Reprocessing of Spent Nuclear Fuel: A Policy Analysis

Todd P. Lagus
2005 WISE Intern
University of Minnesota

August 4, 2005

Sponsored by ASME

Abstract

Nuclear spent fuel reprocessing has lately reemerged as a subject of debate in the energy policy world. Since a 1977 Presidential Directive which deferred reprocessing of spent nuclear fuel (SNF), the United States has utilized a "once through" or "open cycle" system of nuclear fuel processing, which leaves most of the energy content in uranium unused. Current reprocessing technology increases the cost of nuclear electricity while only offering limited storage benefits. Advanced technologies have the potential to increase proliferation resistance while decreasing the need for more geologic repositories. The United States should not immediately engage in spent fuel reprocessing, but should begin aggressive research and development for new reprocessing technologies both for future energy production and proliferation concerns.

List of Acronyms

^{235}U	Uranium 235 Isotope (Fissionable)
^{238}U	Uranium 238 Isotope (Not fissionable)
AFCI	Advanced Fuel Cycle Initiative
ATW	Accelerated Transmutation of Waste
DOE	Department of Energy
EPA	Environmental Protection Agency
FR	Fast Reactor
IAEA	International Atomic Energy Agency
kgHM	Kilogram Heavy Metal
kWh	Kilowatt-hour
LCOE	Levelized Cost of Electricity
LLW	Low-Level Waste
MOX	Mixed Oxide Fuel
MWh	Megawatt-hour
NEI	Nuclear Energy Institute
NERI	Nuclear Energy Research Initiative
NPT	Nuclear Non-proliferation Treaty
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
OCRWM	Office of Civilian Reactor Waste Management
PUREX	Plutonium Uranium Extraction (Reprocessing method)
SNF	Spent Nuclear Fuel
UREX+	Uranium Extraction (Reprocessing method similar to PUREX)

Executive Summary

Nuclear spent fuel reprocessing has lately reemerged as a subject of debate in the energy policy world. Since a 1977 Presidential Directive which deferred reprocessing of spent nuclear fuel (SNF), the United States has utilized a “once through” or “open cycle” system of nuclear fuel processing, which leaves most of the energy content in uranium unused. However, interest in reprocessing has again surfaced, and its potential applications could have major impacts on the utility industry, energy policy, and national security.

SNF reprocessing can have both large benefits and great risks. Currently available reprocessing reactors, which are used in countries such as France, provide added utilization of fresh nuclear fuel but are expensive and create stockpiles of weapons grade plutonium. New technologies have been demonstrated in laboratories that could help curb these proliferation risks. Even more advanced is a technology known as transmutation, which further processes the small amounts of material that contribute to most of the heat load of SNF. With transmutation, repository utilization could improve by a factor of 100.

One main argument against reprocessing has been its lack of economic competitiveness due to relatively cheap natural uranium ore. Several studies indicate that reprocessing increases the cost of nuclear electricity relative to the once through cycle by ten percent. However, since projections indicate that a new repository will be needed every 20-30 years, a main economic and political benefit of reprocessing with transmutation would be the decreased need for geological repositories such as the $60 billion dollar Yucca Mountain in Nevada.

Proliferation risks, however, have and will be major detriments to reprocessing. The United States halted reprocessing in 1977 due to these risks, thinking other nations would do the same. Other nations, however, have continued to reprocess spent fuel, and North Korea claims to have produced weapons using reprocessing. Many agree that due to this policy, the U.S. has fallen behind in nuclear power technology.

After comparing the short and long term benefits, costs, and risks of spent fuel reprocessing, the United States should not immediately deploy commercial reprocessing but should begin steps now to make reprocessing viable in the future. Specifically, the following five recommendations should be considered:

1. The United States should not immediately deploy spent nuclear fuel reprocessing technology.
2. America must aggressively fund research and development programs for reprocessing and transmutation technologies *now*.
3. Reprocessing should not be deployed until a proliferation-resistant, economically competitive reprocessing technology is demonstrated.
4. Collaboration should be undertaken in research, development, and deployment with other nations already possessing reprocessing technology.

5. The U.S. government should provide incentives for nuclear power.

As a result of following these recommendations, the U.S. will regain its global presence in all facets of reprocessing technology to give the nation the best possible energy solution while providing lasting proliferation security.

Table of Contents

About the Author

Todd Lagus is a rising senior at the University of Minnesota Twin Cities. He will graduate in May 2007 with Bachelor of Science and Master of Science degrees in Mechanical Engineering. Todd's main academic interests include fluid mechanics, heat transfer, energy concerns, public policy, and business. He is currently the Executive Vice President of the University of Minnesota Undergraduate Consulting Club, an organization that explores engineering and business aspects of consulting. Todd is also involved in ASME, Tau Beta Pi engineering honor society, Pi Tau Sigma mechanical engineering society, and intramural sports. In 2005, Todd was selected as an intern to represent ASME in Washington, D.C. through the WISE program.

About the WISE Program

The Washington Internships for Students of Engineering (WISE) program is a nine week internship in Washington, D.C. that introduces outstanding engineering students to public policy. The purpose of the program is to examine how technology policy decisions are made and also demonstrate the integral role of engineers in the decision making process. The students, who are sponsored by different engineering professional societies, visit agencies such as the Nuclear Regulatory Commission, Department of Energy, and Office of Science and Technology Policy, as well as attend congressional hearings, meet with congressmen and their staff, and tour facilities like the Pentagon. The students also produce a policy analysis paper on a relevant engineering topic selected by the student and sponsoring society.

Acknowledgements

I would like to thank all those who helped in making this internship possible including ASME and other sponsoring societies that contribute to the WISE program. Special thanks to Francis Dietz, Kathryn Holmes, Patrice Mattingly, Melissa Murray, and the rest of the staff at ASME for their help and guidance with my policy analysis paper. Thanks again to everyone who provided valuable technical and policy information in helping me with my topic. Finally, I would like to thank Dr. Steve Watkins and all the WISE interns for making the summer a great one.

Paper Citation

Lagus, T. P., "Reprocessing of Spent Nuclear Fuel: A Policy Analysis," *Journal of Engineering and Public Policy*, vol. 9, 2005, available http://www.wise-intern.org.

1 Introduction

Energy production is one of the most important issues in everyday life that most take for granted. The topic has been around for all of time, yet it will never cease to be an issue. At this time, policymakers are at a vital point for determining the energy needs of the United States for future generations. Specifically, nuclear technology has once again emerged as a viable option to solve the energy issue, and new nuclear technologies, including advanced reprocessing cycles, are coming into the political spotlight. Implementation of these new technologies will have significant impacts on the utilities industry, energy policy, and national security.

Currently, U.S. nuclear utilities extract only about five percent of the energy content of fresh nuclear fuel when it passes the fuel through a reactor. Since 1977, the United States has relied exclusively on a "once through" fuel cycle for its nuclear power generation, twenty percent of the total electricity generation for the nation. Prior to that time, the country had engaged in the nuclear power technology of reprocessing its spent nuclear fuel (SNF). In short, reprocessing involves taking the SNF and separating out uranium, which makes up the 96 percent of the spent fuel, from the plutonium and other fission products. Both the separated uranium and plutonium can be used in nuclear reactors for further electricity generation, instead of being disposed of through interim storage or in a repository such as Yucca Mountain.

While recycling the useful products in spent nuclear fuel makes sense from a technology point of view, there are many reasons why the United States has not engaged in reprocessing since the 1970s. Proliferation risks have been the main cause in the cessation of the technology by President Carter in 1977, since conventional reprocessing technology can be used to make weapons grade plutonium. Economic viability of the technology is also questionable, since low uranium ore prices help make the once through nuclear fuel cycle more cost effective.

In addition to the conventional reprocessing cycle formerly used in the U.S., there have been efforts to introduce new advanced fuel cycle technologies that deal with some of the issues associated with the older technology. This study introduces both the conventional cycle along with new fuel cycle technologies and analyzes the benefits, economic considerations, and proliferation risks of spent nuclear fuel reprocessing. The final portion of this report takes these analyses and makes a final recommendation on the short term and long term futures of reprocessing.

2 Background

Before delving into the analysis of whether or not the United States should engage in reprocessing from a policy standpoint, it is important to note some of the background surrounding the issue. A brief overview of the nuclear fuel cycle, history of reprocessing, and technical benefits of reprocessing are presented here.

2.1 The Nuclear Fuel Cycle

Most energy obtained from nuclear reactors comes from the naturally occurring fissionable isotope ^{235}U. Non-enriched uranium oxide contains 0.7% ^{235}U, with the isotope ^{238}U making up the remainder of the material. After enrichment of the natural uranium to about 4% ^{235}U, the material can be converted into fuel rods that will be used in the core of a power reactor. When the fissionable uranium content of the fuel falls below a given concentration threshold, the fuel rods are replaced and the fuel is "spent". Spent fuel contains 96% uranium (mostly ^{238}U), 1% plutonium, 0.1% minor actinides (neptunium, curium, and americium), and 3% fission products.[1] Only a small portion (about 1%) of the fission products poses long terms hazards. The uranium, which can be separated from the rest of the products, still has most of its energy content and could be either reused or disposed of as low-level waste (LLW).

2.1.1 PUREX Reprocessing

Current commercial reprocessing technology uses a method known as PUREX, which stands for plutonium/uranium extraction. Plutonium and uranium are each separated from the other spent fuel products which are vitrified and stored in a geological repository such as Yucca Mountain. The uranium may be processed for further fuel use or stored as low level waste, and plutonium stream is mixed with uranium to create a mixed oxide (MOX) fuel for use in power reactors. The pure plutonium stream raises proliferation concerns since it can be used to make nuclear weapons, although sophisticated weapons technology is necessary to deploy the plutonium as a weapon. PUREX technology has been used in the United States and is currently used in other nations such as France and the U.K.

2.1.2 UREX+ Reprocessing with Transmutation

The UREX+ technology with accelerated transmutation of waste (ATW) improves on the conventional PUREX technology by mixing the plutonium with minor actinides, making the process more proliferation-resistant. At no point in the process is pure plutonium ever extracted. Transmutation involves an additional reactor processing step for some of the nuclear material, in this case long-lived highly toxic fission products and actinides. The products of the UREX+ process are shown below.

- Uranium, for reuse or disposal as LLW
- Plutonium/actinide mixture, which can be used either in conventional or fast reactors or could be transmuted
- Fission products to be eventually stored in repository
- Other minor actinides that may be transmuted

The transmutation process could involve processing the one percent discharge resulting from plutonium and minor actinides. Of this small percentage of plutonium and actinides in the spent fuel, only ten percent would be converted into cesium and strontium for another 0.1% of the total SNF, but the result would be an increase of eighteen percent of the electricity from the energy that was produced in the first reactor. The cesium and strontium are hard to transmute, but with thirty year half lives, the toxicity quickly diminishes. The iodine and technetium are long-lived but may be transmuted into stable isotopes.[2] A summary of spent fuel composition along with three processes are shown in Table 2-1.

	Composition	Once Through	PUREX	UREX+ with ATW
Actinides				
Uranium	95.60%	Repository	Reused or LLW	Reused or LLW
Plutonium	0.90%	Repository	MOX Fuel	MOX or ATW
Minor Actinides	0.10%	Repository	Repository	
Fission Products				
Stable/Short Lived	3%	Repository	Repository	Repository
Cesium/Strontium	0.30%	Repository	Repository	Repository
Iodine/Technetium	0.10%	Repository	Repository	ATW

Table 2-1. Composition of Spent Nuclear Fuel and Different Processes.[3]

The feasibility of the UREX+ process has been demonstrated in laboratory-scale tests using actual spent nuclear fuel. According to Robert Shane Johnson, DOE Acting Director of Nuclear Energy, Science, and Technology, the expansion and deployment of the process to commercial power generation for both the UREX+ and ATW technologies still need significant research and development but could be available in 20 years.[4] The transmutation process would still require several years of research and development according to the Advanced Fuel Cycle Initiative. The DOE Advanced Fuel Cycle Initiative (AFCI), launched in 2003, has identified six commercial reactor designs to support the new technologies Generation IV Nuclear Energy Systems Initiative that have promise of commercial deployment before 2030.[5]

2.2 History of Reprocessing Policy

Reprocessing is not new to the United States. In the Early 1950s, the U.S. Atomic Energy Commission initiated production and usage of recycled uranium for both uranium conservation purposes, and for weapons grade plutonium production. While still engaging in reprocessing, the U.S. entered the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in 1968, which is designed to promote nuclear non-proliferation, peaceful uses of nuclear technology, and disarmament.

However, in March 1977, fear of nuclear weapons proliferation (especially after India had developed nuclear weapons capabilities using reprocessing technology) led President Jimmy Carter to issue a Presidential Directive to “Indefinitely defer the commercial reprocessing and recycle of plutonium in the U.S.”[6] The order all but killed U.S. civilian reprocessing and breeder reactor programs. In opposition to any new nations desiring reprocessing technologies, the U.S. has argued that its own example of a once through cycle demonstrates that reprocessing is not necessary to maintain a successful nuclear power program.[7] Other nations such as France and China, however, have not followed suit and have continued to reprocess spent nuclear fuel.

President Reagan lifted the reprocessing ban in 1981, but the commercial reprocessing plants in the United States were no longer considered economically viable; few companies invested in the technology. By 1993, President Clinton had reaffirmed the U.S. policy discouraging reprocessing and shut down research and development.[8]

In recent years, the movement toward SNF reprocessing in the United States has garnered momentum. A May 2001 National Energy Policy report submitted by the National Energy Policy Group chaired by Vice President Richard Cheney made the recommendation that the United States should "develop reprocessing and fuel treatment technologies that are cleaner, more efficient, less waste-intensive, and more proliferation-resistant."[9] Following the Bush administration's National Energy Policy recommendation, the DOE AFCI was created to develop new reprocessing technologies that support future Generation IV nuclear energy systems.

Most recently, the House of Representatives has been seriously looking into reprocessing and advanced fuel cycle technologies. An accompanying report to H.R. 2419, the Energy and Water Development Appropriations Act for FY 2006, directs DOE to accelerate reprocessing research to make a specific technology recommendation on reprocessing by the end of FY 2007. In response, the Energy Subcommittee of the House Committee on Science has held two hearings during the First Session of the 109th Congress, one on the technological aspects of reprocessing and the other discussing the economic aspects and feasibility. Most notably in support of reprocessing are House Appropriations Energy and Water Development Subcommittee Chairman David Hobson (OH) and House Science Energy Subcommittee Chairwoman Judy Biggert (IL), who hails from a state that derives roughly half its electricity from nuclear power. The committee has heard from witnesses on both sides of the reprocessing issues, with some wishing to begin the process of commercial deployment by 2025 and some wanting to take a "wait and see approach" due to uncertainties with economics and proliferation. The following analyses address many of the issues discussed in both hearings.

2.3 Benefits of Spent Nuclear Fuel Reprocessing

Nuclear spent fuel reprocessing has the potential for great technical and societal benefits in the field of energy production. The long term, permanent storage of spent nuclear fuel in the once through cycle has been a topic of great scientific and political controversy. While the construction of the Yucca Mountain geological repository is still underway, the opening date of 1998 set forth by the Nuclear Waste Policy Act (NWPA) of 1982 has long passed and is not expected to come before 2025. The repository has yet to be licensed by the NRC due to political opposition, technical setbacks, and site concerns.

Even with the repository open, the approved 70,000 metric ton capacity of Yucca Mountain will be insufficient to hold the of nuclear waste generated by 2010 based on current nuclear generation rates. Even if the capacity is increased to its ultimate capacity of 120,000 metric tons, Yucca Mountain will be sufficient only until 2030.[10] At current nuclear spent fuel waste generation of 2,000 metric tons per year, a Yucca Mountain-scale repository would be needed every 35 years. Furthermore, to maintain nuclear power as twenty percent of the U.S. generating capacity by 2025, spent fuel generation would require a repository every 20 years.[11] Greenhouse gas emission regulations would only increase nuclear power competitiveness and therefore, overall spent fuel generation.

Political setbacks for the Yucca Mountain repository have marred the siting, licensing, and ultimately the opening of the repository. In July 2004, a federal circuit court decision created problems for Yucca Mountain when it ruled that the EPA's 10,000 year regulatory compliance period for the repository was too short. Similar political setbacks have occurred, including an "outraged" Nevada Governor Guinn veto of the placement of the repository in his state. Controversy in the building and use of long term repositories is not likely to recede, especially with the Secretary of Energy required to make a decision on a second repository between 2007 and 2010.[12]

Spent fuel reprocessing can both utilize the Yucca Mountain facility more effectively and greatly reduce the need to build more of these expensive, cumbersome repositories. The small percentage of fission products account for most of the heat load in SNF, so separating the less radioactive uranium, plutonium, and other short lived isotopes would require only a small amount of waste (the fission products) to be transported and stored at the repository. In current PUREX practice without transmutation, France reduces its spent volume by a factor of four. Even without the uranium, however, the capacity is limited by the small amount of material that contributes to the heat load, and the storage capacity increases only by ten percent. Advanced fuel cycles with transmutation would further increase volumetric savings since the small amount of fission products contributing to most of the heat load can be transmuted into more stable products. With transmutation, the storage capacity could increase by a factor as large as 100.[13] A technological roadmap created by DOE proposes an ATW system which would transmute 87,000 tons of spent fuel over 120 years. To put this amount of spent fuel into perspective, the U.S. has generated about 50,000 tons of commercial spent fuel in the history of its nuclear program.[14]

Fewer repositories would save time and money for licensing, siting, constructing, and transporting spent fuel to the repositories. While some argue that transportation to the reprocessing plants is similar to that of transportation to a repository, the plants (reactors, reprocessing, and transmutation) can be co-located in energy "parks," which would decrease both transportation and security costs.

According to EPA regulations, a repository may not pose a greater risk than the unmined uranium from which the fuel is produced. A 1999 study prepared for DOE models the radiation dosages at a water well 20 km from the Yucca Mountain repository for both untreated spent fuel and fuel treated with ATW. The ATW treatment of the 63,000 tons of reactor fuel and the 7,000 tons of defense related spent fuel results in a fivefold dose reduction over 11,000 years.[15] In his June 16th Congressional hearing testimony, DOE Acting Director of Nuclear Energy, Science, and Technology Robert Shane Johnson has indicated that advanced fuel cycles could decrease the time it takes for nuclear spent fuel to return to natural uranium radiation levels from 100,000 years down to 1,000 years.[16]

Dosage reductions through transmutation could help the approval process for repositories and eliminate some of the long term uncertainty of the waste storage.

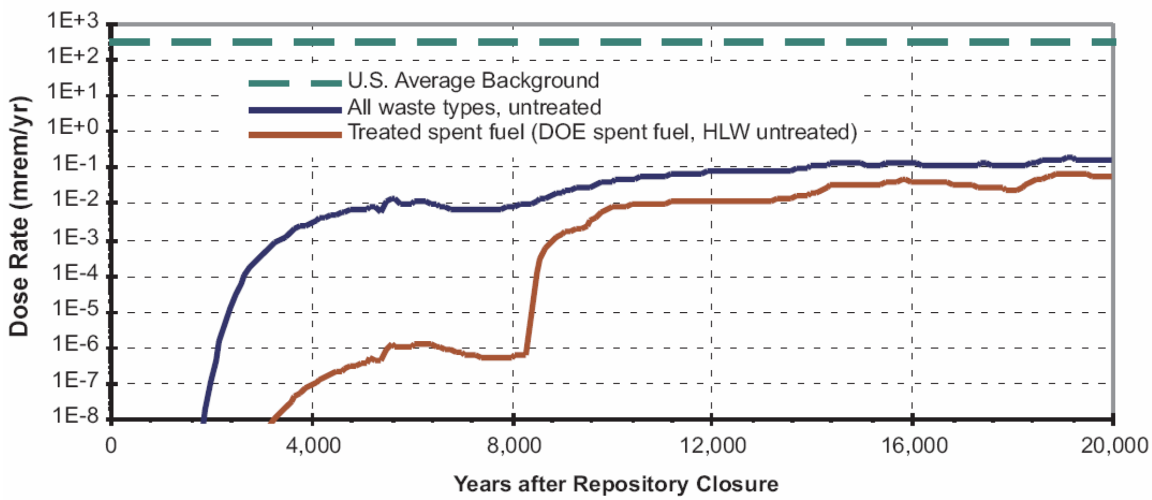

Figure 2-1. Radiation Dosages with and without ATW at 20 km from Repository.[17]

In addition to storage issues, the availability and mining of uranium are also prevalent concerns. By extracting more waste from the uranium using reprocessing, less uranium will have to be mined. While estimates of available uranium ore vary, the Uranium Information Centre in Melbourne, Australia estimates the known uranium ore will sustain the once through fuel cycle for another 50 years at current price levels. It is worth noting that, however, as uranium becomes scarcer and prices rise, the need for more resources will greatly increase mining research and the amount of known uranium.[18] This effect can be likened to the increased resourcefulness in petroleum following the Arab Embargo of the 1970s.[19]

Reprocessing may be necessary to reach the goals set by the Generation IV nuclear reactor program, which has the potential to shape the energy future of the United States. Even programs such as DOE FreedomCAR and Vehicle Technologies, which hopes for the realization of the hydrogen economy by 2040, are dependent on electricity generation for the transportation needs of the country. Given the high and rising oil prices and the potential for greenhouse gas regulation, the next generation of nuclear power is a viable technological solution.

3 Economics of Reprocessing

Perhaps the strongest argument against SNF reprocessing in the United States is the fact that it is currently not competitive in today's energy production market. Most agree that reprocessing is indeed more expensive than a once through cycle, generally due to relatively cheap natural uranium prices; it remains difficult to predict how much more expensive the technology really is. The economic analysis shown here presents a few economic studies which deal with reprocessing, each with slightly different results derived from differing analyses and assumptions.

3.1 Costs of the Once Through Cycle versus Coal and Gas

Since reprocessing has not been practiced in the United States since the 1970s and research has just restarted, it is difficult to find solid economic data on reprocessing. One way to compare reprocessing to the once through nuclear fuel cycle, gas power, and coal power is to first determine the economic competitiveness of the once fuel cycle with the fossil fuel alternatives

A 2004 study conducted at the University of Chicago calculated the levelized costs of electricity (LCOE) without federal financial policies for three electricity sources, which are shown in Table 3-1**.** The LCOE is defined as the lifetime cost of a power plant including construction, production, and decommissioning costs. The cost of electricity is generally expressed in mills/kWh, where one mill equals one tenth of a cent. To put the numbers into perspective, the U.S. generated 789 billion kWh of electricity in 2004.[20]

Energy Source	LCOE (Per kilowatt-hour)	LCOE with Greenhouse Regulation
Once Through Nuclear	47-71 mill	47-71 mill
Coal	33-41 mill	56-90 mill
Natural Gas	35-45 mill	43-71 mill

Table 3-1. Levelized cost of electricity with and without greenhouse gas regulations.[21]

It is worth noting that the capital costs are the dominant factor in determining the cost of nuclear power. While the LCOE costs, which include plant construction costs, of coal and gas are relatively low as compared to nuclear power with or without reprocessing, the operating costs of a once through nuclear cycle are far superior to gas and slightly better than coal. According to the Nuclear Energy Institute (NEI), the 2004 production costs of nuclear, coal, and gas were 16.80, 19.20, and 58.70 dollars per MWh for nuclear, coal, and gas, respectively. Data from 1995-2004 are shown graphically in Figure 3-1.[22]

Although new generation plant capital costs may initially be high, the University of Chicago study makes a point that a learning curve exists with many new technologies. In the absence of government policies, the model shows that after the fifth plant, when most learning has occurred, many once through nuclear power plants could become self sufficient and competitive given an overnight cost of $1,500/kW and a five year construction period.[23]

With sufficient coal supplies, prices are not expected to rise substantially even if the demand for coal rises the predicted 35 to 50 percent over the next 25 years.[24] While supply will not be an issue, greenhouse gas emission regulations, depending on their extent, would assuredly alter the viability of coal as an economic option. One MIT study estimates that, with reasonable regulations on greenhouse gasses, the price of coal power would rise to between $56 and $90 per MWh, and similar numbers of between $83 and $91 per MWh are shown in the University of Chicago Study.[25,26] Although CO_2 regulation amendments were not added to the 2005 Senate Energy Bill, senators including Jeff Bingaman (D-NM) and John McCain (R-AZ) strongly support emission regulations, and the Energy and Natural Resources Committee is expected to act on the issue in the near future.[27]

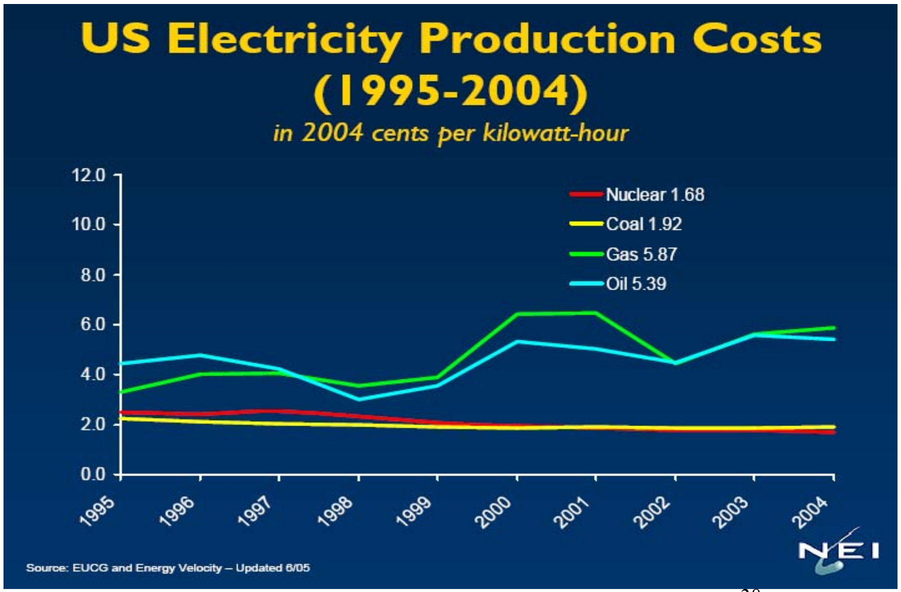

Figure 3-1. U.S. Electricity Production Costs.[28]

Gas prices would not be as substantially affected by greenhouse emission regulations, but still could rise to between $43 and $71 per MWh, again depending on the regulation levels.[29,30] Even in the absence of greenhouse emission regulation, gas prices have risen appreciably in the last few years. Figure 3-2 shows the recent trends in natural gas imports.

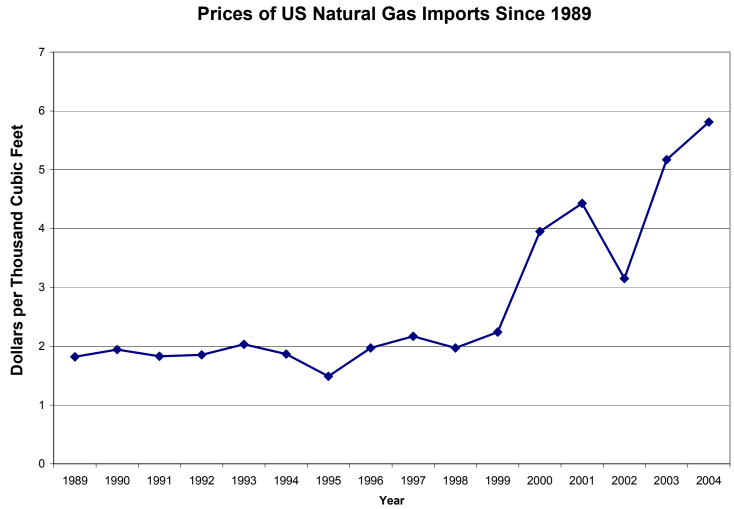

Figure 3-2. Natural Gas Import Prices since 1989.[31]

Looking at the once through fuel cycle, nuclear power in this form is not immediately competitive. However, if the environmental costs of fossil fuels are quantified and regulated or the government provides assistance with capital plant costs, the open fuel cycle may become economically superior. Note that increased nuclear power due to its increased competitiveness will come a much higher abundance of nuclear spent fuel which must be stored at high costs.

3.2 Costs of Reprocessing

The lack of economic data for the closed fuel cycle makes it difficult to analyze the economics of reprocessing. Nonetheless, a small number of economic studies dealing with reprocessing have recently been conducted, and some data may be acquired from recycling programs such as those in France, Japan, and China. Note that the data is for conventional PUREX reprocessing, since UREX+ and transmutation have not been fully developed.

The economic study conducted at the University of Chicago presents some reprocessing data from other nations. Table 3-1 shows electricity costs with reprocessing for three nations.

Country	LCOE (Per kilowatt-hour)
China	39 to 61 mills
France	50 to 60 mills
Japan	83 to 97 mills

Table 3-2. Reprocessing LCOE.[32]

It is important to note that data from other nations should be taken cautiously since other countries may want to either protect their data or present it in a way which makes their technology more desirable.[33] With that in mind, the LCOE numbers represent a broad range of costs for reprocessing. Assuming the numbers could be replicated in the United States, the Chinese and French numbers portray reprocessing as economically competitive with the once through cycle. However, the Japanese costs of reprocessing are considerably higher than the U.S. open cycle costs due to greater capital costs than originally predicted by the Japanese nuclear program.

There have been several studies conducted on reprocessing of spent fuel. During the June 16, 2005 House Science Energy Subcommittee hearing on reprocessing, Matthew Bunn, Senior Research Associate with Harvard University's Project on Managing the Atom, has testified that reprocessing does not have an economic advantage over the once through fuel cycle. In a report from the project entitled *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Bunn et al. asserts that reprocessing in light water reactors (LWR) would have a "breakeven price" of natural uranium ore of \$340/kgHM. The breakeven price is the price at which reprocessing becomes economically equal to the once through cycle. In other words, the price of uranium would need to rise from the current \$40/kgHM to \$340/kgHM to be economically equivalent.[34]

On the surface, it seems that reprocessing would increase the cost of nuclear power dramatically. However, this price difference represents an increase in the cost of only the nuclear fuel, which represents ten percent of the total cost of nuclear electricity**.** At current uranium prices, Bunn's study estimates a total increase in the cost of electricity from reprocessing of 1.3 mils/kWh, which would mark an increase of only eight percent from 2004 production cost of the once through nuclear fuel cycle.

With fast reactor (FR) technology, which could be utilized in advanced fuel cycles, Bunn completes a similar economic analysis. FR technology would constitute a smaller breakeven uranium price of $140/kgHM, but would also raise the electricity cost between 2 mills/kWh and 7 mills/kWh, depending on the price difference between the FR capital costs over the LWR costs.[35]

Dr. Donald W. Jones, who took part in the University of Chicago study, testified on July 12, 2005 at a House Science Energy Subcommittee hearing that reprocessing estimates for most analyses on the technology are similar to Bunn et al. Using results from three studies, including Bunn et al., the average additional cost of reprocessing with current technology equates to an increase of 2.65 mills/kWh from the open fuel cycle. However, the study does not include added fabrication costs with recycling plutonium and uranium, or net costs beyond the LCOE estimates for advanced reactors to consume remaining actinides.[36]

Since the cost data do not include advanced fuel cycle technologies such as transmutation, it is important to include this in the analysis. According to a DOE study *A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology: A Report to Congress*, the cost of a first of a kind ATW system for treating 87,000 tons of spent fuel would total $279 billion over 117 years, a time which includes the 30 year development and demonstration period. At a discount rate of 0%, the electricity generated would cost 43 mills/kWh, and a discount rate of 3% would indicate sales at that price covering 70% of the costs.[37] The large cost of the system that does not produce results until the far off future would make the development considerably difficult.

The following is an ad hoc comparison of repository savings at the assumed 2.65 mills/kWh cost of reprocessing. To calculate repository savings, assume that a Yucca Mountain scale repository would be needed every 30 years, which falls between the 20 to 35 year range presented earlier. At an eventual cost of around $60 billion, the cost of the repository comes to $2 billion. In 2004, United States nuclear power plants generated 789 billion kWh of electricity. Assuming that reprocessing could save $2 billion per year at this level of electricity, the repository savings would amount to 2.53 mills/kWh, an amount that is comparable to the cost of reprocessing. This is a rough estimate using assumptions, and the result is most sensitive to the cost and need for more repositories.

Savings in repository costs could be reflected by a change in SNF disposal funding through the Nuclear Waste Fund (NWF), which is acquired by the DOE OCRWM program through a utilities fee of 1 mill/kWh. This amount does not nearly cover the amount necessary for further repositories, and the fee would assuredly increase for continuation of the once through fuel cycle. Given the record of PUREX, which does not transmute the fission products that contribute the greatest heat load, repository savings are not likely to be significant. Recycling with transmutation, while probably more expensive, would provide the greatest amount of repository savings. Reprocessing will not replace ultimate storage in repositories, but as mentioned earlier would delay or prevent the need for further construction and save utilities some of the fees associated with disposal.

Other repository savings include the litigation involved in creating such massive scale spent fuel projects. DOE has been negotiating with nuclear utilities since 1999 on the missed nuclear waste deadline of 1998. Exelon, a nuclear utilities corporation that operates 17 reactors, reached a settlement with the Department of Justice that it alone would receive $600 million dollars even if Yucca Mountain opens by 2015.[38]

Given the existing economic comparison of reprocessing to the once through cycle, recycling of spent nuclear fuel still has not been proven more economically competitive than the once through system, especially since PUREX is the current commercialized process. Thus, if current conditions persist, investors will not be motivated to undertake commercial reprocessing. However, should the once through cycle become more competitive than gas and coal power, the amount of waste generated could increase appreciably. An increase in the nuclear share of electricity generation would accelerate the need for more repositories and thus improve the competitiveness of the closed fuel cycle.

3.3 Government Economic Policy Involvement

The economic analysis shows that the reprocessing or even the once through nuclear cycle is not yet economically desirable to investors. However, changes in government policies, including environmental regulations already mentioned and economic policies, could improve the competitiveness of both technologies.

The University of Chicago nuclear power study analyzes the effects of government involvement in the future of the once through cycle using several different forms of support: loan guarantees, accelerated depreciation, and investment tax credits. Loan guarantees in this case refer to the obligation of the government to repay part of the loan should a utility company not be able to repay. The 2005 Energy Bill, which passed in July 2005, would make advanced nuclear power plants eligible for federal loan guarantees and provide a tax credit for nuclear power production. This would lessen the risks associated with capital costs for investors, and according to the Chicago study, reduce the LCOE for a nuclear reactor by 4 mills/kWh to 6 mills/kWh.

The next financial subject, accelerated depreciation, refers to the ability of an investor to utilize the investment tax deductions early on in the lifetime of the payment rather than receive the same deduction each year in a linear fashion. Accelerated depreciation helps investors absorb capital costs, which for nuclear power generation are large. The University of Chicago study calculates a reduction in the LCOE for a 7 year depreciation policy of 3 mills/kWh to 4 mills/kWh.

Tax incentives for nuclear power production are the final policies that could make nuclear power and reprocessing more desirable. An investment tax credit of 10 percent would create an LCOE reduction between 6 mills/kWh and 8 mills/kWh, while a 20 percent credit could create cost reductions between 9 mills/kWh and 13 mills/kWh.[39] Production tax credits on a per kWh basis may also be used. Since reprocessing and the once through cycle are not appreciably different for the price, it is sufficient to assume that similar effects for all three of these government policies would occur with policies applied to reprocessing.

While it is no secret that monetary incentives would help the nuclear reprocessing investments, there is still the question of whether or not the government should provide economic support to the industry. As with any government funding, it is politically important not to be viewed by other energy generation industries, i.e. gas and coal, as favoring nuclear power over other sources. Given the recent concerns for global warming, tax incentives and loan guarantees for nuclear technologies seem like a realistic option especially in the absence of emission regulations. Accelerated depreciation also is an unobtrusive option that could help the industry by easing capital costs.

3.4 Government Research Funding

Since the Bush Administration has taken office in 2001, government funding for research in the area of nuclear reprocessing has increased dramatically. For FY 2006, the administration has requested $70 million for the AFCI, an increase of 3.8 percent from the previous year's appropriation. The House has added $5.5 million to its AFCI budget request in its version of the 2005 Energy Bill to accelerate a decision on reprocessing by the end of FY 2007. In related appropriation requests, the House has requested a 12.5 percent increase in the DOE Generation IV Energy Systems Initiative to $45.0 million.[40]

4 Proliferation Concerns

The international interest in developing new reprocessing technologies, including ATW and fast reactors, has been increasing over the last several years. With this promising technology on the verge of development, global proliferation impacts of reprocessing must be considered. Atop the many issues lie reprocessing risks, global cooperation, impacts on U.S. foreign policy, and public acceptance.

4.1 Reprocessing Risks

While reprocessing of spent nuclear fuel may be scientifically viable, one main argument against reprocessing remains the nuclear weapons proliferation concern. In the conventional PUREX reprocessing technology, a pure stream of weapons grade plutonium is separated out of the spent fuel. The plutonium is mixed with uranium to created MOX fuel, which cannot be used as a weapon. Although the final fuel product is not weapons grade nuclear material, the intermediate step in extracting the pure plutonium could allow nations with the technology to create weapon materials for their own purposes or increase the threat of theft of the weapons material from reactor facilities. Over 240 declared tons of separated plutonium has been stockpiled worldwide as a result of civilian reprocessing programs, which is enough to make 25,000 Nagasaki-scale bombs.[41,42] According to Peter Lyons, current NRC commissioner, countries which practice reprocessing impose the tightest of security measures in the process and storage facilities.[43]

Unlike highly enriched uranium, which could be used as a weapon fairly easily, weapons grade plutonium requires complicated implosion technology; thus a terrorist would not easily deploy it as a weapon. However, many believe that nations like North Korea are capable of manufacturing implosion devices, and some 1986 satellite intelligence photos have shown high explosive testing with implosion device-like patterns. U.S. officials have stated that North Korea has re-opened its reprocessing facilities and have probably processed 8000 spent fuel rods containing enough plutonium for five or six nuclear weapons.[44]

In the case of the newer UREX+ technology, the long-lived fission products create more steps in weapons deployment. The new technologies for reprocessing including transmutation would not involve separating pure plutonium, but rather a plutonium/ actinide mixture that would increase the toxicity of the material and protect it from theft and handling. The International Atomic Energy Agency's (IAEA) standard for self protection requires 1 Sievert/hr (100 rems/hr) at one meter. Five Sieverts is a median lethal dose.[45] This technology again has been demonstrated in laboratories, but a great deal of research is still underway.

The actinides also contaminate the plutonium such that it would not be usable as a weapon without sophisticated chemical separation technologies, which few countries, if any, possess.[46] Some argue that there are many other weapons options which are cheaper and easier to fabricate should an enemy decide to strike.[47]

4.2 Nonproliferation Policies

The United States has historically taken a stand as leaders in global nonproliferation. A pioneer in the creation of the IAEA in 1957, the Nuclear Non-Proliferation Treaty (NPT) in 1970, and the Additional Protocol in 2004, the U.S. has dedicated itself to the non-proliferation regime. Especially important since North Korea has proclaimed itself as a "full fledged nuclear weapons state," weapons proliferation issues are currently at the forefront of United States foreign relations and homeland security policies. The Bush Administration has been fully committed to nonproliferation activities, stating that the greatest threat to the United States is the possibility of a radiological materials attack. The President's nonproliferation budget request of $1.64 billion for FY2006 has marked over a 75 percent increase in nonproliferation funding since 2000.[48]

President Bush has made other strong movements to quell international proliferation. The Administration has strongly advocated the March 2004 Senate approval of the IAEA Additional Protocol, an addition to the NPT that contains further safeguards. The costs of implementing the protocol amount to an initial cost of $20-$30 million and annual incurring costs of $10-15 million.[49] The President has also proposed limiting enrichment and reprocessing capabilities only to NPT compliant states that currently possess enrichment and reprocessing capabilities.

Even with the nation's commitment to nonproliferation, not all nuclear weapons issues remain within the country's grasp. In addition to the problems with North Korea, uncertainties with enrichment programs in Iran and Libya still exist. Pakistani chief nuclear scientist Abdul Qadeer Khan has been responsible for the nuclear weapon "Wal-Mart" in which he sold designs for weapons capabilities to a handful of nations and claims to be responsible for nuclear weapons technology in Iran, North Korea, and Libya.

IAEA Director General Mohammed ElBaradei claims that the NPT has become obsolete since he estimates that 35 to 40 nations have the knowledge to develop nuclear weapons technology. He believes the best approach is to put all fissile material generation facilities under international control. ElBaradei also notes that such multilateral control is not likely since nations such as the U.S. with high assets in nuclear weapons and facilities would not be receptive to significant outside influence.[50]

These policies on the spread of nuclear weapons are important because engagement in reprocessing would mark a significant change in U.S. foreign nuclear policy. This could be seen by some as undermining the nonproliferation regime and also could make the United States appear hypocritical when it tells other nations that they cannot develop reprocessing or enrichment technologies. There is, in fact, current discontent within some non-weapons NPT states that feel that the weapons states (U.S., U.K., China, France, and Russia) monopolize nuclear technology and prevent nuclear technology from becoming economically viable.[51]

4.3 International Cooperation

The United States has stopped engaging in reprocessing in an effort to put an end to proliferation of nuclear weapons. The idea has been that America could show the rest of the world that reprocessing is not necessary to achieve successful nuclear power, and, as a result, other nations would also stop engaging in the process. However, nations such as France and Japan have continued to develop new reprocessing capabilities and technologies. By completely cutting nearly all efforts to reprocessing and research, the U.S. has fallen well behind the leaders in terms of nuclear technology.

To the United State's credit, DOE has formed agreements with other nations for the development of nuclear technology. DOE is finalizing a bilateral agreement with France's Commissariat a l'Energie Atomique (CEA) on new topic areas in the DOE Nuclear Energy Research Initiative (NERI) program. Japan has also worked with the U.S. in the past, and there are opportunities for cooperation in the ATW areas of reprocessing technologies. Some of Russia's nuclear submarine technology could benefit America's transmutation programs, however some of the Russian information may be classified.[52] Through international cooperation, more time and money could be saved, and the nations which will practice reprocessing and transmutation can be in control of the reprocessing situations to repress proliferation. Conversely, however, cooperation between the weapons states could be seen as a strengthening of the oligarchy by the non-weapons states.

4.4 Public Opinion

Even with an impeccable record of safety, fear of anything nuclear still exists within the United States public. Whether this fear is warranted or founded in public ignorance, it remains a major hurdle to nuclear development. Going a step further from the current fuel cycle to reprocessing, investing in a technology that has any potential to create nuclear weapon material will most certainly be played to the public by opponents of nuclear reprocessing. However, if reprocessing does in fact play a role in reducing waste, the public opinion effects must be weighed against the perceived proliferation risks.

5 Recommendations

After comparing the short and long term benefits, costs, and risks of spent fuel reprocessing, the United States should not immediately deploy commercial reprocessing but should begin steps now to make reprocessing viable in the future. Specifically, the following five recommendations should be considered:

1. The United States should not immediately deploy spent nuclear fuel reprocessing technology.
2. America must aggressively fund research and development programs for reprocessing and transmutation technologies *now*.
3. Reprocessing should not be deployed until a proliferation-resistant, economically competitive reprocessing technology is demonstrated.
4. Collaboration should be undertaken in research, development, and deployment with other nations already possessing reprocessing technology for both energy security and national security.
5. The U.S. government should provide incentives for nuclear power.

1. The United States should not immediately deploy spent nuclear fuel reprocessing technology.

At this time, many uncertainties surround the current reprocessing technology. Not practiced or researched since the 1970s, its economic drawbacks and proliferation risks have not yet been surmounted, and the full benefits of the advanced fuel cycle cannot yet be realized. Utilities will not be likely to invest in the technology given the already viable once through cycle, which has the front end uranium resources to sustain reactors for decades.

While U.S. engagement in reprocessing would not likely contribute to the global proliferation issue, political support for PUREX reprocessing technology would not be high given the stigma surrounding plutonium production, and the benefits of the process are debatable. The advanced fuel cycle capabilities should solve this problem but have not been fully demonstrated. Advanced fuel cycles will also make possible the realization of storage reduction benefits, but the transmutation technology is not mature enough for commercialization. Therefore, the United States should wait to deploy reprocessing technology.

2. America must aggressively fund research and development programs for reprocessing and transmutation technologies now.

While the U.S. should not immediately deploy commercialization of reprocessing, immediate research and development of reprocessing and transmutation technologies must take place. These innovations could solve vital pieces of the energy issue since the technology has the potential to provide clean energy with a significant decrease in the amount of nuclear waste. A time may come when coal and gas are not viable economically and when the once through nuclear cycle cannot continue to generate excessive amounts of spent fuel. The United States must be technologically ready to efficiently deploy its new advanced fuel cycle.

Besides domestic benefits, research is also necessary to catch up to the other reprocessing nations. The United States made the decision to stop its reprocessing activities in 1977, believing that it would set the standard and the world would follow suit. This has not happened; France, China, and Japan continue not only the practice of reprocessing, but the research and development of new reprocessing and fast reactor technologies. The U.S. has fallen and continues to fall further behind these nations in the search for manageable energy solutions. The time has come to take the lead in the technology and set the example for a viable energy solution.

3. *Reprocessing should not be deployed until a proliferation-resistant, economically competitive reprocessing technology is demonstrated.*

One of the mistakes made during early nuclear reprocessing technology was the relative immaturity of the technology at the time of deployment. The US reprocessing industry has become nonexistent because of this mistake, and therefore the country must remain cautious to prevent similar errors that could damage the reputation of the technology. Deployment should not take place until a fully realized solution can be found.

4. *Collaboration should be undertaken in research, development, and deployment with other nations already possessing reprocessing technology for both energy security and national security.*

Instead of sitting back and watching other nations practice reprocessing in ways which the U.S. views as unsafe and promoting nuclear weapons, America needs to regain its control of the technology and set an example of reprocessing practice that is proliferation- resistant and secure. In a kind of scientific “forward action,” cooperation in research, development, and deployment of advanced reactor technologies ensures not only that the development may be expedited, but that the United States has an integral involvement in the international industry. This will further protect the nation from proliferation threats.

This country believes in fighting the proliferation of nuclear weapons through not recycling its spent fuel, yet nations such as North Korea debatably have already acquired the technology to both produce and deploy weapons grade plutonium. Therefore, the decision of the United States to end reprocessing has not stunted the growth of nuclear weapons in some areas. As an alternative, important even if the U.S. does not ultimately reprocess, the United States and the IAEA need to deal harshly with nations attempting to develop nuclear technology and those who do not comply with the NPT. However, engaging in proliferation-resistant reprocessing with collaboration will allow the United States to detect those who fail to comply with the treaty.

5. The U.S. government should provide incentives for nuclear power.

Many agree that nuclear power is the future of energy, yet no plants have been ordered since the 1970s due to market forces. This is illustrative of the reason why the government needs to play a larger role in the nuclear energy industry by providing loan guarantees, accelerated depreciation, and tax incentives.

6 Conclusion

The energy issue is truly one of the most vital subjects in today's society. From performing everyday tasks to protecting the nation from nuclear weapon threats, electricity generation affects nearly all facets of life. From the utilities industry, the government, to the general public, all have a long term stake in the decisions that will be made in the near future. Spent nuclear fuel reprocessing can mark a crucial turning point, and the decision whether or not to revive the technology must involve a thorough analysis of what is at stake for all parties.

While immediate reprocessing in the United States should not occur, waiting to begin research and development should not continue in the United States. Long term collaboration with other reprocessing nations must be undertaken, and when the time is right, reprocessing should be deployed. As a result, the U.S. will regain its global presence in all facets of reprocessing technology to give the nation the best possible energy solution while providing lasting security.

References

[1] Rodriguez, C., and Baxter, A., "Transmutation of Nuclear Waste Using Gas-Cooled Reactor Technologies," 2000, Proc. 8th International Conference on Nuclear Engineering, Baltimore, MD.

[2] Ibid.

[3] Ibid.

[4] Johnson, R.S., Testimony, United States, Cong. House, Energy Subcommittee of the Committee on Science, *Nuclear Fuel Reprocessing,* Hearing, 16 June 2005, 109th Cong., 1st Sess., http://www.house.gov/science/hearings/energy05/june15/index.htm.

[5] United States, Department of Energy Nuclear Energy Research Advisory Committee and the Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems,* Dec. 2002, http://gif.inel.gov/roadmap/pdfs/gen_iv_roadmap.pdf.

[6] *Nuclear Non-Proliferation Policy,* Presidential Directive/NSC-8, 24 March 1977.

[7] Nuclear Energy Study Group, *Nuclear Power and Proliferation Resistance: Securing Benefits, Limiting Risk,* American Physical Society, May 2005.

[8] von Hippel, Frank N., "Plutonium and Reprocessing of Spent Nuclear Fuel," *Science,* Volume 293, Number 5539, 28 Sept. 2001, pp 2397-2398.

[9] United States, National Energy Policy Development Group, *National Energy Policy,* May 2001.

[10] Finck, Dr. P., Testimony, United States, Cong. House, Energy Subcommittee of the Committee on Science, *Nuclear Fuel Reprocessing,* Hearing, 16 June 2005, 109th Cong., 1st Sess., http://www.house.gov/science/hearings/energy05/june15/index.htm.

[11] Golan, P. M., Personal Interview, 18 July 2005.

[12] *Civilian Nuclear Waste Disposal,* Congressional Research Service Report, Order Code IB92059, 8 March 2005.

[13] Finck, Dr. P.

[14] United States, Department of Energy, *A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology,* DOE/RW-0519, Oct. 1999, http://www.pnl.gov/atw/ReportToCongress/ATWreport.pdf.

[15] *A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology.*
[16] Johnson, R. S.

[17] *A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology.*

[18] Uranium Information Centre, *Nuclear Electricity, Seventh Edition,* 2003, Melbourne, http://www.uic.com.au/ne3.htm.

[19] Finucane, J., Telephone Interview, 6 July 2005.

[20] Nuclear Energy Institute, *Nuclear Output,* 2005, http://www.nei.org/documents/Nuclear_Output_1973_2004.pdf.

[21] University of Chicago, *The Economic Future of Nuclear Power,* Conducted for the U.S. DOE Argonne National Laboratory, August 2004.

[22] Nuclear Energy Institute, *US Electricity Production Costs,* 2005, http://www.nei.org/documents/Electricity_Production_Costs_1995_2004.pdf.

[23] University of Chicago.

[24] University of Chicago.

[25] Deutsch, J., et al, *The Future of Nuclear Power: An Interdisciplinary MIT Study,* MIT, 2003.

[26] University of Chicago.

[27] Abeyta, H., Personal Interview, 29 June 2005.

[28] *US Electricity Production Costs.*

[29] University of Chicago.

[30] Deutsch et al.

[31] Energy Information Administration, *Natural Gas Prices,* June 2005, http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm.

[32] University of Chicago.

[33] Finucane.

[34] Bunn, M., Testimony, Testimony, United States, Cong. House, Energy Subcommittee of the Committee on Science, *Nuclear Fuel Reprocessing,* Hearing, 16 June 2005, 109th Cong., 1st Sess., http://www.house.gov/science/hearings/energy05/june15/index.htm.

[35] Bunn, Matthew, et al, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*, Project on Managing the Atom, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, December 2003, http://bcsia.ksg.harvard.edu/BCSIA_content/documents/repro-report.pdf.

[36] Jones, Dr. D. W., United States, Cong. House, Energy Subcommittee of the Committee on Science, *Economic Aspects of Nuclear Fuel Reprocessing,* Hearing, 12 July 2005, 109th Cong., 1st Sess., http://www.house.gov/science/hearings/energy05/july%2012/index.htm.

[37] *A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology.*

[38] *Civilian Nuclear Waste Disposal.*

[39] University of Chicago.

[40] *Nuclear Energy Policy,* Congressional Research Service Report, Order Code IB88090, 14 June 2005.

[41] Nuclear Energy Study Group.

[42] von Hippel.

[43] Lyons, P., Personal Interview, 20 July 2005.

[44] *North Korea's Nuclear Weapons: How Soon an Arsenal?,* Congressional Research Service Report, Order Code RS21391, 12 May 2005.

[45] Kang, J., and von Hippel, F., *The limited proliferation-resistance benefits of the nuclear fuel cycles being researched by the Department of Energy's Advanced Fuel Cycle Initiative*, 8 June 2005, http://www.armscontrolcenter.org/archives/001711.php.

[46] Abeyta, H.

[47] Kok, K., Email Correspondence, 7 July 2005.

[48] *Nuclear Nonproliferation Issues,* Congressional Research Service Report, Order Code IB10091, 3 June 2005.

[49] Reynolds, A. W., Personal Interview, 24 June 2005.

[50] Reynolds, A. W., *Dr. No, The Ubiquitous Centrifuge, and the Islamic Bomb Wal-Mart,* U.S. Department of State, 11 May 2004.

[51] *Nuclear Nonproliferation Issues.*

[52] *A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology.*