in high level waste streams would have on the additional repository capacity required, unless the minor actinides were separated and then saved for future transmutation. To the extent that minimizing the required additional repository capacity would support the implementation of comprehensive fuel services, the thermal recycle-only approach offers no significant advantage over the LWR once-through fuel cycle.

5.2.6 LWR/HWR (DUPIC) Alternative

The DUPIC partial actinide recycle alternative employs a once-through use of enriched UO_2 fuel in LWRs, followed by mechanical and high-temperature oxidation/reduction processes after discharge of the spent LWR fuel to recover the fuel for reconstitution into fuel for once-through use in HWRs. The discharged HWR spent fuel and the processing waste are stored for an extended period of time (typically 25 years or more total time from discharge to disposal to allow for cooling and radioactive decay), followed by geologic disposal in an engineered repository. This option would continue the use of uranium enrichment, but since the LWR spent fuel in a DUPIC cycle is designed to have a discharge burnup of only 35 GWd/MT, the required uranium enrichment only needs to be 3.5% U-235, lower than for the higher burnup LWR fuels used today.[69] The discharge burnup for the reconstituted fuel used in the HWRs is 15 GW/MT, so that the overall burnup is 50 GWd/MT as in the "no action" option, but achieved with lower uranium enrichment. This process would continue to generate spent fuel at a rate of approximately 1800 MTIHM per year per 100 GW. The Pu-239 fraction is 39%, and overall plutonium production is lower as well.

The dry processing does not separate any of the transuranic material from the uranium, and only the volatile fission product elements (accounting for roughly 50% of the fission product radioactivity) are released and recovered as waste. However, the process of physically destroying the integrity of the fuel assembly removes some of the inherent nonproliferation benefit associated with the current once-through fuel cycle. While the processing of the dry powder that is the interim product of DUPIC does not yield pure plutonium, it would provide an opportunity for a proliferator to access material in much more portable configurations than full size fuel assemblies. The reduction of the fuel assembly from discrete item to bulk material presents numerous and less detectable opportunities to divert material for processing to other facilities. However, the need to conduct the entire process, including fabrication of the DUPIC product into "fresh" fuel, within shielded cells would complicate the undetected diversion of this material. As noted above, CANDU reactors are capable of on-load refueling, which provides the capability for using these reactors for irradiation of uranium targets or fuel assemblies to any desired burnup, meaning to any desired Pu-239 fraction.

5.2.7 LWR/HTGR Alternative

This partial actinide recycle option would utilize high-temperature gas-cooled reactors (HTGRs) to consume transuranics (this fuel cycle will be referred to as the "HTGR Deep Burn Fuel Cycle"). HTGRs have been considered for the deep-burn (relatively high consumption) of transuranic fuel derived from LWR spent nuclear fuel (spent fuel).
A representative system is the deep burn modular helium reactor (DB-MHR) concept being

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[69] Use of higher burn-up LWR fuel in the DUPIC fuel fabrication process is being demonstrated.

developed by General Atomics. The essential feature of the concept is the use of carbide-coated fuel particles (TRISO) that are both strong and highly stable under irradiation. This fuel can also potentially be used as a durable form for permanent disposal of the spent fuel. Recent calculations have suggested that a transuranic material consumption level as high as 60 percent is attainable in a single-pass in the DB-MHR system. The HTGR Deep Burn Fuel Cycle would require one or more facilities to recycle LWR spent fuel (using the same advanced separation options as the Fast Recycle Alternative) and to fabricate HTGR fuel made up of transuranic elements. Based on a steady-state material balance for the HTGR transuranic consumption, it is estimated that approximately four LWRs would be required for every HTGR. Since relatively little experimental data is available for this option, it warrants further study from a nonproliferation perspective.

5.2.8 Fast Reactor Recycle Alternative

This full actinide recycle alternative starts with the once-through use of enriched UO_2 fuel in LWRs, followed by reprocessing to recover the actinide elements (uranium and transuranic elements). The reprocessing waste contains fission products and trace (process-loss) amounts of the actinides. The actinides recovered from reprocessing spent LWR fuel are used as part of the contents of new fast-neutron reactor fuel. The fast-neutron reactor alternative in the PEIS assumes a transuranic conversion ratio of 0.5 (ratio of transuranic material created vs. transuranic material destroyed during an irradiation cycle in the reactor),[70] which means that there is net consumption of transuranic material and, therefore, new transuranic material from spent LWR fuel is needed for each recycle. Spent fast reactor fuel is also reprocessed to recover the actinides, which are also added to new fast reactor fuel, so that the transuranic actinides are recycled indefinitely, with a fraction consumed with each recycle. All processing waste, which contains only trace quantities of actinides, is stored for an extended period of time (depending on the time of processing, with the total time from discharge to disposal typically 25 years to allow for cooling and radioactive decay), followed by disposal in an engineered geologic repository.

The LWRs used in the first cycle with LEU in this alternative are the same as in the no-action alternative, with the same uranium enrichment requirements for about 51 GWd/MT discharge burnup, so uranium enrichment would continue in this case. The fast reactor, which does not require uranium enrichment, has a discharge burnup of 107 GWd/MT. The discharged LWR fuel has the same composition as the fuel discussed in the no-action alternative. The plutonium content of the fuel for the fast-neutron reactors is significant, even at discharge. The initial fast reactor fuel composition has about 32% transuranic material, with plutonium comprising about 88% of the transuranic material. The transuranic material is indefinitely recycled in the fast reactor, with makeup transuranic material added from additional reprocessed LWR spent fuel. Reprocessing of the fast reactor fuel can be done by one of several methods that do not separate plutonium either from the rest of the transuranic material or the uranium. The process loss of the transuranic material to waste is estimated at 0.1%.

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[70] The conversion ratio may be defined in various ways, and is a measure of the efficiency by which a fast reactor consumes (if the ratio is less than one) or generates (if the ratio is greater than one) fissionable material.

From a nonproliferation perspective, this option poses nonproliferation issues similar to those associated with reprocessing and the characteristics of reprocessing products that are encountered in the thermal recycle-only option. Because fast reactors are used to burn actinides in this alternative, it is one of the two fuel cycle alternatives examined in the PEIS that offers large reductions in geologic disposal requirements. This has a positive impact on the viability of comprehensive fuel services. IAEA safeguards would need to verify that the reactor was not operated as a breeder, using a uranium blanket to generate additional plutonium. Nuclear material accountancy methods, especially those relying upon nondestructive assay techniques, would be somewhat more complicated due to the presence of minor actinides. However, the need to conduct the entire process, including fabrication of the product into "fresh" fuel, within shielded cells would complicate the undetected diversion of this material. Use of pyrometallurgical technologies to produce a transuranic metal product for use in fast reactors would present additional safeguards challenges, particularly with respect to the accuracy of nuclear material inventory accountancy, though diversion of nuclear material from the facility should be readily detectable. The transuranic product from such a facility can be highly enriched in transuranic material, most of which would be plutonium, and the plutonium could be separated from this product, either in a separate, aqueous facility or, perhaps with greater difficulty, in a pyroprocessing facility.

5.2.9 Thermal and Fast Reactor Recycle Alternative

This full actinide recycle alternative is similar to the previous one, in that it starts with the once-through use of enriched uranium fuel in LWRs, followed by reprocessing to recover the actinide elements (uranium and transuranic elements). In this case, one (typically plutonium) or more of the actinide elements recovered from reprocessing spent LWR fuel are used as part of the contents of new LWR fuel for one recycle (or perhaps two) in LWRs. The discharged spent LWR fuel containing the recycled actinides is then reprocessed to recover its actinide elements. For both cycles the reprocessing wastes contain the fission products, and trace amounts of the actinides. All of the actinide elements recovered from reprocessing LWR spent fuel, whether recycled in LWRs or not, are used in new fast reactor fuel. The fast reactor design used as the example has a conversion ratio of 0.5, so that all transuranic elements are recycled indefinitely in fast reactors, consuming transuranic material with each recycle. Because fast reactors are used to burn actinides in this alternative, it is one of the two fuel cycle alternatives examined in the PEIS that offers large reductions in geologic disposal requirements once fully implemented. All processing waste is stored for an extended period of time (depending on the time of processing, with the total time from discharge to disposal typically 25 years to allow for cooling and radioactive decay), followed by disposal in a geologic repository. The LWR operating on enriched uranium fuel is the same as for the no-action alternative, with a discharge burnup of about 51 GWd/MT. The specific alternative examined in the PEIS has a single recycle of plutonium in an LWR as U-Pu MOX, again with a discharge burnup of about 50 GWd/MT. The fast reactor spent fuel has a discharge burnup of 105 GWd/MT. The discharged spent MOX-U-Pu fuel has a plutonium content of about 6.2%. This spent fuel is reprocessed to recover all of the transuranic material which is then used in the fast reactor fuel.

The process loss of the transuranic material to waste is assumed to be 0.1%.[71] The plutonium content of the fast reactor fuel is significant; the initial fuel composition has about 38% transuranic material, with plutonium comprising about 82% of the transuranic material. The transuranic material is returned to the fast reactor and is indefinitely recycled, with additional transuranic material added from reprocessed LWR spent fuel to make up for what is consumed. Reprocessing of the fast reactor fuel can be done by one of several methods which do not separate plutonium either from the rest of the transuranic material or the uranium.

From a nonproliferation perspective, this option poses the same nonproliferation issues that are encountered in the fast-neutron reactor option, with minor changes in emphasis.

5.3 NONPROLIFERATION CHARACTERISTICS OF FAST NEUTRON REACTORS

A major component of the full actinide recycle GNEP programmatic alternatives is the use of fast neutron reactors for the transmutation and destruction of the higher actinide elements recovered from spent LWR fuel, as well as those from recycled fast reactor fuel. The fast reactor is being considered since it provides superior ability to operate with substantial loading of the higher actinide elements without generating large amounts of progressively higher isotopes as occurs with irradiation in a thermal neutron spectrum. Absorption of neutrons by the actinide elements can lead to the creation of progressively higher actinide elements, such as californium and berkelium, whose presence makes fuel handling and processing increasingly difficult due to the intense radiation field. This tendency is considerably more pronounced in a thermal neutron spectrum.

Many isotopes that are more likely to be neutron absorbers in the thermal neutron spectrum and negatively impact the neutron balance in a thermal reactor, readily undergo fission in a fast spectrum. The neutron balance would be more favorable in a fast reactor, with less negative impact on the ability of the reactor to achieve and maintain criticality.

There are several characteristics of fast reactors that are relevant to an assessment of the nonproliferation impact of this alternative. Fast reactors breed fissile material (Pu-239) more effectively than do thermal reactors. It is fairly simple to design a fast reactor using U-238 that has a net increase in the amount of fissile material during the irradiation cycle, also referred to as “breeding,” so that the fissile conversion ratio (amount of fissile material created / amount of fissile material destroyed) is greater than 1.0; it can be as high as about 1.6 to 1.8. Conversely, it is straightforward to design a fast reactor with a conversion ratio less than 1.0 that “burns” the fissile material and produces less transuranic material than it consumes. It is worth noting that military plutonium production reactors in the weapons states all were thermal reactors. On-load refueling of those production reactors allowed continuous operation. Low irradiation times yielded plutonium well-suited for weapons use, since with very short irradiation times there is very little buildup of the higher plutonium

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[71] This is particularly important for fast reactors, which have a relatively high concentration of transuranics and need to be recycled multiple times. Such efficiencies are challenging but have been demonstrated for aqueous separations; they have not yet been demonstrated for pyroprocessing.

isotopes in these reactors and the product is mostly Pu-239. The same would be true with respect to depleted or natural uranium blanket assemblies in a fast breeder reactor, where the plutonium production is primarily Pu-239. Therefore, designs that do not have a blanket region, and cannot be modified readily to add a blanket, have nonproliferation advantages over those that do.

5.3.1 Fast Reactor Operation

Fast reactors are operated for an irradiation cycle length typically expected to be from one year to 18 months. At the end of each irradiation cycle, a fraction of the core (typically between 1/4 and 1/3) is removed and replaced with fresh fuel. The spent fuel is stored in the reactor vessel to provide for sufficient cooling until the decay heat decreases to levels low enough to allow for simpler handling and removal of the fuel to external storage locations. It would be very difficult or impossible to operate the reactor with even one assembly removed from the reactor core, since even slight movement of an assembly has substantial reactivity feedback effects, altering reactor power.

The coolant of choice for most fast reactors operated to date has been liquid sodium or an alloy of liquid sodium. Molten lead or a lead alloy has also been used, and in principle it is possible to use gas at high pressure or other materials as well. The chemical reactivity of liquid sodium is such that the reactor needs to be sealed and any gas volumes filled with an inert gas to prevent a violent reaction with air. All of this makes it almost impossible to operate a fast reactor that has on-load refueling for efficient generation of weapons-usable materials in the reactor core. This means that the fissile materials are available only from the fresh or spent fuel assemblies (including blankets, if any – see below), where the spent fuel is either stored within the reactor vessel to mitigate the high decay heat, or in the spent fuel storage location for older spent fuel.

Fast reactors can be designed to either emphasize breeding Pu-239 or burning the higher actinides. At equivalent burnup, fast reactor spent fuel will contain plutonium with a higher isotopic fraction of Pu-239 and less of the higher actinides than spent fuel from thermal reactors. Some of the fast reactors operated to date have also consumed greater fractions of the initial heavy metal loadings than have been achieved with thermal reactors.

5.3.2 Fast Reactor Fuel and Spent Fuel Characteristics

Unlike thermal reactor fuel, fast reactor fuel is much higher in fissile content due to the more prominent neutron capture in U-238 as compared to Pu-239 fission in a fast neutron spectrum and the smaller cross-sections for neutron capture in both isotopes. Typical plutonium content is on the order of 15% for a fast reactor that is nominally "break-even," that is, the amount of fissile material created during the cycle is about equal to the amount of fissile material destroyed. For burner reactors, where there is a net consumption of fissile materials, the transuranic concentration is higher, with enrichment increasing as net consumption increases. For example, at a conversion ratio of 0.5, the transuranic concentration is likely to be in the range of 30%, while for a conversion ratio of 0.25, transuranic concentration can approach 50%. The presence of higher actinide isotopes in addition to plutonium increases this concentration, so that a fuel that contains the transuranics recovered from spent LWR fuel would have a slightly higher transuranic concentration than if only plutonium were used.

5.4 TECHNICAL NONPROLIFERATION CHARACTERISTICS OF SPENT NUCLEAR FUEL SEPARATION AND RECYCLING PROCESSES

The most effective way to destroy the transuranic elements generated by LWR operation is to fission them in fast reactors. In the full actinide recycle alternatives, the spent fuel discharged from the fast reactor would also be reprocessed to recover the actinides for reuse while the fission products would be encapsulated in durable waste forms for disposal. The goals for this reprocessing would be to reduce the proliferation risk relative to current practice by facilitating "take back" or return of spent fuel (though not necessarily to the same country that supplied it) and extending the geologic repository capacities. These goals are achievable by: (1) recycling transuranic elements for ultimate destruction and recovery of energy content, and (2) reducing the volume, long-term radiotoxicity, and heat load of waste in a geologic repository. The transuranic constituents are the primary nonproliferation concern; removing them from the waste stream makes it a much less attractive target.

Given the economies of scale associated with spent fuel reprocessing, high throughput facilities could be a cost effective approach where large quantities of spent fuel are generated. While larger facilities can be challenging to monitor for nonproliferation purposes, limiting the number and location of such facilities can mitigate their associated proliferation and security risks. In particular, limiting them to countries that already have reprocessing facilities, subject to effective international safeguards and physical protection measures, could substantially mitigate the proliferation and security risks associated with such facilities. Aqueous processes, which have been operated at the rate of hundreds of metric tons per year in commercial plants in other countries, are ideally suited for this large scale processing application. The PUREX process is an aqueous solvent extraction process that recovers uranium and plutonium from spent fuel that can be run continuously at a very high throughput. The UREX+ processes expand the range of separations beyond that which can be achieved with a simple PUREX process. Other aqueous separation processes involve co-extraction of uranium with plutonium and possibly other transuranics.

Pyrochemical processing methods are an alternative processing technology that is well suited for recycling spent fast reactor fuel. Because the solvent media can accommodate high concentrations of the fuel constituents, pyrochemical processes are more compact than aqueous processes. The compact and batch nature of pyroprocesses favors co-locating a fuel recycle facility with a group of advanced burner reactors thus reducing the need for a large centralized processing facility and possibly reducing transportation of separated transuranic material, including the plutonium, and the attendant physical protection concerns.

5.4.1 Performance Objectives

A number of performance objectives have been suggested to achieve the waste management goals of the GNEP program, which are also relevant to the nonproliferation objectives:[72]

- *Recover the uranium from spent fuel at sufficient purity that it can be conveniently stored for future use:* To achieve substantial benefits in reduction of waste volume, it is necessary to recover the uranium from spent fuel. The recovered uranium could be stored for future use. This "used" uranium would have lower enrichment than it had before going through the reactor. Disposal as a Class C low level waste is possible, but undesirable due to the value of the material for use as fuel. Treating the recovered uranium as feed material rather than as waste would also remove it as a potential feedstock for a nuclear weapons program.

- *Separate the actinides in solid product form:* Substantial improvements in repository capacity may be achievable by significantly reducing the amount of transuranic elements to be disposed of in a geologic repository. The recovered actinide elements would be used as fuel in thermal and fast spectrum reactors in some of the GNEP alternatives. Treating the recovered actinides as feed material rather than as waste would also be more consistent with their proliferation potential. Processes that do not separate pure plutonium may offer modest nonproliferation benefits. With respect to material attractiveness, the principal benefit comes from diluting the plutonium with comparable or greater amounts of other materials. The inclusion of radioactive elements also offers some benefits, particularly if some fission products are retained.

- *Separate short-lived isotopes, cesium and strontium:* Some alternatives assess the potential to recover and isolate the fission products that contribute the most to spent fuel heat load for the first century after discharge. The key fission products are cesium and strontium, which could be extracted for separate management. One option for management includes decay storage to low activity levels and disposal in an optimized facility. By making the extraction process highly selective and efficient, the resulting cesium/strontium product could be made to contain negligible quantities of transuranic material. This product's proliferation concern is very low; it could only be used in a dirty bomb and has no inherent explosive capability.

- *Recover and immobilize technetium and iodine:* One option for management of long-term radiotoxicity is to recover two key fission products, technetium and iodine, and immobilize them in alternative waste forms suitable for geologic disposal. Some alternatives could include this feature. This product's proliferation concern is very low. While it could be used in a dirty bomb, it has no inherent explosive capability.

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[72] 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), pp. 43-44, available at http://nuclear.inl.gov/gnep/d/gnep-tdp.pdf.

- *Provide robust waste forms:* All other constituents of the spent nuclear fuel, including structural materials and the other fission products, would be incorporated into suitable waste forms for disposal. These waste products are also of minimal proliferation concern, as they have no potential use as explosive materials.

5.4.2 Aqueous Separations Processes

5.4.2.1 PUREX

In the U.S. defense nuclear complex, the PUREX process was used in large-scale production operations at Hanford and Savannah River. The goal of these PUREX operations was to produce weapons usable material, rather than minimize waste. The PUREX process is not under consideration among the GNEP alternatives for civil nuclear power because its use entails the separation of pure plutonium. With the presidential decision to refrain from commercial nuclear fuel reprocessing a few decades ago, U.S. activities related to these technologies decreased. The downsizing of the U.S. nuclear weapons complex over the last decade or so has further decreased the U.S. knowledge and experience base. This loss of experience and R&D can diminish U.S. credibility as a role model and its ability to influence the decisions of others.

5.4.2.2 UREX+ processes

A number of potential flow sheets for the reprocessing of commercial spent fuel that can recover additional components for isolated storage or recycle have been developed based on the original PUREX process. These processes have been given the generic name UREX+, reflecting the design of the processes for initial extraction of uranium. A summary of the products resulting from the various UREX+ processes[73] is shown in Table 5.2. All of the UREX+ processes are distinguished by the fact that they do not separate pure plutonium. The composition of the product streams can be adjusted to match the requirements for fuel fabrication. UREX or UREX+ may then be followed by the extraction and recovery of cesium/strontium and the remaining transuranic elements.

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[73] The PEIS discusses only UREX+1, 1a, 2, 3, and 4.

Process	Product #1	Product #2	Product #3	Product #4	Product #5	Product #6	Product #7
UREX+1	U	Tc	Cs/Sr	TRU/Ln	FP		
UREX+1a	U	Tc	Cs/Sr	TRU	FP/Ln		
UREX+1b	U	Tc	Cs/Sr	U/TRU	FP/Ln		
UREX+2	U	Tc	Cs/Sr	Np/Pu	Am/Cm/Ln	FP	
UREX+2a	U	Tc	Cs/Sr	U/Np/Pu	Am/Cm/Ln	FP	
UREX+3	U	Tc	Cs/Sr	Np/Pu	Am/Cm	Ln/FP	
UREX+3a	U	Tc	Cs/Sr	U/Np/Pu	Am/Cm	Ln/FP	
UREX+4	U	Tc	Cs/Sr	Np/Pu	Am	Cm	Ln/FP
UREX+4a	U	Tc	Cs/Sr	U/Np/Pu	Am	Cm	Ln/FP

Notes:(1) in all cases iodine is removed as an off-gas from the dissolution process.
(2) processes would be designed to avoid the long-term storage of liquid high-level wastes.

U: uranium
Tc: technetium
Cs/Sr: cesium and strontium
TRU: transuranic elements. Pu – plutonium, Np – neptunium, Am – americium, Cm – curium
Ln: lanthanide (rare earth) fission products
FP: fission products other than cesium, strontium, technetium, iodine, and the lanthanides

TABLE 5.2 Suite of UREX+ Processes

5.4.2.3 Other aqueous separation processes

Several separations processes have been developed that yield products similar to those generated by the UREX+ suite of processes. The COEX® process is intended for MOX recycle in light-water or fast reactors. It is based on co-extraction of uranium and plutonium (and possibly neptunium) into one product stream, a second stream containing pure uranium, and a fission product stream. The NUEX® process is a three-cycle process that separates uranium, transuranics (including plutonium), and the fission products into separate streams. NUEX® uses some of the technologies developed for the UREX+ processes. The DIAMEX-SANEX processes separate americium and curium from short-lived fission products. They can be implemented with either COEX® or PUREX. The GANEX process is designed for fast reactor recycle. In the GANEX process, uranium, plutonium, and minor actinides are separated from the short-lived fission products and converted to a mixed actinide fuel.

5.4.3 Pyrochemical Separations

Pyroprocesses have been studied since the 1950s for treating spent fast reactor fuel and used to recycle fuel in the Experimental Breeder Reactor II. These electrochemical technologies were developed to research closing the fuel cycle. The goal was to develop an advanced fuel cycle for a metallic fueled fast-neutron reactor that met the nonproliferation, energy and environmental concerns of the time. Plutonium was co-recovered with the other transuranic elements (neptunium, americium, and curium), a fraction of the rare earth fission products, and uranium, and used to fabricate fresh fast reactor fuel. Electrorefining was used to recover uranium from spent metallic fuel and an electrolytic method was used to recover a mixture of uranium and transuranic elements. High-level waste forms were identified and techniques for fabricating the materials were developed.

5.5 NONPROLIFERATION CHARACTERISTICS OF CANDIDATE REPROCESSING TECHNOLOGIES

A preliminary assessment of the relative proliferation risks of candidate reprocessing technologies under GNEP is underway by NNSA. This assessment focuses on whether these alternative technologies provide nonproliferation advantages with respect to the operation of the facility and its product characteristics relative to the PUREX technology which separates pure plutonium from spent fuel. In particular, this preliminary assessment compares the nonproliferation aspects of three alternative technologies that will not result in a pure plutonium product: UREX+, COEX®, and pyroprocessing technologies. The spent fuel received as input to the facilities examined in this study can be received from light water reactors and/or from fast reactors. COEX® and pyroprocessing plants each produce their own distinct type of product stream that contains plutonium. Specifically, COEX® produces a plutonium oxide product mixed with uranium, while pyroprocessing produces a metal product containing plutonium mixed with uranium, americium, neptunium, curium, and some rare earth fission product impurities. The UREX+ technology offers a suite of options that each produce different plutonium-bearing product streams. UREX+ results in a plutonium product mixed with various combinations of uranium, americium, neptunium, curium, and possibly rare earth fission products.

This assessment evaluates proliferation threats by both states and non-state actors. It considers the possibility that the GNEP processing facility being evaluated is located in a non-nuclear weapon state (NNWS) and considers the risk that the state might remove plutonium-bearing materials from the facility for use in a nuclear weapon or other nuclear explosive device, either clandestinely or after withdrawing from or violating its NPT obligations. The NNWS is assumed to be under full-scope IAEA safeguards with an Additional Protocol in force. It also considers the risk that a non-state actor might gain access to plutonium-bearing materials, whether in a nuclear weapon state or a non-nuclear weapon state.

The evaluation methodology developed by the Gen-IV Proliferation Resistance and Physical Protection Working Group (PR&PP WG) was adopted for this assessment.[74] For the host state, diversion of material, facility misuse, and breakout from nonproliferation obligations can be evaluated. For the non-state actor, theft of nuclear material for use either on-site or off-site can be evaluated. It is assumed that the objective of the threat is to obtain, ultimately, enough plutonium (termed "one significant quantity") to manufacture a nuclear weapon or other nuclear explosive device, such as a test device, an improvised nuclear device, or an ostensibly peaceful nuclear explosive device. Details of weapon manufacture or use are not assessed in this report; instead, the analysis is concerned with acquisition and processing of the material, not the follow-on activities. For each option, the measures of

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[74] See Chapter 3 for a description of this methodology.

proliferation risk considered include the relative difficulty of achieving the objective, the time required, the likelihood of detection, and the characteristics of the material acquired. This enables comparison of the proliferation risk between each reprocessing technology and the PUREX technology. The evaluation in each case begins with receipt of spent fuel and ends with the final material product that would be transferred to a fabrication facility.

The analyses resulted in natural groupings among the process alternatives based on product form. They are presented here in order of increasing proliferation risk relative to PUREX.

Group W	Pyroprocessing is grouped with UREX+1b since both produce plutonium that is not separated from uranium, americium, neptunium, and curium in the final product.
Group X	UREX+1 and UREX+1a produce a grouped transuranic product of plutonium, neptunium, americium, and curium. UREX+1 adds the lanthanides,[75] which would be removed prior to fuel fabrication. UREX+1a produces the same transuranic material product but without the lanthanides. The mixing in of multiple isotopes makes this product less useful than those listed below as a potential weapons material.
Group Y	COEX® and UREX+2a, UREX+3a, and UREX+4a all produce similar products: a mixture of uranium with either plutonium or a combination of plutonium and neptunium. The degree of dilution with uranium affects their potential use as weapons material; the smaller the fraction of plutonium in the product stream, the lower the proliferation concern. The fact that the latter three products include neptunium as well as plutonium does not reduce their proliferation risk relative to COEX®.
Group Z	In the UREX+ suite, UREX+2, UREX+3, and UREX+4 produce plutonium that is not separated from neptunium. All of the uranium from the spent fuel is recovered separately from this product. The proliferation risk of these processes is essentially equivalent to that of the PUREX process. This applies to both state-level and non-state threats.

The letters W through Z were chosen to indicate there are only minor differences in the proliferation risk between these processes and that they are all clustered near the end of the alphabet, with Z representing the highest risk among these process alternatives.

NNSA’s preliminary assessment concludes that for state-level threats, the differences among the technologies in these three groups – W, X, and Y – are not very significant. Further, the additional proliferation resistance of these alternative processes over Group Z – and over

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[75] The lanthanides, also known as the rare earth metals, are elements 57-71 of the periodic table, lanthanum through lutetium.

PUREX in particular – is small. The reason is the ease, given the resources available to a state, with which the various plutonium-bearing materials or the reprocessing process itself could be converted to produce separated plutonium.[76] The remaining nonproliferation advantages and disadvantages depend on factors other than physical form, such as transparency and ease of inspection by the IAEA, and the detectability of clandestine misuse of the plant to produce separated plutonium or diversion of the product to a clandestine facility where the plutonium could be separated. The distinctions among these four groups may be more significant with respect to non-state actors, due to their smaller resource base and lesser ability to hide and control access to clandestine facilities.

While an attempt by the state to separate pure plutonium in facilities using these technologies might be readily detected, once the state has withdrawn or broken out from its nonproliferation obligations, estimates of the time to convert the facility to separate pure plutonium ranges from a few days to a few weeks, depending on the technology and assuming the state has prepared for the breakout by becoming sufficiently familiar with any additional required separations. The significance of the time needed to accomplish this task should be considered in the context of the time needed for the international community to detect and respond to such an event. It could well take the IAEA or the UN Security Council that long (or longer) to negotiate a response to any withdrawal or breakout from nonproliferation obligations. In sum, for a state with pre-existing PUREX or equivalent capability (or more broadly the capability to design and operate a reprocessing plant of this complexity) there is minimal additional proliferation resistance to be found by introducing Group W, X, or Y processing technologies when considering the potential for diversion, misuse, and breakout scenarios.

In a nuclear material theft scenario involving non-state actors, Groups W, X, and Y provide some advantage over Group Z (whose product is plutonium or plutonium not separated from neptunium). These advantages arise from the additional cost, time, and technical difficulty that would be entailed in further processing by a non-state actor of any Group W, X, or Y products to obtain pure plutonium. The proliferation significance of these advantages depends heavily on assumptions about the capabilities (including both physical facilities and the knowledge and experience of the personnel involved), motivations, and strategies of the adversary. It has been presumed that all Group W, X, Y, and Z products (all of which are considered to be Category I nuclear material under current DOE Directives as well as Nuclear Regulatory Commission and international guidelines for nuclear material categorization) present comparable proliferation risks. The main difference is in stored product packaging resulting from differences in volume, mass, radiation, and heat load. Group Z products are likely to be more compact and stored in smaller, more easily transportable packages. Next in ease for storage and transportation are Group Y products. Groups W and X have larger radiation and heat loads and would be more difficult to handle for health and safety reasons. However, even with the lanthanides present the total dose is not very high and would be unlikely to deter an adversary who was willing to accept injury (or self-sacrifice).

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[76] This assessment assumes that normal health and safety requirements might be relaxed significantly in the context of a proliferation breakout or nuclear terrorism scenario.

Groups Y and Z produce secondary streams of materials that contain americium and curium, either with or without neptunium. Further, for UREX+4 and UREX+4a, americium is chemically separated from curium. In all cases, these secondary streams would be either stored for waste disposal or for burning in a reactor. Consequently, for these potentially attractive materials, for the state there is the opportunity for diversion and for a non-state actor there is the opportunity for theft.

This preliminary assessment on candidate reprocessing technologies for GNEP suggests only a modest improvement in reducing proliferation risk over existing PUREX technologies and these modest improvements apply primarily for non-state actors. This finding reinforces the importance of efforts to limit reprocessing activities to a small number of states with strong nonproliferation credentials. It also highlights the importance of developing effective and transparent international safeguards for any reprocessing technologies selected for use under the GNEP program. Even for the nuclear-weapon states, whose reprocessing facilities would not be required to come under IAEA safeguards, there would be a benefit to supporting the development of more effective domestic and IAEA safeguards for reprocessing facilities, including on facilities that use technology alternatives to PUREX. Several of these processes introduce challenges for nuclear materials measurement systems not found in PUREX, in addition to the challenges involved in safeguarding any large throughput bulk processing facility. Improvements in measurement capabilities are needed to mitigate or eliminate these challenges, as well as improvements in compensatory measures. In some cases, considerable effort would be required to develop new safeguards approaches that are tailored to the novel characteristics of the suggested processes.

Since the nonproliferation differences are small between the technologies analyzed in this assessment, any future selection of spent fuel reprocessing technologies should consider the benefits of that particular technology in enabling implementation of back end fuel services and the long term management of nuclear waste.

5.6 NONPROLIFERATION CHARACTERISTICS OF TRANSPORTATION

The GNEP international comprehensive fuel services concept remains under development, and details of the fuel cycle and material forms have yet to be determined. Decisions that have yet to be made, such as whether to co-locate various sections of the separation and fuel fabrication facilities, if such facilities are proposed, would have a large impact on the safeguards, the transportation protection requirements, the security and proliferation risks and, therefore, offer opportunities to limit those risks and associated mitigation costs. The Nuclear Regulatory Commission (NRC), Department of Transportation (DOT), and DOE regulations and directives and IAEA guidelines would help define the requirements and mitigate the risks for any international nuclear material transport proposed as part of the comprehensive fuel services concept.

The nuclear material transportation issues can be grouped into three general categories:

- Once-through fuel cycle with international transport of fresh fuel only;

- Recycle with international transport of fresh fuel and spent fuel; and
- Recycle with international transport of fresh fuel, spent fuel, and separated materials.

These three scenarios will be considered briefly with respect to their impact on nuclear material safeguards and physical protection during transportation. More detailed analyses[77] may be needed in follow-on assessments, and may occur as decisions are made on the course of the GNEP program.

5.6.1 Scenario 1: Once-Through Fuel Cycle with International Transport of Fresh Fuel Only

In this scenario, suppliers would provide foreign customers with fresh fuel assemblies. The risk of nuclear material theft during international transportation would be relatively low due to the low attractiveness of the nuclear materials involved: LEU or thorium fuel. Additionally, the materials shipped internationally would be fuel assemblies, which are relatively easy to safeguard as large, discrete items as compared to bulk materials. In this scenario, the suppliers would not accept the return of spent fuel back. The spent fuel would be left for the recipient country to manage. Spent fuel has somewhat higher attractiveness than the fresh fuel and, therefore, requires additional physical protection. Many countries have experience with this type of fuel cycle and the IAEA has well established programs for monitoring shipments of fresh fuel and monitoring storage of spent fuel.

5.6.2 Scenario 2: Recycle With International Transport of Fresh Fuel and Spent Fuel

In this scenario, suppliers would export fabricated fuel assemblies and accept the spent fuel assemblies for reprocessing or disposal. The risk of nuclear material theft during international transportation would remain relatively low due to the relatively low attractiveness of the nuclear materials involved: LEU or thorium fresh fuel, or spent fuel. However, the increased number of shipments would increase the risk and therefore require an increase in resources to mitigate that risk. As in the previous scenario, the international shipments would be fuel items, not bulk materials. Several countries have experience with this type of fuel cycle and the IAEA has well established programs for monitoring shipments of fresh fuel and some experience monitoring shipments of spent fuel, and the United States has relevant experience in the transport of spent research reactor fuel.

5.6.3 Scenario 3: Recycle With International Transport of Fresh Fuel, Spent Fuel, and Separated Materials

In this scenario, suppliers would engage in international front-end and back-end fuel cycle activities with foreign partners that include the international transportation of materials with increased attractiveness. In principle, these could include fabricated fuel items or bulk materials, though bulk materials could also be shipped in sealed containers that would be safeguarded as items. Fabricated items could include MOX fuel assemblies for LWRs,

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[77] "Nonproliferation Impact Assessment for GNEP: Issues Associated with Transportation," R. Radel, G. Rochau, Sandia Report SAND 2008-1403, February 2008.

metal or oxide fuel assemblies for fast reactors, or minor actinides fabricated into transmutation targets. All the material types are expected to require heightened protection and safeguards, particularly physical protection, for international transport. Specifically, robust shipping containers and additional security personnel would likely be necessary for the more attractive materials. Although the GNEP comprehensive fuel services concept does not contemplate international transport of separated material, such transport has been part of commercial reprocessing services, for example as provided to Japan by the UK and France. Procedures for safety, security, and safeguards used for these shipments may need to be reviewed in the context of possible broader use.

Analysis would be needed to define and meet the safeguards and physical protection requirements under any scenario that dramatically increases international shipment of attractive (direct use) nuclear materials. The legal frameworks for safeguards, security, and export control would also need to be assessed to determine any need for revisions to address new issues. The international transportation protection requirements would depend on which countries and which international waters were involved.

6. ASSESSMENT OF GNEP ALTERNATIVES

6.1 INTRODUCTION

6.1.1 Scope

This assessment of the Global Nuclear Energy Partnership (GNEP) programmatic alternatives draws on the policy factors described in Chapter 3. These factors are designed to address the likelihood of achieving the corresponding GNEP nonproliferation objectives described in Chapter 2. A key factor in achieving those objectives will be the ability to support the concept of reliable international fuel services, as described in Chapter 4, in order to discourage the spread of enrichment and reprocessing technologies. This assessment also considers other factors that affect the nonproliferation impact of the various fuel cycle alternatives, including the ability to influence the fuel cycle practices of other countries and to draw down global stocks of separated plutonium. The programmatic assessment also addresses the technical proliferation risk factors in the second part of Chapter 3. Given the broad nature of the programmatic alternatives, this discussion is largely qualitative. However, it identifies distinctions among several broad categories of fuel cycle alternatives and technical characteristics that are important for assessing nonproliferation impacts of future decisions.

This draft Nonproliferation Impact Assessment (NPIA) does not identify a preferred alternative. However, the programmatic assessment is intended to inform the selection of a preferred programmatic alternative. If a preferred programmatic alternative is identified, subsequent decisions may be needed to determine the details of how that alternative would be implemented. Those details include the specific technologies to be deployed, the timing and scale of that deployment, the location of facilities, the transportation of nuclear materials, and other impacts on the domestic and international fuel cycles. In that context, one key complementary action will be to maintain a robust and responsive technical program to assess proliferation impacts associated with those future choices. This technical capability would be used to carry out follow-on nonproliferation assessments to inform future decisions on selecting among those technical implementation alternatives.[78]

6.1.2 Organization

As noted in Chapter 5, the domestic programmatic alternatives fall into three broad categories, based on technical similarities among the alternatives in each category.

- The first category consists of once-through fuel cycle alternatives, in which spent fuel is treated as waste and disposed of directly in a geologic repository. Four of the programmatic alternatives fit this category: the no action alternative, the thorium fuel cycle alternative, and the heavy water reactor (HWR) and high-temperature gas-cooled reactor (HTGR) alternatives.

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[78] Nothing in this assessment should be read to infer that the commercial spent fuel already generated in the United States will be disposed of in any manner other than the currently planned direct disposal in the Yucca Mountain repository

- The second category consists of full actinide recycle alternatives in which transuranic elements are recycled and removed as much as possible from the waste stream. Both the fast recycle alternative and the thermal/fast recycle alternative fit into this category. The one thermal recycle variant that would potentially fit into this category is one in which all the transuranics are recycled in light water reactors (LWRs) indefinitely. However, since this variant is described in the draft PEIS as difficult to achieve, it is not considered here.

- The third category consists of partial actinide recycle alternatives, under which some of the transuranic elements are removed from the waste stream and recycled but a significant portion remains in the waste stream. This includes the three thermal recycle options using LWRs, HWRs, and HTGRs.

One of the principal factors used to distinguish among these alternatives in terms of achieving nonproliferation objectives is the ability to support a comprehensive fuel services concept that includes the acceptance of fuel supplied to other countries after it has been used in their reactors. This in turn depends on building confidence in the ability to manage that spent fuel responsibly, in particular to manage the long-term hazards of nuclear waste. For this reason, this assessment focuses on radiotoxicity, which describes the intrinsic hazard of the radioactive materials that would be disposed of as waste, rather than waste volume or heat load, which are engineering constraints related to repository geology and design. This assessment is not tied to the Yucca Mountain repository or any other particular repository, but rather to the intrinsic properties of the spent fuel or high-level waste that affect the feasibility and capacity of any potential repository.

The transuranics are the principal source of long-term radiotoxicity,[79] so the ability of each alternative to remove those materials from the waste stream affects the ability of that alternative to support the comprehensive fuel services concept. In general, the ability of any of the full actinide recycle alternatives to achieve the desired dramatic reduction in long-term waste hazards depends on the ability to achieve very high efficiency separation of transuranics from waste.[80] If this separation efficiency were reduced significantly, the waste characteristics of the full recycle alternatives would be similar to the partial recycle alternatives.

6.2 ASSESSMENT OF ONCE-THROUGH FUEL CYCLE ALTERNATIVES

A “once-through” fuel cycle is one in which spent fuel is treated as waste, and is stored until it can be disposed of in a geologic repository. Of the programmatic alternatives and optional variants considered in the GNEP PEIS, four fall into this category:

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[79] Radiotoxicity is used in this NPIA for the dose source term, before consideration of pathways.

[80] Like the PEIS, this assessment assumes 99.9% efficiency in removing all the transuranics from the waste stream, i.e., that only 0.1% of the transuranics in any recycling process end up in the high-level waste stream. This is particularly important for fast reactors, which have a relatively high concentration of transuranics and need to be recycled multiple times. Such efficiencies are challenging but have been demonstrated for aqueous separations; they have not yet been demonstrated for electrochemical processing.

- No action alternative: Low-enriched uranium (LEU) at 4.4% enrichment is used in LWRs and spent fuel is stored pending disposal in a geologic repository.
- Thorium alternative: LEU at 19.9% enrichment is used in "seed" fuel elements, and LEU at 12.2% enrichment is used in "blanket" fuel elements, where it is combined with fertile thorium fuel that generates and partially burns the fissile isotope U-233 as it is irradiated.
- Two thermal reactor alternatives:
  - Heavy Water Reactor (HWR) option: LEU fuel at 2.1% enrichment is used in an advanced Canada Deuterium Uranium (CANDU)-type reactor, which uses heavy water as a moderator.
  - High Temperature Gas-cooled Reactor (HTGR) option: LEU fuel at 14% enrichment is used in these graphite-moderated reactors.

6.2.1 Nonproliferation Impacts

The nonproliferation impacts of the once-through fuel cycle alternatives are very similar in most ways. In general, they have the advantage of keeping the plutonium in spent fuel, which is both unattractive for use in nuclear explosives and relatively easy to safeguard. One disadvantage is that they limit opportunities to discourage the spread of enrichment and reprocessing through direct participation in the back end of the fuel cycle. The United States could continue efforts to discourage reprocessing through the example of managing the back end without reprocessing, but this does not directly relieve pressures for countries to consider closing the fuel cycle in the absence of credible alternatives for spent fuel management. In addition, once-through fuel cycles require the greatest expansion of enrichment capacity. These alternatives also provide no means to draw down international stocks of separated civil plutonium other than the potential use of mixed oxide (MOX) fuel in existing thermal reactors. The following sections discuss these issues in more detail.

6.2.1.1 Influence on fuel cycle

<u>Direct Impact</u>: The main drawback of a once-through fuel cycle in the United States involves opportunity costs and latent risks that are likely to be greater than under other alternatives. The main opportunity cost is that not having a spent fuel recycling program would make it difficult for the United States to play a leading role in offering the type of comprehensive fuel services that GNEP envisions. In particular, it would be difficult to obtain support for importing foreign commercial spent fuel into the United States without a plan for its disposition. Also, as noted in Chapter 4, a number of legal constraints would limit the ability of the United States to accept other nations' spent fuel. The Yucca Mountain repository remains years away from approval to accept spent fuel, the NRC licensing process is pending, construction and operation are subject to future funding

decisions, and repository capacity is limited by law[81] (legislation to adjust the limit is under consideration). Thus, direct U.S. participation in back-end fuel services under a once-through fuel cycle would likely involve long-term storage pending identification of additional repository capacity. The latent risk comes from the accumulations of spent fuel around the world, which increase the likelihood that countries may pursue reprocessing on their own as a spent fuel management strategy, but with the possible motivation of developing a weapons capability. Another potential opportunity cost is the reduction in the U.S. share of the international fuel services market that could result from the inability to offer competitive and attractive fuel service arrangements, which would reduce the U.S. ability to influence fuel cycle practices through consent rights on U.S. exports.[82]

However, there are some differences among the once-through fuel cycle alternatives in terms of radiotoxicity reduction. Compared to the no action alternative, the HWR alternative is essentially identical, the HTGR has a slightly lower radiotoxicity, and the thorium fuel cycle has a slightly different radiotoxicity profile over time (see Figure 6.1 and Table 6.1). Thus, the use of the HTGR fuel cycle overseas would be slightly more attractive since it provides some reduction in long-term radiotoxicity, though perhaps not enough of a reduction to influence decisions.

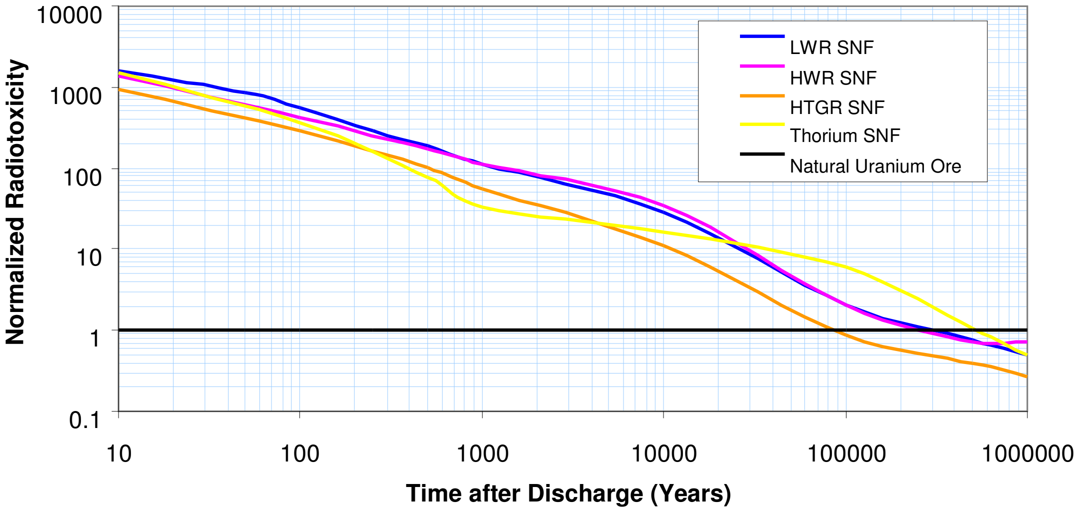

FIGURE 6.1 Radiotoxicity Reduction for Once-Through Fuel Cycle Alternatives

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[81] The Nuclear Waste Policy Act of 1982 (NWPA) limits the initial capacity of Yucca Mountain, the first proposed geologic repository, to 70,000 MTHM of spent nuclear fuel and high-level radioactive waste until such time as a second repository is in operation. In its cumulative impacts analysis, the Yucca Mountain Supplemental Environmental Impact Statement, issued in July 2008, evaluated the disposal of up to approximately 130,000 MTHM of spent nuclear fuel, equivalent to the amount projected from all existing commercial power reactors during all of their projected lifetimes.

[82] As discussed below, international partnerships between U.S. suppliers and foreign reprocessors could mitigate this opportunity cost.

Alternative	Years[83]
No action	240,000
HWR	255,000
HTGR	85,000
Thorium	525,000
Fast reactor recycle	375
Thermal & fast reactor recycle	400
Thermal (LWR)	55,000
Thermal (DUPIC)	unknown
Thermal (DB-HTGR)	unknown

TABLE 6.1 Time before Spent Fuel Reaches the Radiotoxicity of Natural Uranium

HTGR fuel also may be more difficult to reprocess and more robust in a geologic repository environment, which could reduce the likelihood that countries using such reactors would consider reprocessing as a spent fuel management strategy. One option might be for the United States to seek to provide back-end fuel services through an international partnership with a third country. In one scenario the partner country would take back the spent fuel for direct geological disposal or for interim storage pending a decision on its disposition. It may be difficult to find a country willing to accept spent fuel under those terms, particularly if the United States were to insist that the spent fuel not be reprocessed. However, it would only take one willing partner to begin establishing such arrangements.

In another scenario, a partner country with an established civil reprocessing program would take the spent fuel back for reprocessing, retaining the separated plutonium for its own use but most likely returning the high-level waste to the country that generated the spent fuel. While such arrangements would avoid reprocessing in the United States, they would reduce the benefits of that policy by limiting the U.S. ability to argue in general terms that reprocessing was unnecessary and undesirable. Furthermore, the United States would not be able to define the terms and conditions under which spent fuel would be taken back, though U.S. consent rights could provide some leverage to influence those terms. For example, the United States might be able to influence the choice of separations technology and the characteristics and use of the product materials and waste forms through consent rights.

As described in Chapter 4, the ability to offer comprehensive back-end fuel services that include "take back" of spent fuel (though not necessarily to the same country that supplied the fresh fuel) would provide a significant incentive to discourage countries from pursuing their own fuel cycle programs. The potential to influence the back end would be direct: an assured acceptance mechanism could provide a viable spent fuel management alternative for countries that might otherwise consider reprocessing to manage their growing spent fuel inventories. However, there is also the potential to exercise indirect influence on choices at the front end. Coupling fuel supply assurances with assured acceptance of spent fuel could

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[83] Unless otherwise specified, technical data in this section are from "*Performance Summary of Advanced Nuclear Fuel Cycles*", R.A. Wigeland, GNEP-TIO-AI-AI-RT-2008-000268, July 2008.

provide a much more attractive incentive for countries to refrain from seeking to enrich their own fuel than supply assurances by themselves.[84]

Policy Impact: Proponents of a once-through policy argue that the U.S. adoption of a once-through fuel cycle has been effective in discouraging reprocessing by demonstrating that reprocessing is not necessary for the large-scale use of nuclear power. They argue that since the United States adopted this strategy in the 1970s, no new country has begun reprocessing for civil purposes. They also note that U.S. diplomatic efforts both to discourage specific countries from reprocessing and to discourage suppliers from providing reprocessing facilities to additional countries have been strengthened by the ability to argue by example that reprocessing was not necessary for a civil nuclear power program. The United States has also been able to exercise consent rights over reprocessing of spent fuel produced through the use of nuclear material transferred from the U.S. either to block countries from reprocessing or to shape the nonproliferation conditions under which such reprocessing could take place.[85]

However, others argue that economic factors may have been the underlying reason other States have not pursued reprocessing. Those factors include the high cost of building a reprocessing facility, the relatively low cost of LEU and the availability of reprocessing services from France, Russia and the United Kingdom. But the economic picture is changing and those factors may not continue to prevail.

Technical Risk: A principal advantage of once-through fuel cycles is that they do not involve any reprocessing of spent fuel. In addition to avoiding the direct risk of creating relatively attractive materials (see below), this would also reduce the indirect risk of establishing the infrastructure that could be used to separate weapons usable materials. This advantage derives purely from the costs of infrastructure needed for reprocessing, since the technology barriers to reprocessing are relatively modest.[86]

The proliferation risk of once-through fuel cycles arises primarily at the front end, through the demand for large-scale enrichment to produce fresh fuel. This is a common feature of all the once-through fuel cycle alternatives under consideration. A possible variant of the HWR option could avoid the need for enrichment by using natural uranium fuel, as CANDU reactors have done historically, but this resulted in large amounts of spent fuel and less efficient use of uranium resources. The level of enrichment and the overall amount of enrichment (in terms of separative work units or SWU) required varies depending on the fuel cycle in question (see Table 6.2). The enrichment level is also relevant because it takes less effort to produce weapons-grade uranium starting from LEU reactor fuel than from

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[84] Matthew Bunn, "Risks of GNEP's Focus on Near-Term Reprocessing," testimony before Senate Energy and Water Resources Committee, November 14, 2007, http://belfercenter.ksg.harvard.edu/files/bunn-GNEP-testimony-07.pdf.

[85] As discussed in Chapter 2, the Atomic Energy Act requires the United States to obtain assurances in a Section 123 agreement for cooperation from recipients of nuclear material from the U.S. that the recipients will not reprocess that material or material produced through the use of that material without U.S. consent. Such consent rights are also part of the multilateral nuclear export control guidelines of the Nuclear Suppliers Group.

[86] The basic technology for reprocessing was declassified long ago and is readily available in the technical literature, e.g., "Engineering for Nuclear Fuel Reprocessing," J.T. Long, American Nuclear Society, 1978.

natural uranium (which is significant only in the context of a very small enrichment capability – see Table 6.3) and because it may complicate safeguards at enrichment plants by making it harder to detect undeclared HEU production.

Alternative	Maximum Enrichment[87]	Separative work required[88,89] (million kg-SWU per 100 GW-yr)
No action (assume 50 GWd/MT)	4.4%	14.5
Thorium	19.9%	18.9
HWR (ACR)	2.1%	11.1
HWR (using natural uranium)	0.7%	0.0
HTGR	14.0%	21.5
Fast Reactor recycle	4.4%	9.0
Thermal/Fast Reactor recycle	4.4%	9.3
Thermal recycle (LWR)	4.6%	11.8
Thermal recycle (DUPIC)	3.5%	8.7
Thermal recycle (DB-HTGR)	4.4%	11.8

TABLE 6.2 SWU Requirements for GNEP Programmatic Alternatives

For centrifuge enrichment, there is no significant technical barrier between commercial and military enrichment. A plant capable of producing LEU for power plants could also be used to produce high-enriched uranium (HEU) for use in weapons, either by enriching uranium in multiple passes or by reconfiguring the connections among the centrifuges to optimize for HEU production, or by diverting some of the LEU product to a clandestine enrichment facility. Effective international safeguards can be designed to detect such activities in a timely manner, and the risk of detection may also deter some countries from attempting them.[90] As with reprocessing, a small-scale enrichment program, for example a facility that provided fuel for a single large nuclear power reactor, would be sufficient to produce a *significant quantity*[91] of weapons-grade HEU in less than a month. Every programmatic alternative considered in the GNEP PEIS involves some growth in nuclear power and with that some growth in demand for enrichment services.

However, the primary proliferation risk comes not from the total amount of enrichment. Rather, it arises from the possibility that additional countries might acquire an enrichment

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[87] This refers to the highest uranium enrichment level of any of the fuels in the fuel cycle alternative.

[88] These calculations are based on a tails assay of 0.25%. For the closed and partial recycle alternatives the following percentages of electricity are generated from LWRs: 60% for fast reactor recycle, 70% for thermal/fast reactor recycle, 73% for DUPIC, 82% for DB-HTGR.

[89] Annual figures for the once-through alternatives are based on 100 GW of electricity provided by that type of reactor. Figures for the closed and partial recycle alternatives are based on the mix of reactor types presented in the PEIS for that alternative.

[90] This refers to safeguards on declared enrichment facilities. Designing safeguards to detect undeclared enrichment activities is a much greater challenge.

[91] The IAEA defines a significant quantity of fissile material as roughly the quantity a country would need to build a first nuclear weapon, 8 kilograms of plutonium or 25 kilograms of U-235 contained in HEU.

capability, which they could use to produce weapons-grade uranium (see Table 6.3). Furthermore, an increase in the number of countries holding sensitive enrichment technology would complicate efforts to prevent the further spread of enrichment capabilities. Therefore, if the demand for enrichment services is satisfied by an expansion of capacity at a competitive price in countries that already have commercial enrichment programs, there should be less proliferation risk associated with that expansion of enrichment capacity. At present, all planned new commercial enrichment plants would be built in countries that already have such plants. Nonetheless, a large and rapid expansion of demand for enrichment could encourage additional countries to enter the market, particularly if growing demand raises the price of enrichment services. This risk may be marginally greater for the once-through fuel cycle alternatives.

6.2.1.2 Civil plutonium stockpiles

None of the once-through alternatives would enhance significantly the ability to help draw down the stockpiles of separated plutonium worldwide. Although any of the reactor types considered could use MOX fuel, without a spent fuel recycling program involving similar fuels, the demand for such fuel would be limited, and the government would likely need to give reactor operators greater financial incentives to take part. More significantly, the United States would not be in a position to demonstrate the feasibility of a spent fuel recycling approach that maintained balance between the separation and use of fissionable material from spent fuel to minimize stocks of separated plutonium.

6.2.1.3 Material attractiveness[92]

The principal nonproliferation advantage of a once-through fuel cycle lies in the relative unattractiveness of the materials at the back end of the fuel cycle. Fissile material is a small fraction of the total spent fuel mass, and most fuel assemblies (including LWR assemblies) are large, bulky items. For many decades after discharge from the reactor, the presence of highly radioactive fission products creates a high radiation field that makes spent fuel difficult to handle safely, although that field decays significantly over time. Separating the weapons-usable materials from spent fuel normally involves large facilities with heavy shielding and remote handling capabilities, though these are not essential for an adversary who is willing to accept high, perhaps lethal radiation exposure. Spent fuel is normally stored in spent fuel ponds or, after cooling, in heavy sealed dry storage casks, which can be safeguarded effectively. As a consequence, as long as spent fuel is not reprocessed, significant proliferation barriers will remain, although the radiation barrier will decay over time. The attractiveness of the material in the front end is considered to be relatively low, although the LEU can be used as feed stock to produce HEU and can reduce the time needed for breakout from nonproliferation and safeguards obligations for a country with an enrichment capability.

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[92] Material attractiveness is defined in both DOE and NRC regulations in terms of specified ranges of chemical and isotopic compositions of materials. In this report we use the term in the sense presented in "*An Assessment of the Proliferation Resistance of Materials in Advanced Nuclear Fuel Cycles*", C.G. Bathke et al, 8th International Conference on Facility-Operations – Safeguards Interface, March 30 – April 4, 2008, Portland OR, which is correlated with but not identical to the regulatory definitions.

6.2.1.4 Safeguards

As noted in Chapter 5, compared to a full or partial actinide recycle fuel cycle, the international safeguards requirements for a once-through fuel cycle are relatively easy to meet. Particularly when placed in casks, spent fuel would be left in the form of relatively large and countable items. Safeguards approaches for spent fuel are based largely on monitoring to maintain continuity of knowledge on those items and verifying that they have not been tampered with. Spent fuel storage casks could be designed to allow *in situ* confirmation (without opening the cask seal) of signatures of the contained spent fuel. Demand is expected to grow for safeguards and inspection resources as more reactors come on line. As the radiation barrier for spent fuel declines over time, it may be necessary to consider compensating measures to strengthen safeguards and physical protection. The once-through fuel cycle alternatives will also require more safeguards resources for the increased enrichment services than the full or partial recycle alternatives, as the once-through cycle requires more uranium for equivalent electricity production. However, this resource requirement is small compared to that for a large reprocessing plant.

6.2.1.5 Sustainability

As noted above, one stated purpose of a once-through fuel cycle is to provide an example that encourages other countries to refrain from reprocessing. However, that example will seem less compelling in the future if the U.S. long-term strategy for managing its own spent fuel remains contentious and, therefore, may not be perceived as coherent and sustainable. Assuming that the repository at Yucca Mountain is licensed and starts operation some time in the first quarter of the 21st century, a continued reliance on a once-through fuel cycle, particularly in the context of significant growth in nuclear power, will require a significant expansion in U.S. repository capacity.

6.2.2 Distinctions among Once-Through Alternatives

While the various once-through cycles have much in common, there are also some differences in terms of proliferation risk. The thorium and HTGR alternatives involve the use of higher levels of enrichment than current LWRs, which generally use uranium enriched to less than 5%. This reduces the time required to enrich to weapons-grade HEU after a diversion or theft of fresh fuel. However, except for the smallest enrichment capability, the difference in risk between the diversion of LEU at 4.4%, 14%, or even 19.9% enrichment is relatively small (see Table 6.3, where it is shown that two-thirds of the SWU requirement has already been done in enriching uranium to typical LWR fresh fuel needs). A key to limiting that risk is to maintain strong international safeguards to detect diversion and strong physical protection measures to prevent theft, as well as continued efforts to prevent the spread of enrichment technology. A compensating factor is that those fuel cycles starting with higher levels of enrichment produce plutonium in lower quantities and somewhat less attractive isotopic compositions.

There are also differences among reactors in terms of their fuels and operations. While there are variations in fuel design, the HTGR fuels considered in the GNEP PEIS are TRISO fuels based on small coated fuel particles surrounded by layers of hard cladding embedded in prismatic graphite blocks. The graphite matrix and cladding materials tend to make this type of fuel relatively difficult to reprocess. This can be both a positive and a negative feature. On the positive side, deploying such reactors overseas would reduce the risk that the resulting spent fuel might become a proliferation concern. The need to apply non-standard reprocessing methods for HTGR fuel may result in a technical barrier to extracting the plutonium for weapons use. HTGR spent fuel also has somewhat reduced radiotoxicity compared to LWR spent fuel. These factors may reduce incentives for countries to pursue reprocessing to manage inventories of HTGR spent fuel.

Alternative	Maximum enrichment	Additional SWU required to produce 1 SQ	SWU requirement compared to natural uranium feed
Natural U	0.7%	4740	100%
HWR	2.1%	2520	53%
LWR	4.4%	1560	33%
HTGR	14.0%	660	14%
Thorium	19.9%	490	10%

TABLE 6.3 Separative Work Units Needed to Enrich One Significant Quantity (SQ) of 90% HEU[93]

On the negative side, the relatively high enrichment levels of HTGR fuel may pose challenges for implementing fuel supply assurances. Most large-scale commercial enrichment plants produce LEU at up to 5% enrichment, which is typical of LWRs but lower than that required for HTGR fuel. As a result, there are relatively few sources either for commercial supply of enrichment services – or for backup supply assurances – for HTGR fuel. If a significant demand developed for higher enriched fuel, the market to meet that demand would likely develop over time. Furthermore, having fuel that is difficult to reprocess makes it harder politically for a supplier to offer to accept another country's spent fuel. The options available after accepting the spent fuel would be limited to interim storage, direct and permanent disposal, or the application of non-standard reprocessing methods for HTGR fuels. The difficulty might be offset at least in part by the reduced radiotoxicity of HTGR spent fuel.

Heavy water reactors raise issues of proliferation risk that are different from other thermal reactors. The current generation of CANDU reactors was designed to operate with natural uranium fuel. This has the benefit of eliminating the need for enrichment altogether, although at the price of less efficient use of uranium resources. However, the trend in CANDU operations is to use slightly enriched uranium fuel to optimize fuel use and plant performance, which reduces this advantage significantly. The relatively small size and low burnup of CANDU spent fuel bundles could make them relatively easy to handle if diverted or stolen. Further, CANDU reactors require frequent fueling operations while the reactor

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[93] This assumes a relatively high tails assay of 0.4%, which would result in less efficient use of material but reduces the required separative work.

operates (known as on-load refueling) in order to keep the reaction going. In this way, the operation of a CANDU is similar to that of a production reactor designed to produce weapons-grade plutonium for weapons. As a result, some have suggested that CANDUs offer a greater opportunity than other thermal reactors for misuse to support a weapons program.

However, in normal operations CANDU spent fuel has plutonium isotopics that are only slightly more attractive than LWR spent fuel (Table 6.4). In addition, the frequent movement of fuel in a CANDU reactor entails significantly greater effort for international safeguards to account for that fuel. Effective safeguards approaches have been developed and are in use in CANDU reactors that address these concerns.[94]

Reactor/Fuel Type	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Plutonium production reactor[95]	*0.0%*	*94.0%*	*5.8%*	*0.1%*	*0.0%*
Advanced CANDU	*0.5%*	*59.0%*	*25.5%*	*11.0%*	*4.0%*
Advanced LWR	*2.4%*	*50.7%*	*24.7%*	*14.8%*	*7.4%*
HTGR	*1.6%*	*46.2%*	*22.5%*	*20.9%*	*8.8%*
Fast reactor	*4.0%*	*41.9%*	*36.4%*	*6.4%*	*11.3%*
Breeder Blanket[95]	*0.0%*	*97.9%*	*2.1%*	*0.0%*	*0.0%*
LWR MOX (1 pass) [95]	*3.8%*	*36.2%*	*30.4%*	*9.2%*	*9.0%*
LWR MOX (multiple pass)	*3.6%*	*34.2%*	*23.3%*	*10.5%*	*27.4%*
DUPIC	*4.9%*	*39.7%*	*35.1%*	*6.6%*	*13.8%*

TABLE 6.4 Comparison of Pu Isotopics in Spent Fuel

Finally, heavy water reactors require the production of large quantities of heavy water as a moderator. Heavy water can also be used as a moderator in a plutonium production reactor using natural uranium fuel, making diversion of heavy water to support production of weapons-grade plutonium a concern. Heavy water is not normally subject to safeguards, though it has been safeguarded under certain project-specific safeguards agreements and reporting of the scale of operation of a heavy water production plant is required under the IAEA Additional Protocol. Furthermore, heavy water and the facilities, equipment and technology needed to produce it are subject to export control under the Nuclear Suppliers Group Guidelines. Technology important for the production of heavy water is considered sensitive nuclear technology under U.S. law.

6.2.3 Options for Reducing Proliferation Risks

As discussed above, there are a number of options for reducing the proliferation risks associated with these once-through fuel cycle options. The most important is to rebuild

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[94] The IAEA reported that in 2006 the inspection effort for safeguarding 19 on-load refueling reactors (1613 person-days of inspection or PDI) nearly equaled the inspection effort for safeguarding 169 light-water reactors (1690 PDI).

[95] Data for a plutonium production reactor, a breeder reactor blanket and a single pass MOX are presented for comparison purposes only. These are not alternatives under consideration for GNEP. The data for the breeder blanket are taken from measurements of spent fuel at the BN-350 reactor in Kazakhstan.

international confidence in the practicality of spent fuel management premised on direct geological disposal of fuel, both domestically and internationally. Domestically, the strategy could involve building consensus to move forward to license, construct, and operate the geologic repository at Yucca Mountain, the development of alternative repository sites, on-site or centralized interim storage, or some combination of these measures. The key is that the strategy must have the prospect of being sustained over the many decades or even centuries that would be required.

The United States could encourage other countries to embrace the once-through fuel cycle and apply a similar range of disposal alternatives, either through national strategies or through regional[96] and international arrangements. Such arrangements could have many of the same benefits as the GNEP comprehensive reliable fuel services concept. At this time, it appears unlikely that the United States would soon be in a position to take back spent fuel from other countries, either for direct geologic disposition or for interim storage. Nonetheless, having an agreed and sustainable domestic spent fuel management strategy based on the once-through fuel cycle and an operational example of direct disposal of the spent fuel would be a significant asset in demonstrating that such strategies are feasible.

Since a once-through fuel cycle leads to the greatest demand for enrichment services, it is particularly important under these alternatives to minimize the incentives for additional countries to establish enrichment programs. In particular, ensuring that current suppliers are in a position to meet international demand and avoid supply disruptions, including disruptions for political reasons, would require an expansion of enrichment capacity in the United States and elsewhere. Maintaining a major role for U.S. companies in enrichment and fuel supply will help maintain U.S. influence on other countries' fuel cycle choices through consent rights on a large fraction of civil nuclear fuel worldwide. However, if the United States is seen as exercising those consent rights coercively to prevent countries from taking reasonable steps in spent fuel management, this could make U.S. companies less attractive as suppliers in the international nuclear market.

Finally, some of the once-through alternatives would create new nonproliferation and security requirements. If HTGRs or thorium fuels are deployed, they are likely to require new or adapted safeguards measures and updated export control requirements. If LEU with enrichment above 5% becomes prevalent, safeguards approaches and security measures for enrichment facilities and for some of the product material may need to be revised. If HWRs come into more widespread use in non-nuclear weapon states, they could impose severe burdens on IAEA safeguards resources, so it may be necessary to develop new safeguards approaches that maintain effectiveness while containing costs.

6.2.4 Summary of Once-Through Alternatives

The current U.S. nuclear fuel cycle relies on LEU fuel in a once-through fuel cycle. It has been possible to maintain this strategy over the past three decades in large part because there was little growth in the number of operating nuclear power plants and existing reactor sites were able to accommodate spent fuel storage, allowing the difficult spent fuel management

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[96] In this context, "regional" refers to an international geographic region, such as east Asia.

decisions to be deferred. Although this strategy has been technically sustainable, the Department of Energy (DOE) has yet to meet its legal obligation to dispose of spent fuel from domestic reactor operators in a geologic repository. Efforts are underway to design, license, and build a repository at the Yucca Mountain site in Nevada, but that repository is not yet operational. The United States and others (particularly South Korea and Taiwan) are now facing increasing pressures to address spent fuel management challenges.

The fact that the United States has not yet overcome the spent fuel challenges for the once-through fuel cycle has raised questions as to whether a once-through reactor cycle can be sustained indefinitely, either in the United States or in other countries with large nuclear power programs. These questions will become more acute if use of nuclear power – and the resulting generation of spent fuel – grows significantly. As a result, some countries may move to consider reprocessing as a waste management measure. At some point, the depletion of low-cost uranium resources may also lead to the conclusion that recycling spent fuel provides a clear economic or energy security advantage over a once-through fuel cycle. A commitment to a once-through cycle limits U.S. options for meeting its own needs and needs of others in ways that reduce global proliferation risks. The significance of those limits depends on the availability of both sufficient uranium resources and sufficient disposal capability.

To solidify commitments by other countries to refrain from enrichment and reprocessing, the United States must develop credible technical and policy alternatives. Under any of the GNEP programmatic alternatives, the United States will continue to pursue research and development on spent fuel recycle technologies. Such R&D will also provide opportunities for developing the associated safeguards measures needed and continuing policy developments to maintain U.S. leadership in safeguards for complex fuel cycle facilities. To develop policy alternatives, the United States should continue to explore fuel supply and spent fuel management assurances concepts to discourage the spread of enrichment and reprocessing. If the United States chooses to maintain a once-through fuel cycle with the intention of demonstrating that such a fuel cycle is a feasible alternative for other countries, it will need to overcome the current challenges to implementing a sustainable long-term geologic disposal program for spent fuel. This may involve developing an agreed approach to domestic interim storage. As discussed in Chapter 4, interim storage may also be a key element in implementing back-end fuel services internationally.

6.3 ASSESSMENT OF FULL ACTINIDE RECYCLE ALTERNATIVES

For the purpose of this assessment, full actinide recycle is defined as the permanent and nearly complete removal of all the key transuranic (TRU) elements in spent fuel – plutonium (Pu), neptunium (Np), americium (Am) and curium (Cm) – from the waste stream. The alternatives where only one or some of the transuranic elements are removed from the waste stream are discussed in the next section, under partial actinide recycle alternatives. Of the programmatic alternatives and optional variants considered in the GNEP PEIS, two fit into full actinide recycle category:

- **Fast reactor recycle using advanced separations.** Spent LWR fuel is reprocessed, and plutonium and the minor actinides are recovered and recycled in fast reactors.

The fast reactor fuel is also reprocessed and the recovered transuranics blended with the product of LWR spent fuel reprocessing for recycling in fast reactors.

- **Thermal and fast reactor recycle.** Spent LWR fuel is reprocessed and plutonium is recovered and recycled as MOX fuel for one cycle in LWRs. Although the minor actinides could be left in the high-level waste (in which case the approach would more closely resemble the partial actinide recycle alternatives discussed in the next section), this assessment assumes that the minor actinides would be separated for use in fast reactors.[97] After this initial LWR recycle the spent LWR MOX fuel is reprocessed and the recovered plutonium and minor actinides are recycled in fast reactors. The fast reactor fuel is also reprocessed and the recovered transuranics are blended with the minor actinides recovered from spent LWR fuel and the transuranic product of LWR MOX reprocessing for recycling in fast reactors.

6.3.1 Nonproliferation Impacts

The nonproliferation impacts of the full actinide recycle alternatives are very similar to one another and a mirror image to those for the once-through alternatives. That is, the strengths of the once-through are the weaknesses of the full actinide recycle alternatives and vice versa. In general they have advantages that they can provide a more attractive technical basis for discouraging the spread of enrichment and reprocessing by offering comprehensive front- and back-end fuel services that include acceptance and recycling of spent fuel. This approach could also help reduce global separated plutonium stocks. The full recycle alternatives also extract the fissile components of spent fuel into forms that are easier to misuse for nuclear explosives and that pose greater challenges for safeguards than spent fuel. The following sections discuss these issues in more detail, followed by a discussion of the importance of long-term sustainability for these fuel cycles.

6.3.1.1 Influence on Fuel Cycle

Direct Impact: The most attractive feature of these fuel cycle alternatives is that they reduce dramatically the long-term radiotoxicity from spent fuel. As shown in Chapter 5, removing all the transuranics from the waste stream (except for very low process losses) would shorten dramatically the length of time for radioactive decay to reduce the radiotoxicity of the remaining waste below that of uranium ore (see Figure 6.2). This represents an advantage over other alternatives in facilitating acceptance of other countries' spent fuel both in terms of technical options for waste management and in terms of public acceptance and political feasibility of such fuel services, though neither public acceptance nor political feasibility would be certain. The significance of this advantage depends on the relative availability and public acceptance of disposal capability for spent fuel or HLW.

The ability to recycle spent fuel and minimize waste would broaden the range of possibilities for U.S. participation in the global nuclear energy and fuel market, particularly for back-end fuel services. Accordingly, these full actinide recycle alternatives could provide the greatest opportunities for the United States to influence international fuel cycle

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[97] The draft PEIS discusses both possibilities.

practices through direct engagement in the international market. If U.S. Government policy permitted U.S. nuclear vendors to offer an attractive range of products and services, that would strengthen the U.S. ability both to influence the policies of other supplier states and to influence the practices of customers through U.S. consent rights.

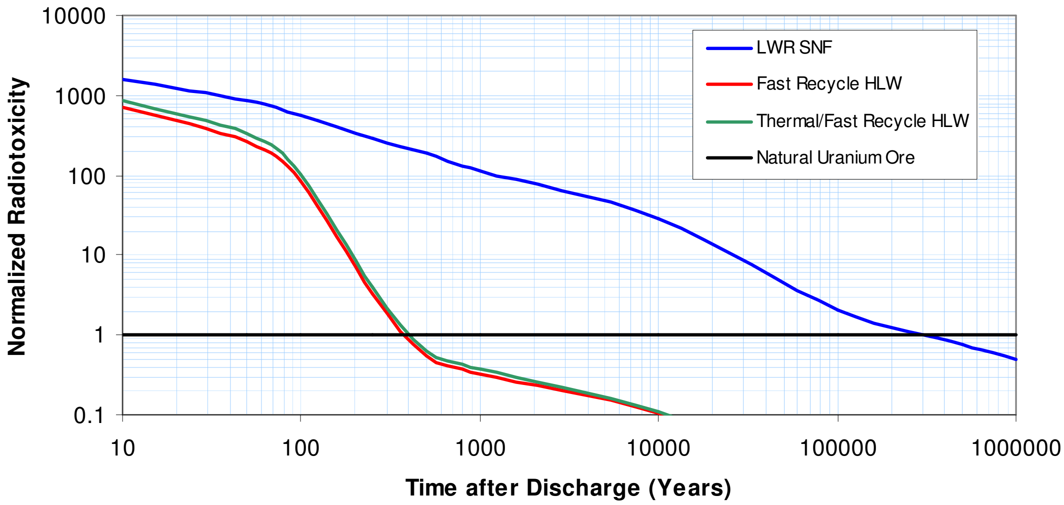

FIGURE 6.2 - Radiotoxicity Reduction for Full Actinide Recycle Alternatives

To the extent that they displace LEU as nuclear fuel, full actinide recycle alternatives also reduce the demand for enrichment compared to the other alternatives (see Table 6.2), because the reprocessed materials (actinides) would be used as fuel to generate electricity. As noted above, this could reduce incentives and opportunities for additional countries to seek to enter the enrichment services business. The full actinide recycle alternatives would reduce demand for enrichment domestically in the advanced fuel cycle states, which could make it easier for existing suppliers to meet international demands. This would contribute to the ability of suppliers to provide comprehensive fuel services that include both assured supply at the front end and assured acceptance of spent fuel at the back end.

It is reasonable to expect that any spent fuel recycling facilities in the United States would be dedicated primarily to meeting domestic nuclear energy and spent fuel management needs. Conceptually, a portion of the initial recycling capacity could be made available for reprocessing spent fuel from other countries under assured "take back" of spent fuel arrangements. Given the expected limits on initial recycling capacity the United States would have to decide on priorities for addressing those international needs.

<u>Policy Impact</u>: By taking an active role in spent fuel recycling, the United States would strengthen its ability to influence how other countries engage in recycling. In choosing to abstain from civil spent fuel reprocessing for the past 30 years, the United States aimed to influence other countries to make the same choice. However, some countries had already chosen to pursue civil reprocessing. The U.S. choice not to pursue that path reduces the U.S. ability to influence the policies and practices of those who do.

Conversely, by choosing to pursue civil spent fuel recycling, the United States could increase its influence among those countries and over time establish a leadership role. Such leadership and influence could take several forms. First, the United States could define and build consensus on goals for spent fuel recycling. The GNEP Statement of Principles provides an example of successful U.S. leadership in this area (see text box below). Second, the United States could cooperate with international partners on research and development for technologies to achieve those goals, subject to constraints on the transfer of sensitive technologies (see Chapter 2). Third, by participating directly in developing the options for providing back-end fuel services, the United States could set standards that influence the choices of other countries, either as users or as providers of back-end services. By working to establish partnerships with other countries to offer a comprehensive package of nuclear energy and fuel cycle services, the United States could help define how those partnerships functioned to meet shared nonproliferation objectives through full actinide recycle.

One potential drawback of deploying a full actinide recycle fuel cycle in the United States is that it might encourage countries that do not currently recycle spent fuel to start doing so. However, compared to the LWR recycle programs currently in use overseas, the technical challenges for countries considering full actinide recycle would be relatively high. It could also increase pressures for international cooperation in reprocessing R&D beyond current technology holders. Proponents of a once-through fuel cycle argue that by embarking on full actinide recycle alternatives, the United States would set an example that some countries would emulate by developing their own reprocessing programs. They argue that efforts to reinforce existing divisions between countries that have reprocessing programs and those that do not will provoke a backlash among developing countries and other aspiring nuclear states that will lead some to pursue reprocessing. However, given the economies of scale necessary to make commercial reprocessing programs cost effective, few countries would have large enough nuclear power programs to justify the expense of building their own reprocessing facilities. If the United States joined other countries that recycle spent fuel in offering back-end fuel services on attractive terms (reliable, affordable, and without onerous conditions), the net effect would be to discourage the spread of civil reprocessing. If the fuel services are structured in a way that gives customers some level of control over how they operate,[98] those customers might be more inclined to rely on such services.

Nonetheless, it is critical that any plan to return to civil reprocessing in the United States address this risk and endeavor to avoid the spread of spent fuel reprocessing technology. As noted in Chapter 4 and below, offering attractive back-end fuel services to other countries could provide a powerful incentive for those countries to avoid the high cost of establishing an indigenous reprocessing program and rely instead on international services, assuming that the cost, reliability and other aspects of the services are sufficiently attractive.

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[98] The International Uranium Enrichment Center in Angarsk, Russia is one example of how this might work. See Chapter 4.

Global Nuclear Energy Partnership Statement of Principles

The goal of the Global Nuclear Energy Partnership (GNEP) is the expansion of nuclear energy for peaceful purposes worldwide in a safe and secure manner that supports clean development without air pollution or greenhouse gases, while reducing the risk of nuclear proliferation.

To ensure that nuclear energy makes a major contribution to global development into the 21st century consistent with non-proliferation and safety objectives, GNEP partners will cooperate with the following objectives while recognizing the need for a variety of approaches and technical pathways in achieving long-term vision of the future global civilian nuclear fuel cycle:

- Expand nuclear power to help meet growing energy demand in a sustainable manner and in a way that provides for safe operations and management of wastes.
- Develop and demonstrate, inter alia, advanced technologies for recycling spent nuclear fuel for deployment in facilities that do not separate pure plutonium, with a long term goal of ceasing separation of plutonium and eventually eliminating stocks of separated civilian plutonium. Such advanced fuel cycle technologies, when available, would 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 utilization of energy resources.
- Develop, demonstrate, and in due course deploy advanced fast reactors that consume transuranic elements from recycled spent fuel.
- Establish international supply frameworks to enhance reliable, cost-effective fuel services and supplies to the world market, providing options for generating nuclear energy and fostering development while reducing the risk of nuclear proliferation by creating a viable alternative to acquisition of sensitive fuel cycle technologies.
- Promote the development of advanced, more proliferation resistant nuclear power reactors appropriate for the power grids of developing countries and regions.
- In cooperation with the IAEA, continue to develop enhanced nuclear safeguards to effectively and efficiently monitor nuclear materials and facilities, to ensure nuclear energy systems are used only for peaceful purposes.

International cooperation among GNEP partners will be carried out under existing and, where appropriate, new bilateral arrangements as well as existing multilateral arrangements such as the Generation IV International Forum and the International Project on Innovative Nuclear Reactors and Fuel Cycles.

Commitments and international obligations, including IAEA safeguards and the requirements of UN Security Council Resolution 1540 will be strictly observed. The highest levels of nuclear safety and security will be maintained.

States that share these goals will be welcome to participate. Through international cooperation, partners aim to accelerate development and deployment of advanced fuel cycle technologies to encourage clean development and prosperity worldwide, improve the environment, and reduce the risk of nuclear proliferation. Participating States would not give up any rights, and voluntarily engage to share the effort and gain the benefits of economical peaceful nuclear energy.

Technical Risk: A related drawback is that the physical infrastructure for reprocessing provides an inherent capability to separate weapons-usable material. Even a relatively small scale or unsophisticated reprocessing plant could produce several "significant quantities"[99] of weapons-usable plutonium per year, and R&D or engineering-scale facilities could have the capacity to separate tens to hundreds of significant quantities per year. In terms of contained plutonium, this amounts to a *significant quantity* in less than a week. In short, the technical hurdles for potential proliferators are low and the logistical hurdles are not very high if they are willing to accept risk, consequently the ability of the international safeguards system to deter and detect clandestine reprocessing activities needs to be robust and reliable.

6.3.1.2 Civil plutonium stocks

Full actinide recycle alternatives have the greatest potential to draw down stocks of separated plutonium worldwide. Domestically, both alternatives would establish a market for plutonium-bearing reactor fuels and a program for qualifying and licensing such fuels in commercial power plants. This would eliminate the elements of technical and regulatory risk for utilities and reactor operators in considering the use of such fuels and would limit the need for incentives for them to do so. The resulting market for plutonium-bearing fuels could be used to address both existing global stockpiles of separated plutonium and the historical imbalance between separation and use of civil plutonium.

In considering the impact on global plutonium stockpiles, it is important to recognize that other countries may consider their plutonium stockpiles as energy resources for their internal nuclear power programs. Three of the largest holders of separated civil plutonium stocks – France, Japan, and Russia – have plans to develop fast reactor programs of their own. International cooperation in the development of fast reactors therefore could have significant nonproliferation benefits by accelerating the deployment of fast reactors worldwide, thereby speeding the drawdown of separated civil plutonium stocks. However, this advantage would be lost if the introduction of fast reactors led to the breeding and stockpiling of separated plutonium.

6.3.1.3 Material attractiveness

The principal drawback of any of the full recycle alternatives is that they would take spent fuel, which is bulky, highly radioactive for many years,[100] and requires extensive processing to separate weapons-usable material, and convert it into a form that is much more compact, less radioactive, and requires little processing to convert it to a weapons-usable form. So long as this reprocessing takes place only in countries that already have reprocessing capabilities, these alternatives would not contribute significantly to state-level proliferation risk.

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[99] The International Atomic Energy Agency defines a significant quantity as roughly the quantity of material a country would need to manufacture its first nuclear explosive device, 8 kilograms of plutonium or 25 kilograms of U-235 contained in high enriched uranium.

[100] Radioactive decay causes significant reductions in spent fuel radiation levels after ~100 years.

However, even if the use of sensitive materials does not spread to additional countries, it could spread to a larger number of sites within those countries with increasing inventories and transport, thereby increasing the requirement for effective physical protection measures against theft or sabotage. Under existing requirements, physical protection measures for such materials must be designed to prevent potential attackers from succeeding in removing such materials from the facility. Stringent physical protection measures would be required for all facilities processing sensitive nuclear materials and for all transport of such materials. This risk applies not only to plutonium and plutonium-bearing materials but also to the minor actinides, particularly neptunium, which in some of the reprocessing alternatives may be produced and stored in separated forms.

Nonetheless, full actinide recycle fuel cycles offer potential security advantages over current approaches to spent fuel recycle (PUREX) in that they permit the separation approaches that do not separate plutonium completely but rather keep it combined with uranium and possibly other actinides. If the plutonium (or other transuranic material) is diluted sufficiently with natural uranium it becomes more difficult to use directly in a nuclear explosive device. As the ratio of transuranics to uranium is reduced, it eventually becomes impractical or even physically impossible for the material to sustain the fast fission chain reaction necessary for a nuclear explosion. Therefore, dilution of plutonium or transuranic material with uranium offers some advantage against the risk of a successful terrorist attack. Regardless of any dilution, however, all the full actinide recycle alternatives involve materials that are sufficiently attractive for potential misuse that they require Category I physical protection measures.

Blending plutonium with minor actinides offers relatively limited reductions in material attractiveness. Plutonium and neptunium produce relatively low radiation fields and can generally be handled in lightly shielded glove box facilities. Neptunium has a critical mass similar to HEU and has no heat or radiation emissions that would complicate its use in a nuclear explosive device.[101] Therefore, blending plutonium and neptunium offers no significant reduction in material attractiveness over pure plutonium. Americium and curium have significantly higher gamma and neutron radiation fields and, therefore, are normally handled in more heavily shielded hot cell facilities. If the recycled material included a homogeneous mix of plutonium and the minor actinides, the resulting gamma and neutron fields would make it more difficult for a terrorist or other non-State actor to handle the material safely. However, the hazards of this level of radiation exposure by themselves would not prevent theft or malicious use of the material and would do little to deter someone who was willing to accept these risks. Retaining some lanthanide fission products in the recycled fuel would also make it harder to handle safely and less attractive for weapons use, though radiation levels would remain well below the “self-protection” threshold.

In the context of a potential diversion by a state, the nonproliferation benefits of blending plutonium either with uranium or the minor actinides are both very modest. Any state operating a spent fuel recycling facility has most or all of the capability required to separate relatively attractive weapons-usable material from the product, whether it contains minor

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[101] See IAEA Document GOV/1998/61 (October 1998), para 6.

actinides or uranium. Nonetheless, for states that currently have civil reprocessing programs, a transition to group actinide separation processes could contribute to confidence in the purely civilian nature of those programs.

6.3.1.4 Safeguards

Closely related to the production of relatively attractive forms of fissionable material is the challenge of developing and applying effective safeguards measures for the complex separation process involved. These separation processes convert large, countable fuel assemblies (items) into bulk material in various quantities and compositions in a processing facility. These materials can be tracked and measured quantitatively through chemical analysis or radiation signatures. However, overall measurement uncertainties for large processing facilities make it difficult to provide sufficiently accurate accounting for large quantities of material through measurement alone. Thus, safeguards approaches for such facilities rely on complex monitoring systems in addition to traditional measurement-based accountancy systems to rule out plausible material diversion scenarios or possible misuse of the facility.

There are also new and as yet unsolved technical challenges associated with advanced spent fuel recycling technologies. The mixed actinide streams that offer modest material attractiveness benefits also pose new measurement challenges. For example, it is difficult to use neutron emissions to infer plutonium mass against the background of copious neutron emissions from curium. For fast reactors, the need to isolate the sodium coolant from the atmosphere, and the fact that sodium is opaque, make it difficult to track and identify individual fuel assemblies in sodium-cooled fast reactors. Developing advanced safeguards methods to detect diversion from or misuse of advanced fuel cycle technologies is therefore essential. Domestic research and development on advanced spent fuel cycle technologies and international cooperation on those technologies provide critical opportunities to develop those safeguards methods.

6.3.1.5 Sustainability

The security and proliferation risks would be magnified if the implementation of full actinide recycle proved unsustainable because of an imbalance either in material or in economics. An imbalance in material flow could arise if the rate of reprocessing spent fuel exceeded the rate at which the separated material was used as reactor fuel. Such an imbalance would result in the accumulation of separated weapons-usable material, with a corresponding growth in the associated security risks and costs.

The costs of separation and recycle of transuranics from spent fuel would be critical in determining whether such imbalances might occur. For example, these costs could make the use of recycled fuel economically uncompetitive compared to fresh uranium fuel. If the costs were met through a government subsidy, the fiscal impact of that subsidy could become politically unsustainable. For example, some increase in the current assessment of one mill ($.001) per kilowatt-hour may be necessary to finance spent fuel recycling.[102] A large increase could become politically unsustainable due to political opposition from utilities and ratepayers.[103]

An economic imbalance would not by itself pose a proliferation or a security risk, but it could increase pressures to make fuel cycle choices that increase those risks. For example, if the resulting price of recycled fuel remained substantially higher than that for fresh LEU fuel, it would create pressures not to use the recycled material in fuel but instead allow it to accumulate, as has occurred historically. Another possibility is that advanced recycle methods designed to remove the transuranics from waste and support assured back-end fuel services could prove to be substantially more expensive than methods that do not offer such benefits. This in turn could create economic pressures to adopt methods that offer few nonproliferation benefits to offset the drawbacks of reprocessing. It is therefore important to pay attention to whether economic interests are aligned or in conflict with nonproliferation interests.

These factors may have contributed to the steady accumulation of separated plutonium in other countries that engage in spent fuel reprocessing. For example, the UK civil plutonium stockpile is approximately 100 tons, with no disposition pathway yet identified. Japan has approximately 33 tons of separated plutonium,[104] most of which is stored in France and the UK, which it has not yet begun to use in its operating power reactors. The pace at which Japan uses this plutonium and additional plutonium to be produced domestically will depend on the rate of MOX fuel loading in Japanese LWRs and when Japan's MOX fuel fabrication is ready to operate. Russia has decided to store separated plutonium pending deployment of fast reactors that would use that plutonium as fuel. Any domestic U.S. recycling program should avoid such accumulations. Since fast burner reactors require large quantities of transuranic material as startup fuel, the working stocks of plutonium required to support a fast reactor program could still be rather large.

While the U.S. fast reactor program is premised on deploying fast reactors as burners, other countries have an interest in deploying them as breeders, primarily for energy security reasons. The distinction is that a burner consumes more transuranics, including plutonium, through fission than it generates through the absorption of neutrons by actinides in the fuel, while a breeder generates more transuranics than it consumes. In general, breeders operate with blankets of natural or depleted uranium within and surrounding the core (in contrast, the Korean conceptual design of the KALIMER-600 fast reactor does not include such a blanket); the plutonium produced through neutron absorption in such blankets could have an isotopic composition similar to or better than weapons-grade plutonium (see Table 6.4

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[102] Several of the studies prepared for DOE by industry consortia discussed raising this fee. Summaries of these studies are available at http://www.gnep.energy.gov/afciparticipants/industryinvolvement.html.

[103] In other contexts, the public has accepted significant increases in the cost of electricity for environmental reasons. For example, it is estimated that for coal-fired power plants, "average operating and maintenance costs for scrubbers, exclusive of capital recovery, are 1.42 mills per kilowatt hour. This increase in electrical rates is about one-half that associated with pre-1990 wet scrubbers." DOE/EIA-0582(97). Including capital recovery can increase this to 7-10 mils/kWhr.

[104] INFCIRC/549/Add.1/10, which is reported by Japan under the Plutonium Management Guidelines for December 31, 2006.

above). Burners replace those blankets with materials that reflect neutrons back into the core.[105] Depending on the reactor design, there could be sufficient flexibility to convert a burner into a breeder by replacing the reflectors with blanket materials.

Therefore, there is a risk that encouraging the development of fast burner reactors could lead to the deployment of fast breeder reactors, which would increase the quantities of highly attractive weapons-usable material in the civil nuclear fuel cycle. As with enrichment and reprocessing, the state-level proliferation risk depends mainly on the number of countries that use such materials. Several countries, including France, Japan and Russia, are planning fast reactors as part of their long-term energy plans. If breeders become economically attractive in advanced nuclear states, it may be difficult to limit the reactor types deployed in other states to thermal reactors that use less attractive materials in their fuels. As future decisions are made on designs and fuel technologies for fast reactors, it is important to weigh these risks and seek to structure the domestic and international fuel cycles to limit stockpiles of separated materials to levels sufficient to meet demands for fuel reliably.

6.3.2 Distinctions Among Full Actinide Recycle Alternatives

The full actinide recycle alternatives in the GNEP PEIS cover a range of options that differ in the timing and degree of nonproliferation benefits. Many of the technical features of these scenarios would be the subject of future decisions if a decision is made to close the domestic fuel cycle.

The fast reactor alternative with advanced separations has advantages in terms of waste reduction but disadvantages in terms of timing. This alternative would remove the transuranics almost completely from the waste stream. As noted above, this provides the greatest potential for supporting comprehensive international fuel services that discourage the spread of enrichment and reprocessing. However, by waiting to deploy spent fuel recycling until advanced separations and fast reactors are demonstrated, this alternative could leave the United States unable to provide such services for several decades.

Under this alternative, the timing risk could be mitigated in one of two ways. First, the United States could offer back-end fuel services in partnership with other countries that offer reprocessing services internationally. While the United States could use such partnerships to encourage those countries to adopt reprocessing methods that do not separate pure plutonium, for the next decade or two they will most likely continue to use PUREX. Such partnerships would likely be based on current practice for the return of high-level waste (which includes the minor actinides) to the country that generated the spent fuel. The second option for mitigating the timing risk would be to offer assistance with interim storage of spent fuel pending the availability of advanced recycling capabilities.

The alternative with thermal and fast reactor recycle could mitigate this timing risk by allowing the earliest practical deployment of domestic spent fuel recycle facilities that could provide acceptance of other countries spent fuel on a selective basis. Until advanced

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[105] While it is possible to have a positive breeding ratio without a blanket, the plutonium generated in the core would have a relatively unattractive isotopic composition.

recycling and fast reactors became available, spent fuel would either be stored or recycled incompletely in existing LWRs. Since LWRs are ineffective at consuming the minor actinides,[106] the minor actinides would most likely either go into the waste stream or be separated and stored pending the availability of fast burner reactors. The former would have the effect of limiting reductions in waste hazards, while the latter would add costs and security requirements without compensating benefits for many years.

A phased implementation of the thermal/fast reactor alternative that began with spent fuel recycling in thermal reactors before fast reactors were demonstrated would involve certain technical and economic risks. It could also delay ultimate implementation of fast reactor recycling by competing for scarce financial, human, and technical resources. This alternative depends on fast reactors to achieve the ultimate benefits of removing the minor actinides from the waste stream. If fast reactors prove to be impractical for technical or economic reasons, the spent MOX from thermal recycle would need to be disposed of as waste or recycled further in thermal reactors. Multiple pass recycling through thermal reactors of both plutonium and the minor actinides becomes increasingly difficult with each recycle due to the buildup of non-fissile isotopes and intensely radioactive higher actinide elements such as californium and berkelium. If such thermal recycle is not practical, the minor actinides in the spent MOX fuel containing large quantities of plutonium and other transuranics would need to be disposed of as waste, and the waste reduction benefits from thermal recycle would be significantly reduced. Thus, using early thermal recycle as the basis for starting on the path to full recycle of all transuranics poses the risk of accepting the near-term nonproliferation drawbacks of full actinide recycle without obtaining the intended long-term nonproliferation benefits.

One way to avoid this risk is to develop an economically and technically credible plan to implement advanced recycling with a contingency plan to mitigate proliferation and security risks should advanced recycling prove impractical. Building a broad political consensus in support of such a plan would help build the policy stability necessary to sustain such a strategy over many decades.

While there are clear benefits to recycling all the transuranics in spent fuel, there are also tradeoffs depending on whether this recycling is homogeneous (all transuranics blended evenly in fuel elements) or heterogeneous (blending plutonium with uranium and neptunium in fuel and fabricating the relatively small quantities of americium and curium into separate targets). Homogeneous recycle of transuranics poses greater technical challenges for safeguards in measuring the composition of mixed materials.[107] In particular, the copious neutrons emitted by curium would swamp the neutron signal typically used to measure plutonium mass. However, as noted above, keeping a blended transuranic stream keeps the plutonium in a form that is slightly more difficult to handle than fully separated material. In contrast, fuels made of plutonium, neptunium and uranium may be relatively easy to fabricate and use. Separate fabrication of americium/curium targets would involve

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[106] The PEIS notes the conceptual possibility of using TRU MOX fuel, but treats U-Pu MOX as the baseline scenario for LWR recycle.

[107] Fuel fabrication can also be a challenge given the expected minor actinide content of the fuel, particularly considering the high radiation fields from americium and curium and the high vapor pressure of americium.

relatively small amounts of material. Although heterogeneous fuels may pose slightly greater proliferation and security risks, they could provide a more practical evolutionary path towards consuming all the transuranics. Because of these tradeoffs, there may be at most a slight preference for homogeneous recycling over heterogeneous recycling of transuranic materials.

A related issue arises with a phased implementation scenario. The basic alternatives for managing the minor actinides in the initial phases are (1) put them into the high-level waste, (2) separate and store them until fast reactors are available, or (3) separate and seek to consume them in thermal reactors. Each of these options has its challenges. Putting minor actinides into the waste stream significantly reduces the waste reduction benefits of spent fuel recycling, which would reduce the feasibility of accepting other countries' spent fuel. Separating and storing the minor actinides poses added costs and security requirements and could entail a change in international safeguards to provide a more formal accounting for those materials.[108] While the quantity would be small compared to global stocks of separated plutonium, stocks of minor actinides could accumulate to tens of tons over a period of decades. Such accumulations could be particularly significant for neptunium, which has a relatively low radiation field and could be used in a nuclear explosive device. Therefore, an alternative would be to recycle neptunium while treating americium and curium as waste.

There are also differences between the two alternatives in the ability to draw down existing stocks of separated plutonium. Both alternatives draw down the stocks of separated plutonium, replacing them with plutonium contained in the far less attractive form of spent fuel. The ratio of the quantity of plutonium output to plutonium input – known as the conversion ratio – depends on both the reactor and the fuel type. Recycle of separated plutonium in LWRs could be significantly slower than in fast reactors. Approximately half of the existing LWRs would be able to use a fraction (approximately a third) of their reactor cores to burn MOX fuel. For example, twenty 1000 MW LWRs, each using MOX fuel with 6.5% plutonium for a third of its core, could use about 8 tons of separated plutonium per year and in principle draw down the entire global stockpile of civil and excess military plutonium within about 44 years. This rate of consumption would roughly match the current rate of growth of separated plutonium stockpiles. However, reprocessing operations at the Japanese Rokkasho Reprocessing Plant are expected to double that growth rate until the Japanese MOX fuel fabrication facility goes on line (expected in 2012). Once deployed, advanced LWRs designed for full core loads could increase the rate of plutonium consumption by more than a factor of three.

In contrast, the initial core loads of fast reactors require much larger quantities of fissile material. For example, a 500 MW fast reactor using 30% plutonium fuel would require 3.5

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[108] Currently the IAEA applies safeguards only to source material (uranium and thorium) and special fissionable material (enriched uranium, plutonium, and U-233). In September 1999, the IAEA Board of Governors decided not to treat neptunium or americium as special fissionable material, since that would add significantly to safeguards costs and since neither material was being separated in large quantities in non-nuclear-weapon states. The Board also asked the Director General to report back if this situation changed significantly.

tons of plutonium for its startup cores,[109] so 50 such reactors would suffice in principle to use up existing global stocks of separated plutonium. Although the United States could choose whether to use its existing stocks of excess weapons plutonium, the ability to affect global stockpiles would depend on the willingness of other countries to make this material available.

Future decisions will need to consider the differences between the various separations techniques. GNEP seeks to improve on current reprocessing technologies by not separating pure plutonium. As noted above, the mixed products might be slightly less attractive than separated plutonium, though all of the reprocessing alternatives produce Category I nuclear materials. In order to produce a pure plutonium product, either the separations process would need to be modified or the impure product would need to be purified chemically. For a country capable of operating a large-scale aqueous reprocessing plant, neither of these steps would be difficult or time-consuming, but the international safeguards approach for such facilities could be designed to detect such changes. Depending on the process, the time needed to acquire separated plutonium through misusing the separations plant could range from a few days to several weeks. The changes in plant chemistry and operations to produce separated plutonium should be readily detectable, and this risk of detection could deter the country from modifying its existing reprocessing facility clandestinely to separate pure plutonium. However, the warning time to the international community to respond to such breakout would be very short, which could reduce the deterrent value of these international safeguards measures. Conversely, for a country that currently operates a reprocessing plant that is designed to separate pure plutonium, modifying that process to avoid separating pure plutonium could help reinforce international confidence in the peaceful nature of its nuclear program. However, given the costs involved such decisions are likely to be made primarily on the basis of whether they improve the overall economics of fuel cycle management.

The considerations are somewhat different for the electrochemical separations processes known as pyroprocessing (see chapter 4). Pyroprocessing normally produces a metallic blend of uranium and transuranics and some level of radioactive impurities from rare earth fission products, although the level of such impurities can be quite low. Depending on the process used and the composition of the spent fuel being recycled, the product can be relatively pure plutonium or transuranic material in a metallic form that can be used in a nuclear weapon or other nuclear explosive device without further chemical processing,[110] or it can be a relatively impure and radioactive metallic fast reactor fuel. Scenarios involving misuse of pyroprocessing facilities tend to be complicated and may require a number of weeks to carry out.[111] Alternatively, the product could be purified in a relatively small-scale

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[109] Utilities generally fabricate and have on hand two cores for use in startup of a reactor.

[110] "An Assessment of the Proliferation Resistance of Materials in Advanced Nuclear Fuel Cycles," C.G. Bathke et al. 8th International Conference on Facility-Operations – Safeguards Interface, March 30 – April 4, 2008, Portland OR. [NOTE: We are determining whether we can cite a separate paper, "Proliferation Risk Reduction Study of Alternative Spent Fuel Processing Technologies," currently marked "Official Use Only."]

[111] There is considerable uncertainty surrounding such estimates. Pyroprocessing remains an experimental process not yet deployed on a production scale. Misuse could take longer than estimated if there are complications in modifying or scaling up the process. On the other hand, development of new pyroprocessing methods could allow for misuse scenarios that take less time to complete.

aqueous separation or ion exchange process on a similar or shorter time scale. Pyroprocessing also poses challenges for material accountancy and would require significant safeguards technology and system development before effective safeguards systems could be implemented even for engineering-scale facilities. An effective safeguards approach for such facilities should be designed to detect both misuse of the facility and diversion of nuclear material.

Finally, while fast burner reactors offer the benefit of being net consumers of the minor actinides, they have an important drawback from a nonproliferation and security perspective. Fast reactors require fuels with a higher content of fissile isotopes than thermal reactors. While U-Pu MOX for a thermal reactor might typically contain 7-10% plutonium, most fast burner reactor designs would use significantly higher densities, e.g. over 30% plutonium for conversion ratio of about 0.5. Therefore, Pu-bearing fresh fast reactor fuel would be considered Category I material, requiring the highest level of protection under NRC regulations and international guidelines.

Moreover, there is a tradeoff between the very modest security benefits that might be obtained by reducing the fissile content and the number of fast reactors needed to create a balanced mix with LWRs. The lower the fissile content, the higher the conversion ratio and the larger the number of fast reactors needed. Thus, reducing this density could lead to undesirable outcomes, such as increased domestic or even international transport of fast reactor fuels. It could also raise the cost of recycling above economically sustainable levels, putting at risk the waste reduction benefits of recycling and the associated nonproliferation benefits of accepting other countries' spent fuel. For this reason, security and nonproliferation considerations regarding fuel density should not be the primary determining factor in fast reactor fuel design, but should be one of many considerations in an overall systems analysis that also addresses costs and nuclear material flows.

6.3.3 Options for Reducing Proliferation Risks

The chief nonproliferation benefit of the full recycle alternatives is that they have the greatest promise of enabling comprehensive, reliable fuel services that include return of spent fuel from recipient states, the best chance of reducing waste hazards, and the best opportunity to reduce the global stocks of separated plutonium. However, as noted in Chapter 4, there are significant constraints on importing foreign spent fuel into the United States. Addressing these constraints will take sustained effort over many years. In the meantime, the United States could pursue comprehensive fuel service arrangements through international partnerships with other countries to provide back-end services. Such partnerships would give the United States leverage to encourage countries that provide reprocessing services both to increase the attractiveness of spent fuel management arrangements to customers and to move toward separation and recycle processes that reduce proliferation and security risks. Successful demonstration of such arrangements in any country could make it more feasible for others, including the United States, to take similar steps.

The chief drawbacks of the full recycle alternatives are the sensitivity of the materials they would produce and the technologies they would use, which require significant safeguards and physical protection measures to mitigate the associated security and proliferation risks. Efforts already planned and underway would address many of the needed safeguards measures, including the measurement of novel material types such as mixed transuranic materials, monitoring of novel processes such as pyroprocessing, and safeguards approaches for new facility types such as fast reactors. The fuel cycle R&D activities of the Advanced Fuel Cycle Initiative would provide valuable opportunities to develop and evaluate these techniques.

A number of measures are available to manage inventories and flows of sensitive nuclear materials in ways that mitigate the associated security and nonproliferation risks. These include reducing stockpiles of separated nuclear materials to the minimum necessary for working stocks, minimizing domestic transport of separated materials through collocation of facilities, and avoiding international transport of those materials to the extent possible. To draw down stockpiles of separated plutonium and bring them into equilibrium with demand, the United States could work with countries that do not have plans for the disposition of their plutonium stocks to develop such plans. One option would be to use those stocks to produce startup cores for fast reactors. A more immediate option (in the thermal and fast reactor recycle alternative) would be to use those stocks to produce MOX fuel for LWRs, which would also seed the market for recycled plutonium in the United States. Such an arrangement could seek to phase out international transport of separated materials through a rapid transition to a reliable fuel services program under which plutonium would only be transported internationally in the form of spent fuel. The slow progress in disposition of excess plutonium in the United States and Russia shows that international cooperation to reduce plutonium stockpiles would take time and concerted effort.

Finally, to mitigate the risk that economic pressures might force difficult nonproliferation and security choices, the U.S. Government could work to ensure the economic sustainability of its approach to spent fuel management. This depends in part on efforts to reduce the cost of alternatives with the greatest prospect of significant proliferation and environmental benefits, such as full actinide recycle, as well as an improved understanding of the potential synergies or tradeoffs between economic and nonproliferation interests. It is particularly important to understand better how international fuel service arrangements can send price signals that make indigenous enrichment and reprocessing programs uncompetitive and therefore economically unattractive. To inform future fuel cycle decisions, NNSA plans to continue proliferation risk assessments and to continue to refine/develop and validate the methodology for such assessments.

6.3.4 Summary of Full Actinide Recycle Alternatives

The previous section on once-through fuel cycle alternatives concluded that the current U.S. once-through fuel cycle – the no action alternative – has not yet been implemented fully, which raises questions about whether this approach can be sustained. As a result, the value of the U.S. example as a credible model for other countries has diminished over time and may prove difficult to rebuild. By abstaining from spent fuel reprocessing, the United States has chosen to forgo significant opportunities to influence countries that are pursuing reprocessing and certain options for helping other countries manage their spent fuel.

Conversely, either one of the full recycle alternatives would provide new opportunities for international cooperation to limit the spread of enrichment and reprocessing. However, these potential benefits would come with certain costs, including managing certain increased security risks and giving up on attempting to demonstrate by example that a once-through fuel cycle is a feasible and desirable option for all countries.

Managing a transition to full actinide recycle in a way that achieves these nonproliferation benefits and avoids the drawbacks noted above would be challenging. In particular, it is essential that there be a sound economic and business model to support spent fuel recycling and comprehensive fuel services, that a broad policy consensus be reached and sustained over decades, and that both the business model and the policy consensus have a sound technical foundation. It is equally essential to ensure that nuclear safeguards and security best practices are implemented globally and that nonproliferation objectives be integrated into the economic, policy, and technical foundations of the fuel cycle.

For both of the full recycle alternatives, fast reactors are a key element in building an international fuel cycle that discourages the spread of enrichment and reprocessing. Such a fuel cycle could provide both assured fuel supply and assured return of spent fuel under attractive terms. Only fast reactors are capable of reducing spent fuel management from a several hundred thousand year problem to a several hundred year problem. They are also better suited than other reactors to drawing down stocks of excess plutonium worldwide and bringing the fuel cycle into balance.

Recycling LWR spent fuel in a mix of thermal and fast reactors may offer the prospect of reducing the overall costs of the nuclear energy system. A phased implementation that begins with recycle in thermal reactors may make it possible to begin to achieve the structural benefits of full actinide recycle decades earlier than a spent fuel recycle system that uses only fast reactors. However, there are also risks of adopting such a phased approach, since LWR recycle by itself offers limited reduction in long-term radiotoxicity, unless indefinite LWR recycle of plutonium proves viable. Embarking on thermal recycle before the technical and economic feasibility of a fast reactor fuel cycle is demonstrated could, therefore, involve significant risk regarding the ability to achieve the intended nonproliferation benefits associated with U.S. participation in back-end fuel services.

6.4 ASSESSMENT OF PARTIAL ACTINIDE RECYCLE ALTERNATIVES

For the purpose of this assessment, a partial actinide recycle fuel cycle is one in which some of the actinide content of spent fuel is recycled but some remains in the waste stream. This can occur either through incomplete separation and reuse of the transuranics, with some or all of the minor actinides going to the waste stream, or through a limit on the number of times fissionable material in spent fuel is recycled, so that second or third generation spent fuel is disposed of as waste. Of the programmatic alternatives and optional variants considered in the GNEP PEIS, three fit into this category:

- **LWR recycle.** Involves repeated recycle of plutonium in LWRs, effectively removing plutonium – but not all of the minor actinides[112] – from the waste stream.
- **DUPIC**. Involves thermal and mechanical processing of spent LWR fuel, which includes oxidation/reduction and grinding of spent fuel into powder and fabricating that powder into CANDU fuel. This fuel is used once in a HWR and is then disposed of. The Republic of Korea and Canada have jointly developed this process for the Direct Use of PWR Spent Fuel In CANDU reactors.
- **Deep Burn HTGRs**. Involves the chemical separation of LWR spent fuel and fabrication of oxide fuel for high temperature gas-cooled reactors. The fuel would contain only the recovered transuranic elements with no added uranium and would consume a significant fraction of the transuranics in a single use before disposal of the spent fuel.

6.4.1 Nonproliferation Impacts

Although these alternatives are structurally intermediate between the once-through and full actinide recycle alternatives, their nonproliferation impacts tend to be closer to one extreme or the other. In terms of waste management benefits, these alternatives are much closer to once-through fuel cycle alternatives. Those benefits therefore may not be sufficient to enable acceptance of other countries' spent fuel. In terms of material attractiveness and safeguards, these alternatives pose the same added challenges as the full recycle alternatives.[113] In terms of facilitating drawdown of existing stocks of separated plutonium, these alternatives are intermediate between the once-through and full actinide recycle alternatives.

6.4.1.1 Influence on fuel cycle

Direct Impact: The additional electricity generation that can be achieved without further enrichment or fuel fabrication reduces the quantity of spent fuel and high-level waste destined for geological disposition per unit of energy generated. In general, the second generation spent fuel will have a higher concentration of long-lived transuranics than the initial spent fuel. However, given the increase in energy generated, there can be a reduction in the amount of transuranic waste per unit energy generated. This can be substantial (up to a factor of 3) in the case of the 'deep-burn' alternative. Since the transuranic waste component drives the long-term radiotoxicity, the effective reduction in radiotoxicity is generally less than a factor of two (see Figure 6.3).

Complete data are available only for the LWR recycle alternative, under which no spent fuel is sent to a repository but the high-level waste has a high burden of minor actinides. The long-term radiotoxicity is reduced, but not dramatically. Data for a fuel cycle with a single

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[112] The option that removes all of the minor actinides is not considered in this assessment, though if practical it would be considered a full actinide recycle alternative.

[113] The DUPIC fuel cycle is an exception, since it involves only limited separation of fission products from fissionable material and therefore does not greatly increase material attractiveness compared to spent fuel in the once-through alternative.

pass LWR recycle of plutonium MOX are included for comparison purposes, to show that such a fuel cycle offers no significant reduction in long-term radiotoxicity. Because of limited relevant experience, no data are available for the other two (DUPIC and DB-HTGR) alternatives, but given that spent fuel is disposed in both cases, it is reasonable to expect that the long-term radiotoxicity for DUPIC would be similar to that for spent HWR fuel, or slightly higher due to the greater buildup of transuranics. Similarly, it is reasonable to expect that the long-term radiotoxicity of spent fuel from the DB-HTGR approach, combined with the HLW from processing the spent LWR fuel, would be similar to that for spent HTGR fuel and roughly a factor of 2-3 lower than for spent LWR fuel.

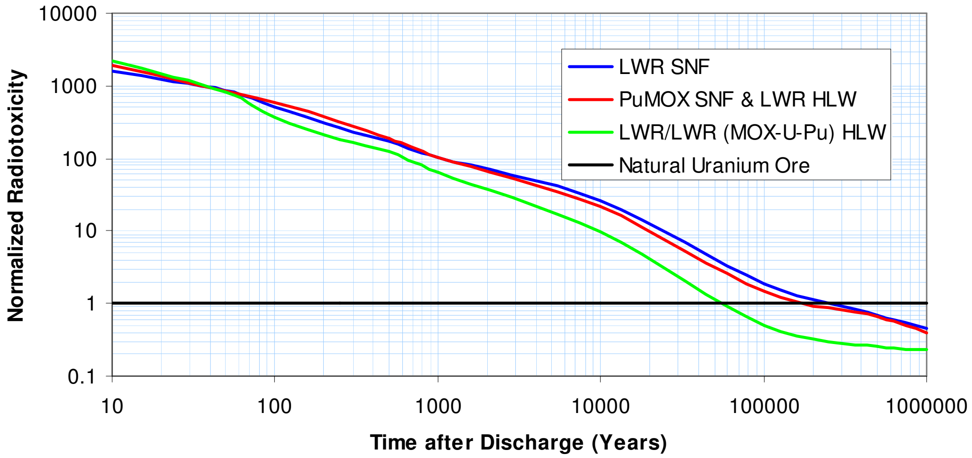

FIGURE 6.3 Radiotoxicity Reduction for Partial Actinide Recycle Alternatives

Because the long-term radiotoxicity reduction benefits are relatively modest compared to once-through fuel cycles, these alternatives may be more challenging to use as the basis for participating in international fuel services that include acceptance of other countries' spent fuel. Returning high-level waste to the countries that generated the spent fuel could make such arrangements more acceptable to the country accepting the spent fuel. However, it could also make the arrangements less attractive to the countries that generated the spent fuel than removal of spent fuel without the return of waste (though possibly more attractive than retaining the spent fuel).

One factor that could make such arrangements feasible is the possibility that imported spent fuel is perceived as a resource rather than a liability, since the recycled fuel would be used to generate electricity. The resulting spent fuel and high-level waste would be no different from that produced by purely domestic electricity generation. As long as the scale of a spent fuel acceptance program remained modest compared to domestic spent fuel generation, the overall impact on domestic nuclear waste would be modest. Spent fuel acceptance arrangements might be politically feasible if the economic and nonproliferation benefits were considered sufficient to justify taking responsibility for the spent fuel. If such arrangements were not an option, the ability to offer back-end fuel services under the partial recycle alternatives would probably depend on partnerships with other countries willing to take back spent fuel.

As with the full recycle alternatives, these partial recycle alternatives involve some reduction in overall uranium enrichment requirements, which could make it easier to offer assured enrichment services internationally with more limited expansion of the existing enrichment infrastructure. This could help maintain U.S. consent rights and other forms of influence over international nuclear fuel cycle policy, particularly if the United States is able – over time – to extend fuel assurances that include back-end services. In addition, whereas the full recycle alternatives can encourage a significant transformation in commercial reprocessing practices, the partial recycle alternatives offer incremental changes over current practice. There are potential benefits and costs to be considered, including the benefit of removing spent fuel containing plutonium from countries that would otherwise store it in country, against the cost of partial actinide recycle encouraging additional states to pursue civil plutonium programs on the grounds that the technology is in reach and required for reasons of national energy security.

<u>Policy Impact</u>: The partial recycle alternatives would result in the United States giving up the ability to demonstrate by example that reprocessing is not a necessary part of a nuclear power program in return for the possibility of U.S. participation in international comprehensive fuel services.

<u>Technical Risk</u>: Reprocessing is necessary for even a single recycle, but the approach does not maximize the sustainability of the fuel cycle. DUPIC extracts more energy value from a given PWR spent fuel assembly, but still culminates in long lived spent HWR fuel that requires a final disposition path.

6.4.1.2 Civil plutonium stocks

Compared to the once-through fuel cycle alternatives, two of these partial recycle alternatives offer a potential for drawing down existing stocks of separated plutonium worldwide in a similar manner to the full actinide recycle alternatives. The LWR and HTGR recycle alternatives would provide the economic and regulatory basis for burning plutonium-bearing fuel in U.S. power reactors. By contrast, the DUPIC fuel cycle is not designed to use previously separated plutonium and, therefore, would not facilitate such use.[114]

6.4.1.3 Material attractiveness and safeguards

The proliferation and security risks of these three alternatives are significantly different. The LWR and Deep Burn HTGR alternatives involve large-scale chemical separation of transuranics from spent fuel for fabrication into recycled fuel. This involves the same security and proliferation risks and the same safeguards challenges as the full recycle

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[114] Although CANDU reactors can burn plutonium using the CANFLEX fuel bundle, this is not one of the alternatives evaluated in the PEIS or NPIA. Nonetheless, if CANDU reactors were deployed in the United States, they could be considered for drawing down existing stockpiles of separated plutonium.

alternatives described above. These alternatives involve reprocessing to separate uranium and plutonium for use as fuel, with the remainder of the spent fuel going to the waste stream. The material attractiveness, proliferation risks, and safeguards challenges are similar to those for the full recycle alternatives.

By contrast, the DUPIC recycling process releases the volatile and some semi-volatile fission products from spent fuel but does not otherwise separate fission products or uranium from plutonium or the minor actinides. This process does not reduce significantly the processing that would be required to separate weapons-usable material from the spent fuel. However, it does convert large items (fuel assemblies), which are relatively easy to keep track of, into bulk material, for which accounting is generally more difficult. This creates opportunities for diversion of plutonium-bearing material and corresponding safeguards challenges to detect such diversions. Although it is difficult to measure plutonium mass directly, it is possible to monitor the flow of plutonium bearing materials in an indirect manner since plutonium is never separated from curium, which is a strong neutron emitter. The IAEA has implemented a safeguards approach based on such indirect monitoring at the DUPIC Fuel Demonstration Facility in the Republic of Korea. Once the material is fabricated into new HWR fuel, the fuel cycle has roughly the same nonproliferation and safeguards characteristics as the HWR once-through cycle discussed above.

6.4.2 Options for Reducing Proliferation Risks

The options for reducing proliferation risks under a partial actinide recycle alternative are a mix of those for the once-through and full actinide recycle alternatives. As with the once-through fuel cycle, the United States could promote international cooperation and assistance on spent fuel management. However, unless the United States is able to accept foreign spent fuel for recycling or disposal, its options will be limited by a reliance on other countries for storage, disposition or recycling of spent fuel.

As with the once-through but particularly the full actinide recycle alternatives, some of these alternatives create new safeguards, physical protection and export control demands that would have to be addressed. As with the full recycle alternatives, the initial deployment of a partial recycle alternative could be used to draw down existing stocks of separated civil plutonium and bring the fuel cycle toward equilibrium. While these partial recycle alternative fuel cycles probably face fewer technology risks than the full recycle alternatives, they still face economic and political risks that may affect whether they can be sustained over time. Steps similar to those described under the full actinide recycle alternatives should be taken to minimize those risks.

6.4.3 Summary of Partial Actinide Recycle Alternatives

As noted above, the characteristics of the partial actinide recycle alternatives tend to be similar to either the once-through or full recycle alternatives rather than intermediate between the two. Because the reduction in long-term radiotoxicity is limited, it is unclear if the waste management benefits of the partial actinide recycle alternatives would be sufficient to support implementation of comprehensive fuel services that include acceptance of spent fuel from recipient countries and thereby achieve the associated nonproliferation benefits. However, they have the advantage over once-through fuel cycles in that they could allow the United States to consider imported spent fuel as an energy resource. Partial actinide recycle alternatives could help reduce barriers to U.S. participation in back-end fuel services, particularly if accompanied by acceptable arrangements to store and/or dispose of high-level waste from reprocessing outside the United States. In terms of the ability to draw down separated plutonium stocks, the partial recycle alternatives offer the same modest benefit over a once-through fuel cycle as the full recycle alternatives have.

However, two of the three partial recycle alternatives – the LWR and Deep Burn HTGR alternatives – offer the same security and proliferation risks as the full recycle alternatives due to the type of spent fuel reprocessing that is required and the attractiveness of the materials involved. By contrast, the DUPIC fuel cycle has substantially lower risks and, therefore, could offer some benefit if it provided a basis for acceptance of spent fuel.

6.5 SUMMARY OF PROGRAMMATIC ALTERNATIVES

The once-through and full actinide recycle alternatives have contrasting advantages and drawbacks. Once-through fuel cycle alternatives would avoid production of materials that are highly attractive for use in a nuclear explosive device. They also would avoid the large-scale deployment of separations processes at the back end capable of producing weapons-usable materials. For those largely technical factors, the once-through fuel cycle alternatives present lower proliferation and security risks. However, the risks associated with spent fuel cannot be discounted, particularly over long time periods. Many decades after discharge from a reactor, the radiation field would be reduced significantly and the spent fuel would no longer be considered “self-protecting.” While large-scale chemical separations would still be required to separate the weapons-usable material from the spent fuel, much lower levels of shielding could be used. While these once-through fuel cycles would allow the United States to argue against new civil reprocessing programs on the basis that civil reprocessing is not necessary, this fuel cycle approach has proven challenging for the United States to implement as a sustainable long-term waste management strategy. Therefore, such arguments may not be effective in persuading other countries to follow this strategy. Once-through fuel cycles would also limit the U.S. ability to participate in offering comprehensive fuel services to other countries as a tool to limit the spread of proliferation-sensitive fuel cycle technologies. Such participation would depend either on taking other countries’ spent fuel for direct geologic disposal, which faces political, legal and public acceptance challenges, or on partnerships with other countries to provide back-end fuel services, which would reduce the U.S. ability to take the lead in defining those services.

On the other hand, the full actinide recycle alternatives would produce materials with significantly greater attractiveness for potential use in nuclear explosive devices than those in a once-through fuel cycle, but offer new opportunities to extend U.S. influence to address international fuel cycle challenges. Comprehensive fuel services offer a potentially transformative means to limit the further spread of enrichment and reprocessing capabilities, and fast reactors offer a potentially promising means for restoring balance in the fuel cycle and drawing down stockpiles of separated plutonium. The partial recycle alternatives may offer some of the benefits, but also suffer from most of the drawbacks of the full recycle alternatives.

To facilitate a side-by-side comparison of alternatives, these factors are summarized in a descriptive form in Table 6.5.

Nonproliferation Impacts	**Once-Through Fuel Cycle**	**Full Actinide Recycle**	**Partial Actinide Recycle**
Fuel Cycle *Direct influence on international comprehensive fuel services and incentives to refrain from enrichment and reprocessing*	*Lowest* influence: *Greatest* barrier to U.S. participation in comprehensive fuel services. Spent fuel has the highest long-term radiotoxicity. *Higher* demand for enrichment services, particularly for thorium and HTGR options.	*Highest* influence: *Lowest* barrier to U.S. participation in comprehensive fuel services. Minimizes long-term radiotoxicity and treats spent fuel as energy resource. *Lower* demand for enrichment services.	*Intermediate* influence: *Intermediate* barrier to U.S. participation in comprehensive fuel services. Treats spent fuel as energy resource, but offers limited reduction in long-term radiotoxicity. *Lower* demand for enrichment services.
Fuel Cycle *International fuel cycle policy*	*Mixed*: Could reinforce efforts to discourage reprocessing, but unlikely to influence countries that are already pursuing reprocessing.	*Mixed*: Could encourage a major transformation in how commercial reprocessing is carried out, but could reduce ability to argue that reprocessing is unnecessary.	*Lower*: Could encourage an incremental change in commercial reprocessing practices, but could reduce ability to argue that reprocessing is unnecessary. *Mixed* for DUPIC.
Fuel Cycle *Inherent proliferation risk of technology*	*Lowest* risk: Does not create technical basis for separating weapons-usable material from spent fuel. HWRs have *higher* risk of misuse.	*Highest* risk: Capable of separating weapons-usable material, though some modification may be needed depending on the separations technology used.	*Highest* risk: Capable of separating weapons-usable material, though some modification may be needed depending on the separations technology used. DUPIC has *low* risk because it involves limited separation, although HWRs have *higher* risk of misuse.

Plutonium Stocks	*No improvement*: Reactors could use existing plutonium stocks in MOX fuel, but are not currently licensed to do so.	*Potential significant reduction*: Recycling creates a market for plutonium-bearing fuel. Fast reactor startup would require large quantities of plutonium	*Potential reduction*: Recycling separated plutonium creates a market for plutonium-bearing fuel. DUPIC alternative is *no improvement* since it would not reduce separated plutonium stocks.
Material Attractiveness	*Lowest*: Spent fuel is bulky and highly radioactive, though radioactivity decays over many decades. HWR spent fuel bundles are smaller and radioactivity decays more quickly. HTGR spent fuel is difficult to reprocess. Enrichment of fresh fuel varies, but all is LEU.	*Highest*: Removal of fission products and separation of actinides greatly reduces barriers to theft, misuse, or further processing, even without separation of pure plutonium. Fast reactor fuels have higher concentration of weapons-usable materials.	*Highest*: Removal of fission products and separation of actinides greatly reduces barriers to theft, misuse, or further processing, even without separation of pure plutonium. Thermal reactor fuels have lower concentration of weapons-usable materials. *Low* for DUPIC, which has limited removal of fission products.
Safeguards	*Lowest* cost and difficulty: Spent fuel assemblies can be tracked as items. Costs are significantly *higher* for HWRs. *Low to medium* cost and difficulty for thorium or HTGR, which require new safeguards approach.	*Highest* cost and difficulty: Separation processes require continuous monitoring against diversion and novel bulk materials present new measurement challenges. Novel processes may provide new opportunities to detect misuse.	*High* cost and difficulty: Separation processes require continuous monitoring against diversion; bulk material measurement presents familiar challenges. A safeguards approach has been developed for DUPIC.

TABLE 6.5 Policy Assessment of GNEP Programmatic Alternatives

As noted above, a detailed assessment of the technical factors in proliferation risk associated with these fuel cycle alternatives would be premature. The choice of a specific programmatic alternative will define a fuel cycle strategy, but not the technical and structural details of implementation necessary to conduct a full assessment. The discussion above provides some general commentary on how each of these alternatives might be graded on each of the seven PR/PP technical factors listed in Chapter 3. For example, the technical difficulty of misusing the fuel cycle processes used in a once-through fuel cycle is likely to be greater than under any of the alternatives that involve reprocessing. The cost of safeguarding large reprocessing facilities is likely to be high.

Beyond such general comments it is impossible to perform a full and fair assessment of all the technical risk factors without a more complete definition of the technical elements of each alternative. The alternatives discussed in this assessment are those presented in the GNEP Programmatic Environmental Impact Statement. Their technical elements were chosen to be representative of the range of alternatives and their environmental impacts, not to represent the range of potential proliferation impacts. Future decisions should consider the available alternatives in sufficient detail to understand those impacts more clearly. For this purpose, it is important to continue efforts to develop, refine, and validate methods for proliferation risk assessment.

Going beyond current approaches to proliferation risk assessment, it would be useful to try to transform the risk assessment methodology, which is essentially reactive, into a design methodology to reduce proliferation risks. Such a methodology could be based on engineering and systems concepts developed to limit the known sources of proliferation risk. The existing PR/PP assessment methodology could be used to validate those design approaches. Because of the importance of economic factors in determining the practicality of approaches to nuclear energy and fuel cycle systems, another important addition to existing proliferation risk assessment would be combined economic and nonproliferation analyses. Such analyses would be designed to determine where economic pressures and nonproliferation interests may be aligned, for example in structuring fuel service arrangements to be both viable business arrangements and attractive incentives to restrain the spread of enrichment and reprocessing. These analyses would also identify and avoid fuel cycle approaches that risk creating tradeoffs between economic and nonproliferation interests.

Under any of the alternatives, it will be important to continue efforts to develop effective safeguards and security measures, for both domestic and international use. Each of these alternatives, including the “no action” alternative, assumes that the Department of Energy’s existing Advanced Fuel Cycle Initiative (AFCI) would continue. This is important for the nonproliferation impact assessment because AFCI provides critical new opportunities to develop and test advanced security measures and advanced safeguards technologies and approaches. Safeguards programs should take advantage of ongoing fuel cycle research and development domestically and internationally for opportunities to test and evaluate innovative safeguards and security technologies under realistic operating conditions. International collaborations undertaken by the Department under AFCI could also provide expanded opportunities to develop such measures, technologies, and approaches in cooperation with other countries. However, these programs should also remain flexible enough to respond to unanticipated events and unintended outcomes, such as the spread of advanced reactor and fuel cycle technologies to additional countries.

7. APPENDIX LIST OF OTHER REGULATIONS AND GUIDANCE

The United States agencies responsible for regulating the use and transport of radioactive materials are the U. S. Department of Energy (DOE), the U.S. Department of Transportation (DOT) and the U.S. Nuclear Regulatory Commission (NRC). In general, facilities that handle or use nuclear material in the United States are subject to either DOE or NRC regulation. The agencies' respective regulations apply to activities on regulated sites and on shipments to or from the regulated site. DOT regulations also apply when transportation on public roads is involved. Export and import of nuclear equipment and materials are under the purview of the DOE, NRC and the U.S. Department of Commerce (DOC).

The International Atomic Energy Agency (IAEA), along with the United Nations (UN) establishes safety standards for the international transport of nuclear materials. Member states are responsible for regulation within and shipments to or from their States.

The following is a selective and not necessarily complete list of relevant domestic regulations and international standards and guidance pertinent to the use and transport of radioactive materials.

7.1 DOMESTIC U.S. REGULATIONS

10CFR71: Packaging and Transportation of Radioactive Material. This regulation sets the requirements for packaging, preparation for shipment, and transportation of Type A(F) and Type B quantities of radioactive material.

10CFR73: Physical Protection of Plants and Materials. This regulation contains requirements for the physical protection of radioactive materials at fixed sites and in transit. This regulation also defines Categories I, II, and III quantities of SNM for transit (see Table 1).

10CFR74: Material Control and Accounting of Special Nuclear Material. Categories of SNM are defined in 10CFR74. Different categories of SNM require different levels of protection and accountability rigor. This regulation contains requirements for the material control and accounting (MC&A) of SNM at fixed sites and for documenting the transfer of SNM.

10CFR110: Export and Import of Nuclear Equipment and Material. The regulations in this part prescribe Nuclear Regulatory Commission (NRC) licensing, enforcement, and rulemaking procedures and criteria, under the Atomic Energy Act, for the export of nuclear equipment and material, as set out in §§ 110.8 and 110.9, and the import of nuclear equipment and material, as set out in § 110.9a. This part also gives notice to all persons who knowingly provide to any licensee, applicant, contractor, or subcontractor, components, equipment, materials, or other goods or services, that relate to a licensee's or applicant's activities subject to this part, that they may be individually subject to NRC enforcement action for violations.

10CFR810: Assistance to Foreign Atomic Energy Activities. The Department of Energy (DOE) has the statutory responsibility for regulating the transfer of nuclear technology and technical assistance. 10 CFR Part 810 applies to technology transfers and technical assistance to all activities of the nuclear fuel cycle, including non-power reactors. Transfers for non-sensitive nuclear activities to some countries are generally authorized. For other countries, or for assistance involving sensitive technologies (production reactors, accelerator-driven subcritical assembly systems, enrichment, reprocessing, plutonium fuel, heavy water production and non-power reactors above 5 MW) a specific authorization is required from the Secretary of Energy.

15CFR730-774: Export Administration Regulations (EAR). The EAR controls dual-use items and technologies whose export requires a Department of Commerce (DOC) export license. The Department of Energy (DOE) works with the Department of Commerce (DOC) to maintain the "Nuclear Referral List," which identifies dual use items requiring particular attention, such as high-precision machine tools, special metals, high-speed cameras, and sensitive electronic equipment. This list is reflected in Supplement No. 1 to Part 774 of the EAR. DOE reviews and makes recommendations concerning DOC dual use export license applications for items included in the "Nuclear Referral List", as well as items that may have utility in the production of other categories of weapons of mass destruction and missile delivery systems.

49CFR172: Hazardous Materials Table … and Security Plans. Sections 310, 403, 436, 438, 440, and 556 of 49CFR172 pertain to marking and labeling of radioactive material. Section 800 describes the requirements for the development and implementation of plans to address security risks related to the transportation of hazardous materials in commerce.

49CFR173: Shippers – General Requirements for Shipments and Packagings. Sections 401-476 provide general requirements for the transport of radioactive materials. The scope, as stated in Section 401, states, "This subpart sets forth requirements for the packaging and transportation of Class 7 (radioactive) materials by offerors and carriers subject to this subchapter. The requirements prescribed in this subpart are in addition to, not in place of, other requirements set forth in this subchapter for Class 7 (radioactive) materials and those of the Nuclear Regulatory Commission in 10CFR71."

49CFR174: Carriage by Rail. Sections 700-750 provide requirements for Class 7 (radioactive) materials during rail transport. These include special handling requirements (700), regulations for radiation levels of transport cars after use (715), and requirements for leakage incidents (750).

49CFR175: Carriage by Aircraft. Sections 700-705 provide requirements for Class 7 (radioactive) materials during air transport. These include limitations and requirements (700) and special requirements for plutonium shipments (704).

49CFR176: Carriage by Vessel. Part 176 provides requirements for vessel transport. Section 69 provides stowage requirements for hazardous materials.

49CFR177: Carriage by Public Highway. Section 842 regulates the transport of Class 7 (radioactive) materials during transport on public highway. Section 843 regulates contamination levels of transport vehicles.

49CFR178: Specifications for Packagings. Part 178 regulates the manufacturing and testing specifications for packaging and containers used for the transportation of hazardous materials in commerce. Subpart K provides specifications for transport of radioactive materials.

49CFR179: Specifications for Tank Cars. Part 179 regulates the manufacturing and testing specifications for tank cars used for the transportation of hazardous materials in commerce.

49CFR180: Continuing Qualification and Maintenance of Packagings. Part 180 prescribes requirements pertaining to the maintenance, reconditioning, repair, inspection and testing of packaging.

DOE-P-470: Integrated Safeguards and Security Management (ISSM) Policy. Section 4.1 establishes requirements for safeguards and security planning, evaluation, and management within the DOE complex. Section 4.2 integrates physical protection into DOE operations. Section 4.6 prescribes DOE requirements for MC&A at DOE facilities.

7.2 INTERNATIONAL STANDARDS AND GUIDANCE

IAEA-TS-R-1: Guidelines for the Safe Transport of Radioactive Material. Guidelines are specified for radiation protection and emergency response. Requirements are set for nuclear material packaging and shipment.

IAEA-INFCIRC/225: The Physical Protection of Nuclear Material and Nuclear Facilities. Section 8 details the requirements for physical protection of nuclear material during transport. Separate requirements for Category I, II, and III special nuclear material are specified.

IAEA-INFCIRC/254: Nuclear Suppliers Group (NSG) Guidelines. The NSG is an export control arrangement, providing guidelines for control of nuclear and nuclear-related exports. Members of the NSG voluntarily adhere to the Guidelines (first published in 1978) which are adopted by consensus and through exchanges of information on developments of nuclear proliferation concern. Part 1 of the NSG Guidelines (the “Trigger List” controls) governs exports of nuclear materials and equipment and technology that “trigger” requirement for IAEA safeguards at the recipient facility. Part 2 of NSG Guidelines governs exports of nuclear-related dual-use equipment, materials and technology.

IAEA-INFCIRC/209: Zangger Committee Guidelines. Zangger Committee (ZC) Guidelines, first published in 1974, harmonize implementation of the NPT's requirement to apply IAEA safeguards to nuclear exports. Article III.2 of the Treaty requires parties to ensure that IAEA safeguards are applied to exports to non-nuclear weapon states of: (a) source or special fissionable material, or (b) equipment or material especially designed or prepared for the processing, use or production of special fissionable materials. The ZC maintains and updates a list of equipment and materials that may only be exported if safeguards are applied to the recipient facility. The ZC is an informal group and its decisions are not legally binding upon its members.

Convention on the Physical Protection of Nuclear Material. This international convention was signed in 1980 and amended in 2005 (although the amended convention is not yet in force). The convention, when amended, would make it legally binding for countries to protect nuclear facilities and material in peaceful domestic use, storage as well as transport. It would also provide for expanded cooperation between and among states regarding rapid measures to locate and recover stolen or smuggled nuclear material, mitigate any radiological consequences of sabotage, and prevent and combat related offences.

Recommendations on the Transport of Dangerous Goods. The so-called “Orange Book” is produced by the United Nations (UN) Economic and Social Council. In the special case of nuclear material, work is coordinated with the IAEA. These recommendations address the following areas:

- List of dangerous goods most commonly carried and their identification/classification
- Consignment procedures: labeling, marking, and transport documents
- Standards for packaging, test procedures, and certification
- Standards for multimodal tank-containers, test procedures and certification

8. BIBLIOGRAPHY

Nonproliferation Impact Assessment for GNEP: Issues Associated with Transportation, R. Radel, G. Rochau, Sandia report SAND 2008-1403, February 2008

“Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems,” Revision 5, Generation IV International Forum, GIF/PRPPWG/2006/005, November 30, 2006.

“Framework for Proliferation Resistance and Physical Protection for Nonproliferation Impact Assessments,” Robert Bari, BNL-80083, Brookhaven National Laboratory Formal Report, March 2008

“Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems,” Revision 5, Generation IV International Forum, GIF/PRPPWG/2006/005, November 30, 2006.

“Nuclear Infrastructure Nonproliferation Impact Assessment,” U.S. Department of Energy, DOE/NE-0019, September 2000.

“Proliferation Resistance Fundamentals for Future Nuclear Energy Systems,” IAEA Department of Safeguards, IAEA (International Atomic Energy Agency), 2002, IAEA, STR-332, Vienna.

“Calculations of Proliferation Resistance for Generation III Nuclear Energy Systems,” Yue, M., L. Cheng, I.A. Papazoglou, M.A. Azarm, and R. Bari, Global 2005, Japan, October 9-13 2005.

“Advanced Safeguards Approaches for New Reprocessing Facilities,” P.C. Durst, I. Therios, R. Bean, A. Dougan, B.D. Boyer, R. Wallace, M. Ehinger, D. Kovacic, K. Tolk, PNNL-16674, June 2007

“Advanced Safeguards Approaches for New TRU Fuel Fabrication Facilities,” P.C. Durst, M. Ehinger, B.D. Boyer, I. Therios, R. Bean, A. Dougan, K. Tolk, PNNL-17151, November 2007

“Advanced Safeguards Approaches for New Fast Reactors,” P.C. Durst, I. Therios, R. Bean, A. Dougan, B.D. Boyer, R. Wallace, M. Ehinger, D. Kovacic, K. Tolk, PNNL-17168, December 2007

“Report on Proliferation Implications of the Global Expansion of Civil Nuclear Power,” International Security Advisory Board, DoS, April 7, 2008,

“Limited Proliferation-Resistance Benefits from Recycling Unseparated Transuranics and Lanthanides from Light-Water Reactor Spent Fuel,” J. Kang, F. von Hippel, Science and Global Security, 13:169-181, 2005, http://www.princeton.edu/~globsec/publications/pdf/13_3%20Kang%20vonhippel.pdf

"Falling Behind: International Scrutiny of the Peaceful Atom," H. Sokolski, editor, February 2008, http://www.StrategicStudiesInstitute.army.mil/

Matthew Bunn, "Risks of GNEP's Focus on Near-Term Reprocessing," testimony before Senate Energy and Water Resources Committee, November 14, 2007, http://belfercenter.ksg.harvard.edu/files/bunn-GNEP-testimony-07.pdf.

"UREX/COEX Proliferation Risk Reduction Study," R. Bari, J. Choi, J. Phillips, J. Pilat, G. Rochau, R. Wigeland, K. Sylvester, Brookhaven Report BNL-PRR-2007-001, March 2007.

"Proliferation Risk Reduction Study of Alternative Spent Fuel Processing Technologies," R. Bari, L. Cheng, J. Choi, J. Phillips, J. Pilat, G. Rochau, I. Therios, R. Wigeland, M. Zentner, undergoing final review.

"A Nonproliferation Impact Assessment of the GNEP Program," M. Goodman, R. Bari, P. Heine, J. Phillips, M. Regalbuto, M. Rosenthal, J. Sprinkle, R. Wallace, R. Wigeland, M. Yates, Los Alamos report LA-UR-08-1856, presented at 8th International Conference on Facility Operations-Safeguards Interface, March 30-April 4, 2008, Portland.

"An Assessment of the Proliferation Resistance of Materials in Advanced Nuclear Fuel Cycles," C. Bathke, R. Wallace, J. Ireland, M. Johnson, K. Bradley, B. Ebbinghaus, H. Manini, B. Smith, A. Prichard, presented at 8th International Conference on Facility Operations-Safeguards Interface, March 30-April 4, 2008, Portland.

The NRC Advisory Committee on Nuclear Waste and Materials (ACNW&M) report, "Background, Status, and Issues Related to the Regulation of Advanced Spent Nuclear Fuel Recycle Facilities: A White Paper of the U.S. Nuclear Regulatory Commission's Advisory Committee on Nuclear Waste and Materials."

Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, U.S. Department of Energy Office of Civilian Radioactive Waste Management DOE/EIS-0250F-S1, June 2008.

"Room at the Mountain: Analysis of the Maximum Disposal Capacity for Commercial Spent Fuel in a Yucca Mountain Repository," Electric Power Research Institute, Report 1013523, May 2006, Kessler, J.

"Performance Summary of Advanced Nuclear Fuel Cycles," R.A. Wigeland, GNEP-TIO-AI-AI-RT-2008-000268, Rev. 2, July 2008.

9. LIST OF ACRONYMS

AFCI – Advanced Fuel Cycle Initiative
ANM – Alternate Nuclear Materials
AP – Additional Protocol
CANDU – CANada Deuterium Uranium
COEX$^{®}$ – CO-EXtraction of actinides
DB-Pu – Deep Burn Plutonium
DE – Detection Resource Efficiency (PR/PP measure)
DIAMEX – DIAMide EXtraction
DOE – Department of Energy
DP – Detection Probability (PR/PP measure)
DUPIC – Direct Use of Spent PWR Fuel in CANDU
GANEX – Grouped ActiNides EXtraction
GIF – Generation IV International Forum
GNEP – Global Nuclear Energy Partnership
GW – Gigawatt
HEU – High-Enriched Uranium
HTGR – High-Temperature Gas-Cooled Graphite-Moderated Reactor
HWR – Heavy-Water-Moderated Reactor
IAEA – International Atomic Energy Agency
INFC – International Nuclear Fuel Center
LEU – Low-Enriched Uranium
LWR – Light Water Reactor
MT – Material Type (PR/PP measure)
MOX – Mixed-Oxide
MTIHM – Metric Tons Initial Heavy Metal
NDU – National Defense University
NEPA – National Environmental Policy Act
NNSA – National Nuclear Security Administration
NPIA – Nonproliferation Impact Assessment
NPT –Treaty on the Non-Proliferation of Nuclear Weapons (1970)
NNPA – Nuclear Non-Proliferation Act
NNWS – Non-Nuclear Weapons States
NSPD – National Security Presidential Directive
NTI – Nuclear Threat Initiative
NUEX$^{®}$ – New Uranium Extraction
NWS – Nuclear Weapons States
PC – Proliferation Cost (PR/PP measure)
PEIS – Programmatic Environmental Impact Statement
PP – Physical Protection
PR – Proliferation Resistance
PR/PP – Proliferation Resistance and Physical Protection
PT – Proliferation Time (PR/PP measure)
PUREX – Plutonium and Uranium Reduction and EXtraction
R&D – Research and Development

RG-Pu – Reactor Grade Plutonium
RDD – Radiation Dispersal Devices
SANEX – Selective ActiNide EXtraction
SFM – Special Fissionable Material
SNF – Spent Nuclear Fuel
SNT – Sensitive Nuclear Technology
SQ – Significant Quantity
SWU – Separative Work Units
TD – Technical Difficulty (PR/PP measure)
TRU – TRansUranic Material
UREX – URanium EXtraction
WG-Pu – Weapons Grade Plutonium
WMD – Weapons of Mass Destruction

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