Sustainability Of U.S. Nuclear Energy: Waste Management And The Question Of Reprocessing

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Executive Summary

Nuclear energy offers the only alternative to fossil fuels that can provide widespread, base-load electricity. It is safe, cost-effective, and geographically nondiscriminatory. Moreover, with near-zero emissions, nuclear energy helps check the rise in global CO₂-levels. In order to truly diminish fossil fuel dependence and mitigate climate change, the nuclear energy industry must grow substantially this century.

There is one major problem that could forestall this envisioned “nuclear renaissance”—that is the absence of a viable long-term waste management solution. Different countries have chosen different waste management policies, from direct disposal of used nuclear fuel to reprocessing and recycling certain actinides (the long-lived, heavy elements) while disposing of the rest. Whatever the policy, no long-term solution has been implemented in any country.

In the United States, the Nuclear Waste Policy Act mandates a policy of direct disposal in a deep geologic repository. The recent failures to implement such a repository in Yucca Mountain, Nevada have raised questions about the political practicality of this policy. The Obama Administration has called forth the Blue Ribbon Commission to reexamine all options for nuclear waste management, including the use of reprocessing.

Reprocessing is the separation of used nuclear fuel into its constituents, which can then be stored or recycled into new fuel. Employing a fuel cycle with reprocessing reduces the volume and lifespan of high-level radioactive waste and increases fuel supply. However, there are serious concerns regarding its cost competitiveness and the proliferation risk of isolated plutonium in reprocessing product streams (the highly radioactive fission products in unprocessed used fuel protect against human tampering).

In devising a waste management policy, the issue of long-term waste burden should rank highest in importance. Unprocessed nuclear waste contains highly radioactive actinides that persist for millions of years, far beyond our capacity to reliably ensure their isolation. The U.S. must adequately protect future generations that have no say in the policy decisions made today. Implementation of reprocessing and recycling for all actinides would dramatically reduce the timeframe of concern and thereby obviate any question of what “adequate” protection means for the distant future.

The concerns over economics and proliferation are, by no means, insurmountable. The low price of new uranium fuel makes any reprocessing uneconomical for the time being, but this may change in the future. In any event, the fuel cycle and waste management costs comprise only 10-20% of total generation costs, so this should not dictate policy. As for proliferation risk, no reprocessing technology will ever be proliferation proof, regardless of what radioactive components are left in the plutonium product stream. Nonetheless, the U.S. has a proven sixty-year record of protecting its own nuclear liabilities. Furthermore, whether or not the U.S. chooses to reprocess, the technology has already spread throughout much of the world, reducing the international ramifications of its decision.

In short, the reduction of the waste burden from a full actinide reprocessing and recycling scheme far outweighs the possible economic costs and proliferation fears. The conventional reprocessing scheme used abroad, which recycles the plutonium but no other actinides, does not sufficiently reduce the waste burden. Only the full actinide alternative is a suitable long-term solution, but significant innovation is still required before it can be implemented. The Department of Energy must immediately commence with an integrated research, development, and demonstration program for reprocessing technologies in coordination with advanced reactors for recycling. The results of this long-term program will allow the United States to transition toward a more sustainable waste management policy—one which supports the growth of nuclear energy and thereby the security of our entire energy future.
Foreword

About the Author
Nathan R. Lee graduated in May 2010 from the University of Pennsylvania with a B.S.E. in Materials Science & Engineering. During his time at Penn, Nathan balanced coursework in engineering with his interests in history, political science, business, and law. Within engineering, he focused on energy-related materials research, including self assembly of polymer thin films, hybrid organic-inorganic solar cells, and transmutation of nuclear waste. He led his own independent research project for three years with Dr. Russell Composto’s Polymer Group and is currently preparing his results for publication. For the following academic year, Nathan has decided to volunteer with Pagus Africa to teach math and science to middle school children in Ghana. Upon his return, he will continue to pursue his interest in technology public policy through graduate studies or policy work. Nathan was selected by the American Nuclear Society for sponsorship in the WISE summer 2010 program.

About the WISE Program
Washington Internships for Students of Engineering (WISE) is a nine week summer program that brings top engineering students from around the country to Washington, D.C. to learn about and influence the policymaking process. The purpose of the program is to prepare the next generation of engineers to bridge the gap between technology and policy issues. Six engineering professional societies sponsor one to two students to participate in the program. During the program, the students meet with representatives of relevant organizations including the Congress, the Office of Science and Technology Policy, the State Department, and various regulatory agencies. With the guidance of an individual mentor from his or her sponsoring society, each student composes a report on a technology policy issue of interest, culminating in a policy recommendation. The reports are published online in the WISE Journal of Engineering & Public Policy, and students publicly present their recommendations on Capitol Hill.

Acknowledgements
I would like to thank all the members of the American Nuclear Society for giving me the chance to gain first-hand experience working and breathing technology public policy for nine weeks in Washington. In particular, I would like thank Dr. Alan Levin, Mr. Christopher Henderson, and Ms. Sarah Leversee for their consistent support, insight, and guidance throughout the experience. I also want to thank all the folks at the Nuclear Energy Institute for kindly hosting me in their office and being helpful resources for information. In addition, Dr. James Bresee at the Department of Energy, Dr. Thomas Cochran at the Natural Resources Defense Council, and Mr. John Buydos at the Library of Congress each provided valuable perspectives on the subject. Finally, I want to acknowledge Ms. Erica Wissolik for making the whole program happen and all my fellow interns for making it great.
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Introduction

Need for Nuclear

Global energy supply is one of the most pressing issues facing this planet. As populations continue to rise, and developing nations increase demand for electricity, the limitations to the fossil fuel-dominated economy are becoming exacerbated. These include diminishing resources, geopolitical tensions, and the growing evidence of the link between CO₂-emissions and climate change. In response to these issues, countries around the world are looking to alternative energy sources that can supply growing demand economically, reliably, and without harmful emissions.

With this backdrop, it is no surprise that many are calling for—and investing in—what has become known as a “nuclear renaissance.” While renewables such as wind, solar, and hydro must also play a role in an improved energy economy, only nuclear energy can provide economical and widespread base-load electricity at near-zero emissions. Moreover, it is a proven, mature, 50-year industry whose safety record is dramatically superior to that of fossil fuels—both for human health and the environment.

As of August 2010, there are 440 nuclear power plants operating across 29 countries, providing 14% of global electricity.¹ The industry grew rapidly in the 1970s following the oil crisis but effectively stagnated thereafter due to concerns about safety and costs (although growth continued in parts of Asia). However, with a longer-standing safety record and recognition of its timely advantages, the industry has begun to resurge, with a new set of plants under construction (Fig. 1). The International Energy Agency, part of the Organization for Economic Cooperation and Development (OECD), projects a nuclear energy capacity in 2050 more than triple that of 2009—an ambitious but achievable goal. This would provide 24% of the larger energy demand of the day and greatly contribute to emission reduction goals.²

The Nuclear Waste Problem

There is one issue that threatens to prevent this nuclear renaissance from coming to fruition—that is the long-term management of nuclear waste. After more than forty years of commercial nuclear power, not a single country has successfully implemented a long-term solution to the management of high-level waste (HLW), that is, the most radioactive, longest-lived, waste products generated by a nuclear plant. If not properly isolated, this waste poses a hazard to human health and the environment for millions of years. Most experts agree that, regardless of the particular fuel cycle and waste management policies chosen by each country, the final waste product will have to be stored in a contained environment deep underground known as a geologic repository. Approving a site as a permanent geologic repository has proven technically challenging and politically intractable in many countries that have tried. Without a permanent repository, most waste is currently stored onsite at plants in pools of water or steel casks. While onsite storage is temporarily safe, it is an unsustainable solution, as many plants are already reaching capacity, and consistent, comprehensive supervision over millions of years is an unreliable proposition. Therefore, technically sound and politically viable solutions must be implemented in the relevant countries for the long-term management of nuclear waste. Otherwise, the projected growth in nuclear power—and the benefits it would bring to the global energy situation—will surely be undermined.

The Question of Reprocessing

Although a geologic repository is generally accepted as being necessary for the final disposal of HLW, there is significant debate regarding interim treatment after discharge from the plant and before disposal. Among the most divisive questions is whether to reprocess the used nuclear fuel, which is the dominant component of HLW, to partition it into its constituents. By doing so, some argue that the separate product streams that result can be more effectively managed to reduce the waste burden. Different storage sites could be designed for the different radioactive substances depending on their characteristics. Moreover, certain components of the used fuel could be recycled to produce new fuel, significantly extending fuel supply. Other components

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4 For the purposes of this paper, “reprocessing” refers to any separations process of used nuclear fuel.
5 “Used nuclear fuel” and “spent nuclear fuel” are equivalent terms for the purposes of this paper.
could be transmuted in specialized reactors to reduce the long-term waste burden, easing both the technical and political complications hovering around the siting of a permanent repository.

However, serious drawbacks have to be considered before implementing a waste management policy based on reprocessing. Although the long-term waste burden can be mitigated, current reprocessing technologies increase the short-term hazard through the production of significant amounts of low-level waste. There are also serious nuclear weapons proliferation concerns regarding the separation of plutonium. Finally, if the price of uranium remains low, it may simply not be cost-effective. These drawbacks will be measured against the benefits on a technical, political, and economic basis as it pertains to the United States. The merits of both immediate as well as future implementation will be considered.

**Background**

*Fuel Cycle Overview*

A typical nuclear power plant utilizes the immense heat released via a nuclear fission reaction—the splitting of an atom’s nucleus—to convert water to steam which, in turn, spins a turbine to generate electricity. Only certain heavy, radioactive elements are fissile; these are found in the actinide series of elements on the periodic table. The most common actinide in nuclear fuel is U-235, that is uranium with 235 protons and neutrons. However, uranium extracted from the mined ore is 99.3% U-238, which is fertile, not fissile. Thus, before this material can be used as fuel in a light-water reactor (LWR), which is the dominant reactor design, the level of U-235 must be enriched, from 0.7% to 3-5% for most commercial reactors.

The composition of the fuel is predominantly the same before and after burnup (Fig. 2). For a normal LWR, approximately 95% of the used fuel remains uranium, depleted to 0.8% U-235.6 The residual is comprised of plutonium and various other actinides that result from neutrons absorbing onto U-238 and fissions products that result from the splitting of U-235, some of which are stable and some radioactive. Because the plutonium can be recycled and the stable fission products pose no danger, only about 0.6% of the material must categorically be deemed “waste.” Even so, within this category, there exists a wide array of radioactive products with a wide range of life spans.

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Managing this broad spectrum of waste products is technically intricate. The two most critical factors are the radiotoxicity and heat release, the former primarily due to health considerations and the second due to engineering limitations of storage. Both of these attributes vary between constituents and evolve over time for each one, although they do tend to correlate (Fig. 3).

Figure 3. Radiotoxicity and heat generation for different waste products over time. Strontium and cesium are most active in the first millennium, after which long-lived actinides dominate.8

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8 Piet, Bjomard, Dixon, Gombert, Laws, Matthem.
Recognizing this sharp variation in the characteristics of the used nuclear fuel, one can understand the interest in partitioning and recycling it rather than simply burying underground altogether. Because the dominant component, uranium, is not highly radioactive, separating it dramatically reduces the HLW volume. In theory, this could then be recycled into new fuel. The short-lived fission products, which contribute the most to short-term heat content, could be isolated and monitored until they cool. The residual fissile material, namely plutonium and certain other actinides, could be separated for recycling into new fuels for reactors that are particularly fitted for it, significantly extending fuel supply. The burning of these actinides, i.e., destruction via fission, would dramatically reduce the long-term radiotoxicity and heat content of the nuclear waste, lowering the stakes of a permanent repository.

Fuel cycle analysts frequently categorize the waste management policy by the degree of completeness to which the used fuel is recycled. Terminology varies, but three basic fuel cycle levels are often:

- “Open” or “Once Through”— no reprocessing, direct disposal of used nuclear fuel
- “Limited Recycle”— limited separations, one-pass recycle through reactor
- “Closed” or “Full Recycle”— complete separation of used fuel, iterative recycling, actinide burning in dedicated reactors

Each level progressively reduces the burden on the permanent repository and increases fuel supply but also increases concerns over by-product waste, cost, and proliferation of plutonium. Different countries have chosen different cycles based on their own particular priorities. The United States has, to date, maintained a once-through fuel cycle and, therefore, has pursued a policy of direct disposal.

**U.S. History of Direct Disposal Policy**

In the first decades of the nuclear industry’s growth, there was very limited focus on developing a long-term waste management policy in the United States. It was only in 1982 that Congress passed the Nuclear Waste Policy Act, endorsing a policy of direct disposal of used nuclear fuel. It mandated that a permanent, underground repository for HLW be established by the mid-1990s. To pay for this new program, the Nuclear Waste Fund was established, which requires utility companies to pay a fee for nuclear-generated electricity.

The Department of Energy (DOE) was tasked with siting and managing the new repository. Although the DOE investigated several sites in several states, the Nuclear Waste Policy Amendments Act of 1987 established Yucca Mountain in Nevada as the sole site to be further characterized. Many regarded this as a politically-motivated decision because Nevada had notably less Congressional power than the other states under consideration. The issue remained divisive with a variety of disputes, the most notable one over the compliance period for isolation of radioactive waste, which was amended from 10,000 to one million years. Nonetheless, the Bush Administration successfully completed the formal process specified in the legislation, certifying the site as suitable for a repository and getting Congressional endorsement of the finding. In 2008, against the will of the Nevada state government, the DOE submitted its license application for Yucca Mountain to the Nuclear Regulatory Commission (NRC).

Recent events have complicated this process greatly. The Obama Administration instructed the Secretary of Energy to withdraw the license application for Yucca Mountain, and it drastically
reduced funding for the facility in the FY2010 budget. The NRC licensing board has ruled that the DOE cannot withdraw the application unless Congress overturns the Nuclear Waste Policy Act. The DOE has filed an appeal, and judicial proceedings continue as of the time of writing. Approximately 20 years of labor and $10 billion have been invested in the Yucca Mountain project.

**U.S. History of Reprocessing Policy**

With such resistance to the implementation of a direct disposal program, it might seem surprising that reprocessing was not utilized to attempt to ease the process. However, the history of reprocessing used nuclear fuel has been anything but easy. Originally, reprocessing technology was developed in the World War II-era Manhattan Project for the purpose of separating plutonium to build the first atomic bomb. When commercialization of nuclear power began after the war, it was assumed reprocessing would be essential to maintain fuel supply under the assumption that fresh uranium would be in low supply but high demand. However, world demand did not grow as much as expected, and the supply of mined uranium was significantly underestimated, removing the urgency for reprocessing. Furthermore, commercial reprocessing attempts that were made encountered technological failures, regulatory obstacles, and generally proved uneconomical. In 1977, President Carter formally banned funding for reprocessing in the U.S. based primarily on proliferation concerns. Although President Reagan lifted this ban in 1982, the Nuclear Waste Policy Act effectively preempts reprocessing. Whatever the case, the U.S. nuclear industry has never reversed its established practice of a once-through cycle in which fresh fuel is burned and directly disposed thereafter (of course, this latter part having yet to be implemented).  

 Nonetheless, the United States has made progress in the development of reprocessing technologies. The DOE has a long-standing program on the research and development of advanced fuel cycle technologies, including separations technology for reprocessing, that was reinforced in 2002 under President Bush’s Advanced Fuel Cycle Initiative (AFCI).  

 AFCI became the technology advancement component of Bush’s broader nuclear energy initiative of 2006, the Global Nuclear Energy Partnership (GNEP), which envisioned the transition toward a close fuel cycle through the development and demonstration of separations and recycling technologies. Its focus was on incremental improvement of existing technologies to enable near-term technology deployment. Among other ambitious projects, GNEP called for the conducting of an engineering scale demonstration of the UREX+ separation process (an aqueous-based process for separating uranium).

 However, GNEP’s ambitious goals have not come to fruition. Under the Obama Administration, the DOE has cut most of the funding for GNEP’s domestic projects. In its place, the DOE, with former Berkeley scientist Steven Chu now at the helm, has setup the new Fuel Cycle Research

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12 Andrews, Congressional Research Service.
and Development program to focus on longer-term, transformational breakthroughs. Clearly, policy changes have been frequent, and the future of reprocessing remains unclear. The results of the Blue Ribbon Commission, called forth by the administration to review all the options for HLW management amidst the Yucca Mountain controversy, might shed new light on the subject.

Other Nations’ Waste Management Policies
Each nation has its own criteria for evaluating waste management alternatives, and therefore it is no surprise that nuclear waste policies differ between countries. Nonetheless, for crafting the best solution for the United States, specifically regarding whether and how to reprocess, it is instructive to analyze the political circumstances surrounding the issue in other countries with similar, large-scale nuclear power programs. Although each nation’s priorities may vary, certain commonalities persist, such as concerns over safety, cost, and national security. The waste policies of France, Japan, and Canada have been highlighted as examples.

France
France is the greatest international champion of nuclear power, providing over 75% of its electricity through the use of 59 nuclear power plants. Without any major domestic supply of fossil fuels, and especially fearful after the 1970s oil shocks, the powerful central government embarked on a massive nuclear power program to build a secure energy infrastructure. To further reduce fuel supply dependence, the French elected from the outset to reprocess its used fuel to minimize the amount of imported uranium needed to operate the plants. They developed a massive aqueous separations plant at La Hague (Fig. 4) to partition the uranium, plutonium, and the residual waste. Some of this plutonium is then recombined with uranium to make mixed oxide fuel (MOX), which is recycled through the reactor (one-pass only). Although France officially plans to transition to iterative recycling with fast reactor transmutation, it has faced repeated technical and political obstacles in developing this “full recycle” infrastructure. Whatever the fuel cycle, the government has recognized the inevitable need for a permanent geologic repository and is trying to license one by 2015. Unlike the siting of the nuclear plants however, local communities have been overwhelmingly opposed to construction of this facility.¹³

Japan
Japan runs 53 nuclear power plants, accounting for 34.5% of its electricity production. Japan’s waste management policy has been largely motivated by the desire to postpone the need for a geologic repository, ensure stable fuel supply, and allow general flexibility in its energy policy. Early on, Japan shipped large amounts of used nuclear fuel for reprocessing in France to be returned for domestic MOX production. Since then, Japan has begun investing in its own aqueous reprocessing plant while pursuing long-term development of fast reactor infrastructure. This program has suffered a series of setbacks, including a fatal accident at a uranium processing plant in September 1999. Despite these setbacks as well as the large capital costs of the investments, Japan has continued the implementation of its waste management policy and is nearing completion of a full-scale reprocessing facility in Rokkasho. As for final disposal, the HLW will remain at Rokkasho until a geologic repository is sited—a task the government has promised will be completed within 50 years, despite the anticipated public opposition.

Canada
Canada operates 17 nuclear reactors, providing 15% of the nation’s total power. Like other nuclear countries, it has a long history of controversy surrounding its waste management policy. In 1978, the government instructed the dominant nuclear power company to develop a plan for geologic disposal for the nuclear waste. However, in 1989, granting the plan was technically sufficient, the country’s environmental agency recommended more time be given to investigation due to public acceptance issues. In 2002, Canadian Parliament enacted the Nuclear Fuel Waste Act mandating the nuclear industry to create its own Nuclear Waste Management Organization to investigate and recommend a waste policy to the government based on technical research and

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15 Vandenbosch, Vandenbosch.
interaction with the public. It selected direct geologic disposal, screening out reprocessing as an option based on its cost, production of wastes, and proliferation concerns.\textsuperscript{17}

**State of Reprocessing Technology**

**Aqueous Reprocessing**

The primary methods of reprocessing used nuclear fuel have all used aqueous solutions. The original plutonium separation process developed in the Manhattan Project utilized caustic soda for dissolving the fuel cladding, nitric acid for dissolving the fuel, and bismuth phosphate to precipitate the plutonium. This served the purpose of extracting plutonium for weapons, but it produced large volumes of HLW and could not recover the uranium.\textsuperscript{18}

To isolate both the plutonium and uranium, Oak Ridge National Laboratory developed the *Plutonium Uranium Recovery Extraction* (PUREX) process in 1949. This still uses nitric acid for dissolution but, instead of a direct precipitation reaction, an organic solvent and tri-butyl phosphate (TBP) are added to selectively partition the uranium and plutonium from the rest of the materials. A separate solvent can then be added to separate the plutonium from the uranium. This solvent extraction process is more efficient than previous processes because it can be run continuously, the solvent can be recycled, and waste is minimized. Although the U.S. halted its commercial reprocessing, PUREX has become the dominant technique abroad, employed by France, England, Russia, and Japan.\textsuperscript{19}

There have been a number of modifications of the PUREX solvent extraction process, including UREX, UREX+, TRUEX, DIAMEX, SANEX, and UNEX. Most modifications constitute an additional reagent at a particular point in the process to try to enhance proliferation resistance (i.e., by leaving the plutonium product stream mixed with radioactive minor actinides) or to reduce waste. However, the fundamental process remains the same, as do the basic concerns. These include:

- **Safety.** Concerns such as accidental “criticality” (producing a self-sustaining nuclear reaction) and “red oil” (decomposition of TBP chemical in nitric acid that can result in explosion).\textsuperscript{20}
- **Waste.** Large quantities of low-level chemical waste produced.
- **Proliferation.** Isolation of plutonium is technically feasible regardless of final products streams. Extensive pipes and tanks makes accountable monitoring of dangerous materials especially difficult.

**Electrochemical Reprocessing**

An alternative category of reprocessing technologies has also been explored that involve non-aqueous media. These reprocessing techniques are often lumped under the terms “dry” or “pyro,” but they are more accurately described as “electrochemical.” Development of the present generation of these technologies was initiated in the 1980s as part of the Integral Fast Reactor

\textsuperscript{17} Vandenbosch, Vandenbosch.
\textsuperscript{18} Todd, Idaho National Laboratory.
\textsuperscript{19} Todd, Idaho National Laboratory.
\textsuperscript{20} Todd, Idaho National Laboratory.
program at Argonne National Laboratory. The technology is particularly suited for processing the metallic fuel used in fast reactors, although tests have shown that it could eventually be adapted to process typical used oxide fuel as well. The basic process involves melting the used fuel in a high-temperature bath of molten salts followed by the application of current through metal electrodes to separate specific metal components.\textsuperscript{21}

Electrochemical processing offers a number of advantages over aqueous reprocessing. First, it offers better compatibility with advanced fast reactors (that is, those which utilize metal alloy fuel) that would be necessary to implement a closed fuel cycle. Second, it is a more compact system, allowing for collocation with the reactor more easily. This reduces transportation risks and accommodates more precise monitoring of plutonium. It also preempts the safety issue of red oil (but introduces new concerns regarding the high operating temperatures).\textsuperscript{22}

Unlike the aqueous systems, however, electrochemical reprocessing is not a mature technology. It has been successfully demonstrated on an engineering scale in a batch process, but not yet at a commercial level.\textsuperscript{23} The smaller flow of used metal fuel in fast reactors lessens the issue of scale, but, if it is to be adapted for reprocessing the much larger used oxide fuel stream from conventional LWRs, its throughput will have to be dramatically increased. Moreover, new waste treatment technologies need to be developed to treat the unique product streams.\textsuperscript{24}

**Reprocessing: Analysis of Benefits and Drawbacks**

In attempting to analyze the merits of reprocessing used nuclear fuel in the United States, one cannot fully divorce its specific role from the broader question of the best fuel cycle option. Therefore, while emphasis is placed on the aspect of reprocessing, the benefits and drawbacks of the corresponding fuel cycles (Figs. 5-7) are incorporated. Moreover, because the state of the separations technology is such that the optimal selection depends on the specific reactor with which it’s paired—and because this selection will likely change with future advancements—the general questions of whether, when, and how much to reprocess are emphasized over the question of what specific technology to employ. Answers to these questions will subsequently guide the selection of the best technology choice.

\textsuperscript{21} Goff, Idaho National Laboratory.  
\textsuperscript{22} Goff, Idaho National Laboratory.  
\textsuperscript{23} Goff, Idaho National Laboratory.  
Figure 5. Once-through fuel cycle with direct disposal (projected to 2050).\textsuperscript{25}

Figure 6. One-pass plutonium recycle with aqueous reprocessing (projected to 2050).\textsuperscript{26}

Figure 7. Full actinide recycle with pyroprocessing (projected to 2050).\textsuperscript{27}

\textsuperscript{26}Massachusetts Institute of Technology.
Of course, there are many issues which are relevant to this analysis. To arrive at some sort of coherent conclusion, it is important to prioritize them. For the question of reprocessing in the U.S., the issues of waste burden, nuclear arms proliferation, and economics and fuel supply are used as the principal foundations of the analysis.

Waste Burden

For this report, waste burden is defined as the direct negative effects of the waste itself (e.g., radiation risk to people and environment) and the difficulties involved in mitigating them (e.g., siting and engineering waste facilities). Each fuel cycle produces different amounts of waste, varying in radiation level and duration (Table 1). Because some components of nuclear waste remain dangerous for millions of years, selecting the optimal fuel cycle scheme requires consideration of both the near-term and long-term implications. In analyzing such an intricate issue, it is useful to employ the concept of intergenerational equity—or “fairness” to both immediate and distant generations.

Table 1. Waste flows generated in each fuel cycle. Volume measured per terawatt-hour (TWh) of electricity.28

<table>
<thead>
<tr>
<th>Fuel Cycle Scheme</th>
<th>High-Level (m³/TWh)</th>
<th>Low-level, Short-lived (m³/TWh)</th>
<th>Low-Level, Long-lived (m³/TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Once-through</td>
<td>4.1</td>
<td>15</td>
<td>0.3</td>
</tr>
<tr>
<td>One-pass Pu recycle</td>
<td>0.7</td>
<td>17</td>
<td>1.9</td>
</tr>
<tr>
<td>Full Actinide recycle</td>
<td>0.2</td>
<td>7</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Near-term Burden

The near-term waste burden of the once-through cycle in the United States is considerable but effectively managed through contained pool and dry cask storage. There is consensus that this strategy is sustainable at least until midcentury.29 On the other hand, there has been substantial criticism of the generation and management of low-level waste from PUREX reprocessing plants abroad. As Table 1 shows, the total waste volume increases for the conventional Pu recycle scheme used today. However, implementation of the full actinide recycle would cut total waste volume nearly in half.30

As for the near-term burden regarding the siting and engineering of a geologic repository, any improvement would be minimal. Under the current once-through cycle, there is already almost enough used fuel to fill a Yucca-type repository to its statutory capacity of 70,000 metric tons, and, by 2050, there would be enough to reach its technical capacity of 120,000 (Fig. 8).31 Under the most ambitious policy, even the one-pass Pu recycle could not be fully implemented in the U.S. before that year.32 Given this timeframe, the accepted need for a repository, and the long

27 Massachusetts Institute of Technology.
28 Nuclear Energy Agency, OECD.
30 Nuclear Energy Agency, OECD.
31 Todd, Idaho National Laboratory.
32 Committee on Science and Technology, U.S. House of Representatives.
delays that are endemic to the siting process, it will probably be necessary to move forward with siting a geologic repository that is engineered for direct disposal before any dependable alternative is available.\textsuperscript{33}

![Figure 8. Timeframe for reaching capacity at Yucca Mountain under current once-through cycle.\textsuperscript{34}](image)

**Long-term Burden**

In the long term, one begins to see the true benefits of the recycling options. The total relative radiotoxicity of the waste—the most important indicator in the long-term—exponentially improves with degree of recycling (Fig. 9). Although engineers attempted to design Yucca Mountain to minimize radiation release for a million years into the future, the confidence with which they, or even we as a society, can plan for scenarios on that timescale is low. Under the plutonium recycling scheme, the radiotoxicity of the waste falls to the level of natural uranium after 10,000 years—a more reasonable but still daunting number. Only under the full actinide recycle does the timeframe of concern drop below a millennium, where finally our predictive capacity becomes adequately reliable. With this fuel cycle, the long-term burden our society is placing on the future can be measured and mitigated.

\textsuperscript{33} In case a breakthrough in the reprocessing or recycling technologies occurs later in the century, or policy simply changes, planning for near-term retrievability of the waste from the geologic repository, as was designed in Yucca Mountain, would be a favorable contingency plan.

\textsuperscript{34} Todd, Idaho National Laboratory.
Figure 9. Relative radiotoxicity over time for direct disposal, plutonium recycle, and full actinide recycle.\textsuperscript{35}

With regard to the long-term consequences to siting and engineering HLW repositories, there is certainly a net benefit in implementing either recycling scheme. Both separate the uranium from the used fuel, significantly reducing the HLW volume being sent to the repository. Moreover, the reduction in total fuel consumption from recycling, which is modest for one-pass Pu and dramatic for the full recycle, reduces total HLW production. As a result, fewer repositories would need to be sited in the future, lessening political controversy. The full recycle has the added benefit of removing the actinides that are the dominant long-term heat sources, increasing the allowed packing density of waste by a factor of 4.3 to 5.4 and thereby further reducing repository demand.\textsuperscript{36}

\textbf{Proliferation}

No matter how much some nuclear energy proponents might play down the dual purpose of nuclear technologies, as long as the fundamental driving force remains the splitting of the atom, so too will the risk of proliferating those technologies for use in an atom-splitting bomb. Seeking a proliferation-proof nuclear energy policy is futile; instead, a smart policy should aim to maximize proliferation resistance under the given circumstances.

In the case of reprocessing used nuclear fuel, the principal concern is over the isolation of plutonium in the product stream, which could then be converted for use in a bomb. Unprocessed used nuclear fuel is sufficiently secure against physical enemy intrusion due to the multiplicity of highly radioactive components it contains. Since plutonium itself is not highly radioactive, it becomes much easier to approach after separation. Although newer reprocessing technologies leave different radioactive contaminants in the product stream to offset the loss in proliferation

\textsuperscript{35} Todd, Idaho National Laboratory.
\textsuperscript{36} Nuclear Energy Agency, OECD.
resistance, none of them remain significantly “self-protecting” by the International Atomic Energy Agency (IAEA) standards (Fig. 10).

There are several avenues by which plutonium proliferation could occur. A terrorist group or rogue state could steal the plutonium from the product stream of another country’s reprocessing plant or could acquire the technology itself on the black market to isolate plutonium themselves. Another risk involves a state legally operating a reprocessing facility but illegally diverting plutonium from the product stream or operating a clandestine plant in parallel. Any of these scenarios could occur for all the reprocessing technologies considered. While the risk levels for one-pass Pu recycling and full actinide recycling would vary based on total material flow, amount of transport required, technology safeguards, and additional factors, the fundamental issue of plutonium isolation is the same.

President Carter’s decision to ban reprocessing in the U.S. was ostensibly motivated by this issue. It was supposed to deter other nuclear countries from reprocessing as well, thereby bolstering global nonproliferation. However, they did not follow suit; several countries now operate reprocessing facilities. Consequently, the proliferation ramifications of implementing reprocessing in the United States in the 21st century are no longer the same as perceived in the early stages of the nuclear industry. Not only has the international deterrent argument been largely discredited, but the marginal impact in the global proliferation risk from initiating reprocessing in the U.S. would be much less substantial now that there already exists an established international reprocessing market. Furthermore, by entering this market, some argue

Figure 10. Dose rate relative to IAEA self-protection standard for various reprocessing product streams.37
that the U.S. might actually slow the dissemination of reprocessing technology by providing the service to other countries that wish to reprocess their used nuclear fuel, making domestic development less economical.38

However U.S. reprocessing would affect the global interplay, by far the most critical factor for deciding whether to reprocess domestically would be our own ability to prevent direct proliferation. In this arena, the U.S. has proven over the last sixty years that it can effectively manage and safeguard large plutonium stockpiles and dangerous technologies.39 Moreover, improvements are already underway in utilizing real-time monitoring of material flows to detect and prevent proliferation attempts.40

**Economics and Fuel Supply**

For any national policy, its fate will ultimately depend, in part, on its economic viability. The moratorium on reprocessing in the U.S. is arguably a product of this as much, if not more, than waste burden or proliferation concerns. After all, the nuclear energy industry is a business. The economics of reprocessing depends, primarily, on the cost of acquiring uranium ore. The reason is that, although the cost of reprocessing and disposal is higher than that of direct disposal, the value of the recovered fissile material increases with the price of natural uranium. Therefore, the theoretical “breakeven” price at which direct disposal and reprocessing have the same net present cost can be calculated by satisfying the following equation:41

\[
\text{Cost of interim storage} \quad \text{& disposal of spent fuel} = \quad \text{Cost of reprocessing} \quad \text{and disposal of HLW} \quad - \quad \text{Value of recovered fissile material}
\]

This calculation can be performed for either recycling scheme considered, adding the additional cost of fast reactors on the right side of the equation for the full actinide recycle. Of course, depending on the underlying assumptions—such as the working efficiency of the technologies, sunk capital costs, and myriad other factors—very different values may be found. A 2003 Harvard study calculated that the breakeven price of uranium for the conventional Pu recycle would be $360 per kilogram of uranium (kgU) and $340 kgU for the full actinide recycle. If the capital cost of a fast reactor eventually became comparable to that of a LWR, the price would fall to $140 kgU.42 The uranium price, however, has not even reached $100 kgU in over twenty years (Fig. 11). Whatever the assumptions, most studies concur that the current uranium market makes reprocessing of any kind in the U.S. uneconomical.

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39 Committee on Science and Technology, U.S. House of Representatives.


42 Bunn, Fetter, Holdren, Van Der Zwaan.
Although uranium demand has grown with the expansion of the nuclear industry, supply has grown in step. Like other natural resource commodities, efforts to maintain a steady market have incentivized exploration for new mines as well as enhanced mining techniques. Under current consumption rates, presently identified uranium resources will last for over 100 years. While growth in supply may not be able to match demand indefinitely, most studies do not show the price of uranium reaching any reprocessing breakeven price until at least midcentury—and several predict far longer.

Nonetheless, these economic indicators do not discredit the prospects of reprocessing. There is a large degree of uncertainty in forecasting nuclear energy growth, uranium production, and the development of advanced fuel cycle technologies, so a national waste management policy cannot depend on the industry evolving in one particular way. Moreover, because the new infrastructure for an advanced fuel cycle would take multiple decades to deploy, a practical policy must anticipate future economic conditions even if they conflict with present ones.

Even if breakeven prices are never reached, there is still an economic argument that supports reprocessing. In some countries, there is a high cost associated with being dependent on a foreign supplier of fuel. For those risk-averse countries that demand energy security, there might be an economic advantage to reprocessing used nuclear fuel domestically even if it entails more direct costs. Conventional one-pass Pu recycling reduces uranium demand by 11%; a full recycle would do so by more than two orders of magnitude. However, despite the fact that the United States is dependent on foreign sources of uranium, its close relationships with supplier states reduce the relevance of this argument.

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45 Bunn, Fetter, Holdren, Van Der Zwaan.
46 Massachusetts Institute of Technology.
47 Nuclear Energy Agency, OECD.
Finally, it is important to note that the economic ramifications of changing the fuel cycle are quite small compared to other parts of the nuclear energy industry. Capital, operations, and maintenance account for 80-90% of total generation costs, dwarfing the significance of fuel cycle economics. Although fuel cycle costs are not immaterial, they should not be the principal driving factor in a policy decision.\textsuperscript{48}

**Findings**

This report bases its findings on a comparative analysis of fuel cycles, with a focus on the role of reprocessing. On the basis of waste burden, compared to the current once-through cycle, one-pass Pu recycling is detrimental in the near term and moderately beneficial in the long term. A full actinide recycle would be superior both in the short and long term. However, in any case, the time lag for implementation means that a new reprocessing policy would not appreciably ease the current controversy over Yucca Mountain or the general need to site a geologic repository for existing waste.

In terms of proliferation, reprocessing of any kind has an undeniable risk of plutonium isolation, regardless of the fuel cycle in which it is employed. On the other hand, the present risks of the established international reprocessing market reduce the additional risk of a U.S. reprocessing program. More importantly, the United States already effectively guards against proliferation of its nuclear liabilities and continues to improve its capacity to do so. Thus, proliferation concerns, while substantial, are not insurmountable.

The economics of reprocessing raise several questions. Analysis of the breakeven uranium price shows that the full actinide recycle would be more economical than the conventional one-pass Pu recycle, although neither is cost-effective with current uranium prices. While uranium demand is rising, expanding production is maintaining a low price. As a result, the once-through cycle will most likely remain the most cost-effective option until at least midcentury. Nonetheless, the possibility of a changing market, combined with the long-term, anticipatory nature of nuclear policy, means that capital investments in a new fuel cycle might become “economical” before the arrival of the economic conditions that call for it. Whatever the case, fuel cycle costs are only a small portion of the total industry costs, limiting their importance in policymaking.

In synthesizing the findings from each issue analysis, it is clear that the full actinide recycle is superior to conventional one-pass Pu recycling. However, the question of whether or not to reprocess in the U.S. at all is a harder question to answer. Implementing reprocessing as part of a full actinide recycle in the U.S. reduces the waste burden, increases proliferation concerns, and is ambiguous in terms of economics and fuel supply—depending on the timing. A suitable policy recommendation must reconcile these conflicting issues. To do so, one must decide the magnitude of each issue to determine which should ultimately determine the policy. As for proliferation, the concerns are legitimate but can effectively be mitigated. In terms of economics and fuel supply, it has been shown that any economic disadvantage to eventual implementation of reprocessing is neither definitive nor disastrous; on the other hand, the long-term benefit to

\textsuperscript{48} Nuclear Energy Agency, OECD.
fuel supply is indisputable but potentially unnecessary. In short, neither proliferation nor economics and fuel supply should dictate policy.

Analysis indicates that the issue of waste burden has the most extensive ramifications regarding the question of reprocessing. The failure of the United States to implement a durable waste management policy raises serious doubts about the long-term sustainability of the once-through fuel cycle. Even if the U.S. succeeds in siting multiple geologic repositories to contain all the used nuclear fuel, the most rigorous engineering process cannot definitively ensure its isolation for the millions of years it remains harmful. Multitudes of unborn generations, who have no say in the policy decisions we make today, will face the consequences of them. Although there are considerable unknowns in the issues of proliferation and economics as well, the vast timeframe of the waste burden issue raises deeper concerns of unknown unknowns. To achieve intergenerational equity, we must have confidence in our near-term institutional controls and humility in predicting the evolution of distant times.

Given the high stakes of this issue, waste burden should be the driving factor in forming a policy on nuclear waste management and reprocessing. Therefore, the dramatic reduction in the longevity of the waste burden resulting from the full actinide recycle seems to justify its implementation. However, an immediate transition toward this cycle is neither necessary nor advisable. The current once-through cycle and waste management policy are safe, economical, and sustainable in the immediate future. More importantly, significant innovation is still required before the technology is ready to support a transition of this scale. Thus, for the time being, the government should primarily focus on researching and developing these technologies to prepare for deployment later this century.

**Policy Recommendation**

- The United States should maintain its current once-through cycle for the time being. The DOE should proceed with siting a geologic repository for direct disposal.

- The DOE should establish an integrated research, development, & demonstration program for reprocessing and advanced reactor technologies to prepare transition toward a full actinide recycle. The program should maintain a long-term vision, with a proper balance between revolutionary and evolutionary progress.

- In particular, the program should emphasize improving the electrochemical reprocessing technique from a batch process to a high-throughput, commercial-scale one. Efforts to improve aqueous reprocessing should continue as well.

- In parallel to this program, the DOE should continue its research initiatives in high-burnup reactors to improve efficiency and reduce waste production as well as modeling, simulations, and real-time monitoring to improve material accountability and proliferation protection.

- The DOE should work collaboratively on these initiatives with other countries already possessing advanced fuel cycle technologies since different countries are more advanced
in different areas. Together we can more effectively advance international goals of waste reduction, nonproliferation, and energy security.

**Conclusion**

Given rising energy demand and heightened concerns over our fossil fuel economy, nuclear energy is poised to grow substantially this century. However, the waste burden of the current once-through cycle in the United States will not be sustainable in the long term. For this growth to occur, therefore, we must eventually transition toward an advanced fuel cycle that utilizes reprocessing. The conventional one-pass Pu recycling alternative does little for sustainability, only modestly improving fuel supply and waste burden while posing legitimate proliferation concerns. Instead, the United States must promote the development of improved reprocessing technologies, real-time proliferation monitoring systems, and other advanced fuel cycle technologies. By committing to a long-term program of goal-oriented research, development, and demonstration of these technologies, perhaps by midcentury the U.S. will have the option to implement a closed fuel cycle. Indeed, the future of nuclear energy—and thereby the security of the broader energy system—depends on it.

**Works Cited**


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