Nuclear Fuel Reprocessing

Technological, Social, and Economic Problems

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Abstract

This paper analyzes the technological, economic and social feasibility of reprocessing spent nuclear fuel in the United States. In nuclear reprocessing, spent fuel is refined to decrease the amount of waste generated in a nuclear reaction and to extract usable materials for fuel in future reactions. Reprocessing technology is analyzed as well as its economic costs, environmental impacts, and implications on domestic policy. We find that while reprocessing technology is very promising, it is not economically feasible in the foreseeable future when compared to direct disposal. Besides economic barriers, new policies that focus on standards and procedures and accommodate public or private businesses in gaining jurisdiction for reprocessing facilities must be considered before nuclear reprocessing can be done at the commercial level.

I. Technology

Nuclear power has considerable advantages that help achieve energy goals in the United States. Since an increased use of nuclear power would decrease levels of carbon dioxide (CO_2) emissions, it would not contribute to global warming (Pacala). It has caused fewer deaths than coal, natural gas, or hydroelectric power (Berry). As opposed to other energy sources, it produces more electricity than wind or solar power (Burgess). In 2011, nuclear power accounted for 14% of the world's electricity, making it the third largest source after coal and natural gas. In 2008, 76.8% of France's electricity was generated by its 59 reactors, showing that a significant amount of one country's energy can successfully come from nuclear power.

Nuclear power is an effective energy source because a small amount of uranium can release a large amount of energy. In order to be used as fuel in a nuclear reactor, uranium must first be enriched. Natural uranium contains 99.3% of ^{238}U, which will not react in a nuclear reaction, and 0.7% ^{235}U, which will. In order to be used, ^{235}U must be enriched to 2-5%. Nuclear energy is released through splitting atomic nuclei, called fission. In fission, the nucleus of a heavy atom absorbs a neutron and splits, releasing energy in the form of heat, gamma radiation, daughter nuclei and more neutrons. This can be seen in the equation

$$^{235}U + {}^{1}n \rightarrow {}^{92}Kr + {}^{141}Ba + 3n + \gamma$$

where n is a neutron, Kr is the element krypton, Ba is the element barium, and γ is gamma radiation. If completely fissioned, one kilogram of ^{235}U would release 8×10^{13} Joules of energy. This is comparable to the amount of thermal energy in 2,700 tonnes of coal or 1,900 tonnes of oil (Schnitzer 12-14).

Nuclear reactors work by converting the heat released in fission to electrical energy in a process similar to the generation of electricity from gas or coal. The heat released in the reaction is used to convert water into steam, which is used to power a turbine-generator system. The steam is condensed into water and later reused in the cycle. Uranium is enriched and reacted to produce uranium (IV) oxide (UO_2), which is molded into pellets. The pellets are put into metal tubes called fuel elements, which are bundled together into fuel assemblies that make up the reactor's core; there can be 193 fuel assemblies, or over 36,000 fuel elements. To help control the reaction, coolant flows around the fuel assemblies, and control rods, made of neutron absorbent material, absorb the neutrons to avoid an uncontrollable chain reaction (Schnitzer 14-15).

Nuclear fuel is burned until it has been used to a point where it is no longer economically viable ("Safety and Security of Commercial Spent Nuclear Fuel Storage"). The nuclear fuel is called spent fuel and contains 95% ^{238}U, 1% ^{235}U, 1% plutonium, 0.1% minor actinides, and 3% stable fission products. It is classified as high-level waste (HLW) because the unstable fission products in it are highly radioactive and generate dangerous levels of heat and radiation; they account for 95% of the total radioactivity in electricity generation (Silverio 282-283). Spent nuclear fuel is cooled for three to five years in a spent fuel pool, which has thick steel and concrete walls surrounded with water to prevent radiation from escaping. After this time, the heat generated by the majority of the radiation waste is reduced by a factor of 100 ("Safety").

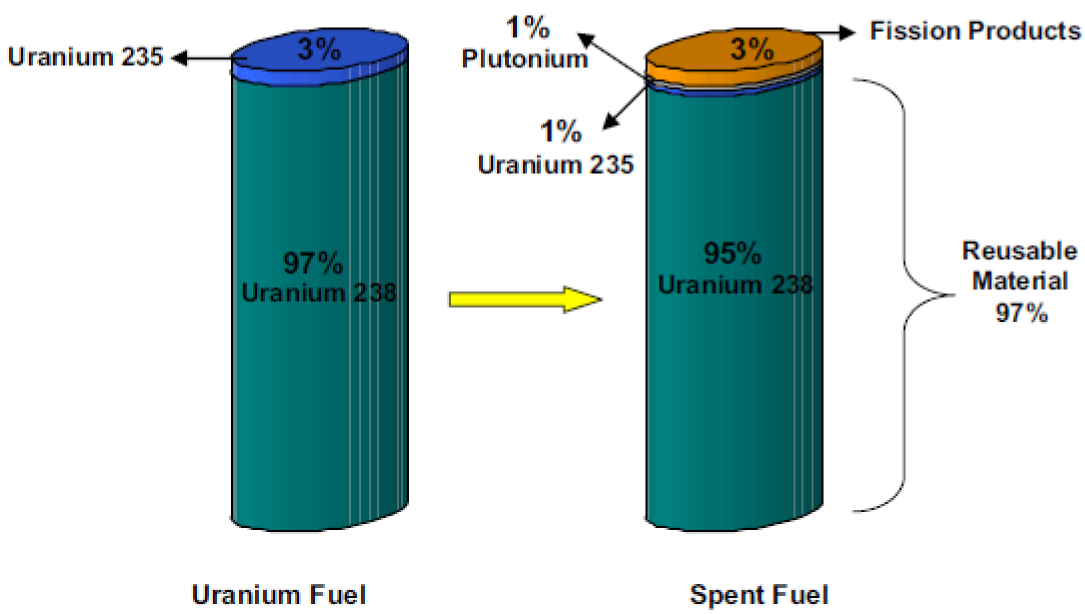


Figure 1: The composition of nuclear fuel and spent nuclear fuel. (Silverio 283)

After nuclear waste has cooled in the spent fuel pool, it can be disposed of or reprocessed. As stated above, spent fuel is made up of 96% uranium, which could be extracted and used again. In addition to uranium, plutonium and other transuranics can be reused after reprocessing as well (Castano 121). Reprocessing also reduces long-term toxicity of the waste, decreases long-term heat production (making whatever is not reprocessed easier to store), and reduces the amount of HLW (Silverio 283).

Reprocessing was first done in the 1940s although its initial purpose was to recover plutonium for nuclear weapons. This clearly shows how nuclear proliferation is a major obstacle in reprocessing. Around the world, China, France, India, Russia, and the United Kingdom reprocess spent fuel, while Canada, Finland, and Sweden keep spent fuel for possible future reprocessing. There is no civil reprocessing plant currently in operation in the United States, but three have been built in the past. All three—West Valley in New York, Morris in Illinois, and Barnwell in South Carolina—were deemed inoperable in the early to mid 1970s; Barnwell specifically due to government policy banning reprocessing due to proliferation (Silverio 283).

While several methods of reprocessing exist, many have been discontinued due to safety and practicality. Bismuth phosphate was the first method developed for reprocessing. Nuclear fuel was dissolved in nitric acid, and plutonium(IV) oxide (PuO_2) was precipitated from solution. While it had a recovery rate of over 95%, it did not recover uranium and it left a large amount of radioactive waste. While the Butex process recovered uranium, it used dibutyl carbitol as a solvent in order to extract the uranium(IV) and plutonium(IV) from nitric acid (Sood and Patil, 548) A reaction between nitric acid and dibutyl carbitol caused an explosion in Windscale, UK, leading to its retirement from reprocessing (Castano 122).

PUREX (Plutonium Uranium Extraction)

The most commonly used process in the world is Purex. It was invented in 1947 in the United States and first used at Oak Ridge National Laboratory. It operates on the basis of an oxidation-reduction reaction and uses tributyl phosphate (TPB) as solvent.

The spent fuel rods are mixed with hot nitric acid to dissolve them. Depending on regulations that vary by region, radiokrypton, xenon, carbon-14, tritium, and other products are either released or collected. The aqueous solution is pretreated, undergoing pH adjustment to about 2.5, cooling, clarification, and valance adjustment of plutonium ions by nitrogen peroxide (N_2O_4). Using a solution of 30% TPB by volume in a hydrocarbon diluent, uranium and plutonium are separated by extraction; this removes 99% of the fission products. Plutonium, but not uranium, is reduced from Pu(IV) to Pu(III) by a reducing agent such as ferrous sulfamate. The separated plutonium and uranium are precipitated and purified; plutonium is converted to plutonium(IV) oxide (PuO_2) and uranium is converted to uranium trioxide (UO_3). The nitric acid vapors are condensed and reused, and the remaining HLW is solidified to be disposed of.

Purex is an improvement over previous reprocessing methods due to its lowered cost, less volatile and flammable solvent, and reduced waste due to the recovery of nitric acid. However, because it recovers plutonium, is raises the question about the risk of nuclear proliferation (Castano 122-123). Considering how early reprocessing efforts were concerned with extracting weapons-grade plutonium to create nuclear bombs, any country that would reprocess spent nuclear fuel—either its own or another country's—could easily obtain this plutonium for militaristic use. Currently, this method is being used by China, France, India, Japan, Russia, and the United Kingdom (Silverio 283).

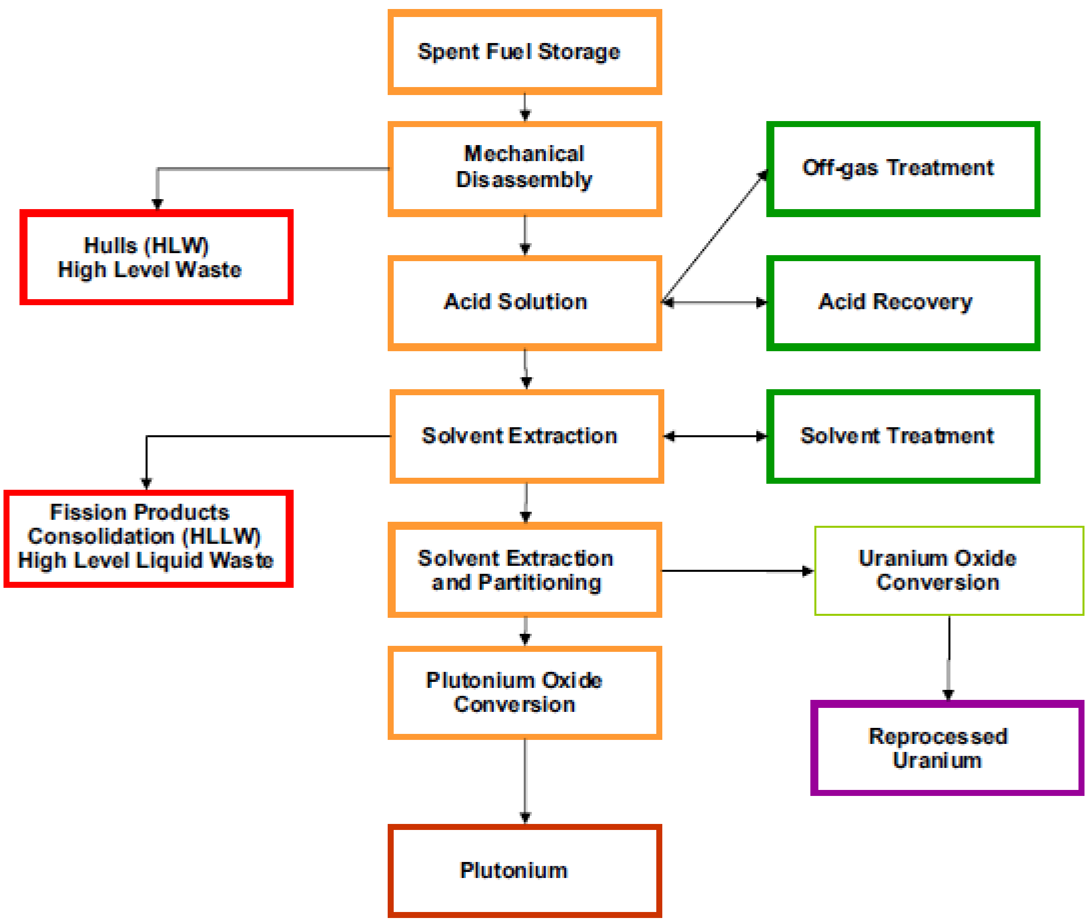


Figure 2: The steps in the Purex reprocessing process. (Silverio 284)

PUREX Derivatives and Modifications

UREX (Uranium Extraction)

To address concerns about nuclear proliferation, Urex has been developed as a modification of Purex. It prevents plutonium from being extracted independently by using acetohydroxamic acid as the solvent. This forms plutonium and neptunium complexes, which prevents plutonium recovery. Urex recovers 99.9%+ of uranium and rejects 99.9%+ of transuranic waste. Additionally, Urex produces less waste at the end of its cycle than Purex, and the waste that it does produce is low-level waste (LLW) (Castano 123).

TRUEX (Transuranic Extraction)

Another modification of Purex, Truex extracts transuranics from nuclear waste and is noted for its effectiveness in extracting actinides. It uses CMPO (carbamoyl methyl phosphine oxide) with TPB to form the solvent (Castano 123).

SANEX (Selective Actinide Extraction)

Sanex serves the interest of using actinides for nuclear fuel. It separates actinides from lanthanides for this purpose. Sanex is still under development, and various solvents are being studied, such as SANEX-N (bis-traizinyl-pyridines (BTPs) and SANEX-S (a misture of Cyanex-3017 and 2,2-bipyridyl) (Castano 123).

DIAMEX (Diamide Extraction)

The goal of Diamex is to reduce the organic waste generated as carbon, hydrogen, nitrogen, and oxygen by using the solvent malondiamide. This waste reduction prevents the creation of acidic gases, and thus minimizes the chances of acid rain. Diamex is not yet implemented, but will most likely be used in Europe (Castano 123-125).

Pyrochemical Process

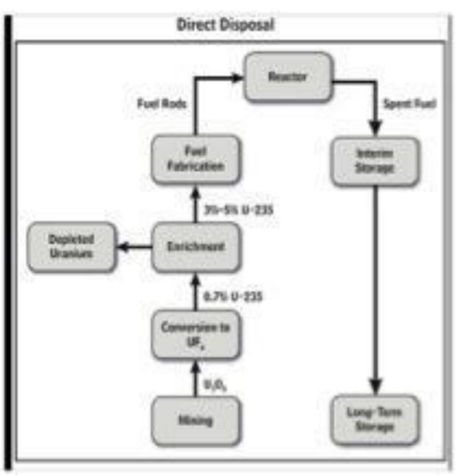
The previous methods mentioned were aqueous; they depended on a solvent to extract the desired chemicals. Pyro-chemical processing, or pyroprocessing, is a physical recovery method that relies on metals and salts being at high temperatures. It is based on melt-refining, volatilization, gas-solid reactions, fractional precipitation, vacuum distillation, electro-deposition, electro-refining, and electro-winning. In this process, spent fuel is cut into small pieces, mounted on an anode dissolution bracket, and dissolved in a molten salt bath (500-800 ºC). A cathode is inserted (typically steel with cadmium chloride ($CdCl_2$)), and most of the actinides and fission products are transferred to the electrolyte as chlorides. Due to the current between the anode and the cathode, the uranium is oxidized and then reduced at the cathode as uranium metal.

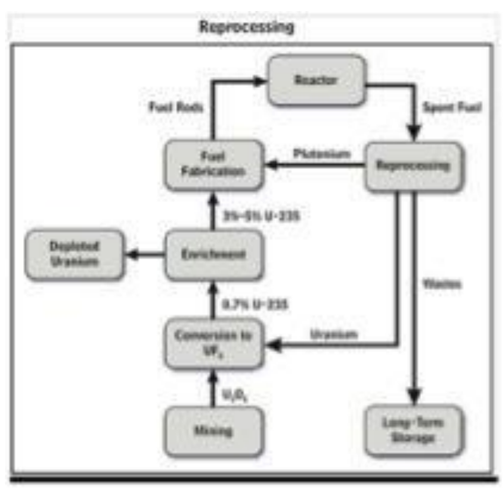
After uranium extraction, the steel cathode is removed and a liquid cadmium cathode is inserted. With the cadmium cathode in place, uranium, plutonium, and some lanthanides deposit in the cadmium while reactive fission products remain in the salt electrolyte. Less-reactive fission products do not dissolve and remain in the anode bracket.

The advantages of pyroprocessing include shorter cooling periods, shorter turnaround times for fuel recovery, the ability to recover actinides (uranium, plutonium, etc.) with one process, fuel-flexibility, and the minimization of generated transuranic wastes. The specific advantages relative to aqueous reprocessing methods are that it does not use a solvent that could cause a criticality accident (i.e., an uncontrolled nuclear chain reaction) and that it costs less. However, pyroprocessing does not separate spent fuel, as well as aqueous methods, which poses a problem should more and more impure fuel be used in reactors (Castano 125).

II. Economic Analysis

When determining the economic feasibility of nuclear reprocessing we must perform a cost-benefit analysis to determine whether reprocessing is an economically better alternative to direct disposal. Reprocessing spent fuel adds several steps to the nuclear fuel life cycle, all of which incur costs. These include the upfront costs for constructing reprocessing facilities as well as operating costs to keep the facilities functioning. Further,





when comparing reprocessing and direct disposal, we must consider the future costs of both uranium and storage. Through reprocessing, nuclear power plants use less raw uranium because reprocessed uranium from the spent fuel is sent back to the cell. As a result, less storage is needed for waste and less raw uranium needs to be mined. We also must consider less quantifiable costs, such as the proliferation of nuclear weapons, environmental concerns, and the health risk of incorrect disposal. As becomes obvious when delving into the costs and benefits, coming to a definitive dollar amount for reprocessing is difficult due to the highly subjective, future-dependent factors involved in the process. In our analysis, we will attempt to describe these costs and the economic difference between reprocessing and direct disposal.

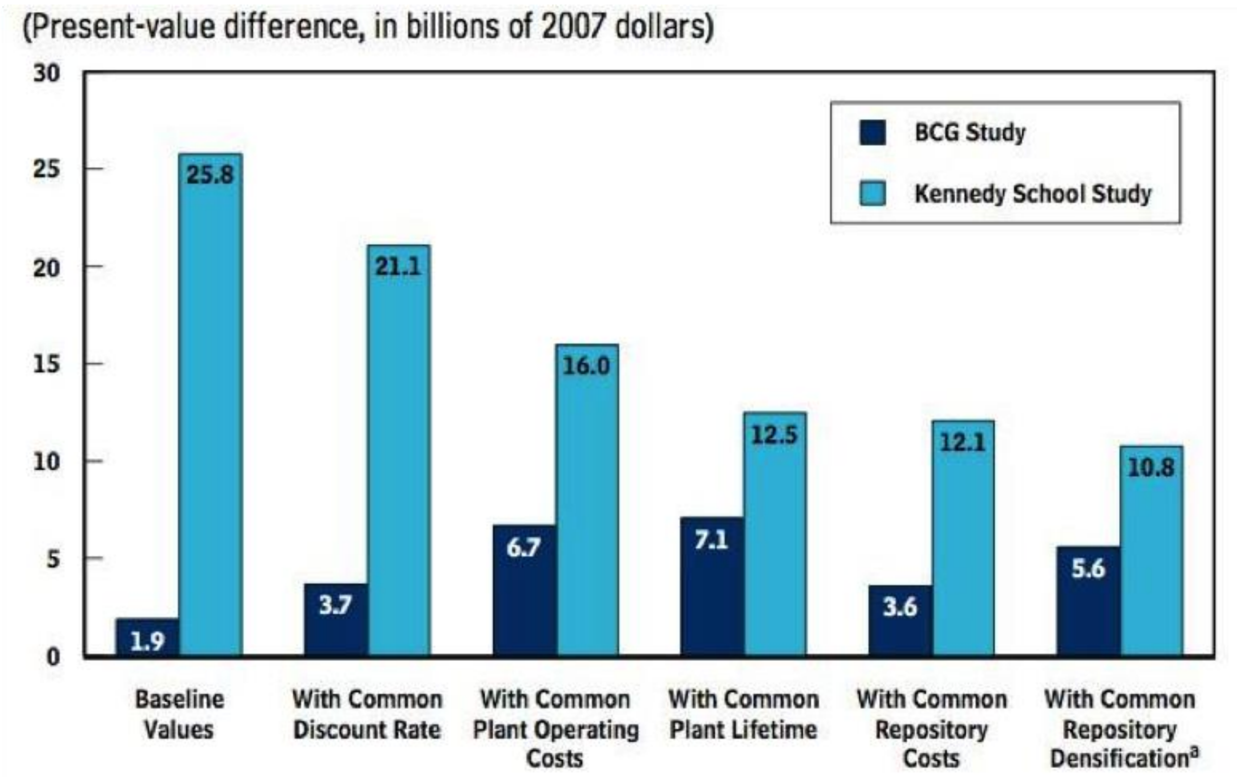
The consensus, while considering the current spot price of uranium, as well as projected future prices, is that it is more expensive to reprocess fuel than it is to enrich uranium. However, uranium prices routinely fluctuate and have shown a tendency to spike quickly due to various factors. Worldwide demand for uranium is expected to rise in the foreseeable future as China, India, South Korea, and Russia have plans to build new plants and as existing plants begin to operate at a higher capacity. Several research analysts are predicting a future rise in prices as supply shortages take place—using high demand estimates, planned mining capacity will run-out in 2028 (Mack, 2012) (Hanly et al., 2012). However, some believe this demand will be dampened because of increased efficiencies of the plants and processes ("Uranium Markets", 2013). Due to a plethora of variables, namely the volatility of the price of uranium that contributes to these estimates, it is difficult to predict a window of time for when reprocessing will be cheaper than enriching new uranium. Instead, we will work to quantify how much more expensive it is to reprocess than to use the direct disposal method.

Another major factor is the price and availability of storage. There are two types of facilities necessary when dealing with nuclear waste: storage facilities and disposal facilities. The storage facilities are where the spent fuel rods are taken after they are no longer useful in the reactors. The spent rods are placed in a pool of boric acid meant to both lower rod temperatures and absorb some of the radioactivity. Because of space shortage in these temporary facilities, pools are often near full-capacity, posing a threat for a possible nuclear reaction. The disposal facilities are where the spent fuel rods are taken after temporary storage and permanently deposited. There have been several discussions on alternative options for permanent storage, but currently the most realistic option is burying the waste in the ground (Orszag, 2007) (IAEA, 2003). There are several risks when considering these types of disposal sites. For example, if the waste is buried near a fault line or water source, the radioactivity may spread. For these and many other reasons, currently there is no operational long-term disposal facility in the world. However, as space in the temporary facilities becomes scarce, many political battles are being fought over what geographic areas can be used as disposal sites. In the United States, the most hotly contested issue of this kind is over the Yucca Mountain Project. As is evident, these storage areas are tough to come by; hence, a main benefit of reprocessing is that less storage is necessary ("The Bane of Nuclear Energy: Nuclear Waste, n.d.).

In 2007, the Congressional Budget Office reviewed many studies that compared the economic efficiency of reprocessing versus direct disposal. The CBO found two to be most precise—one by Boston Consulting Group and the other by Harvard University's Kennedy School of Government. The CBO is thorough in its analysis as it includes all of the costs associated with reprocessing; these include facility development, operating costs, uranium recovery costs, transportation, and long-term disposal of wastes. The study only reports numbers for Thermal Reactors rather than Fast-Neutron Reactors (Orszag, 2007). The reason they chose Thermal Reactors was because no commercial fast-neutron reactors exist in the United States, nor are there plans to build any. The Kennedy School study does address the fast-neutron reactor and claims that it would add on substantial cost to reprocessing because of the large capital expenditures that would be required to build them. In conclusion, the BCG study estimated that reprocessing would cost about $30 more per kilogram of spent fuel, while the Kennedy School study found that reprocessing would cost $700 more per kilogram. When these kilogram values are taken into consideration with the amount of spent fuel that is expected from the lifetime of existing plants, the studies show that reprocessing would cost approximately $2 billion (BCG) to $26 billion (Kennedy) (Bunn et al., 2003).

In the midst of the disparity of estimates between the two most viable studies, the CBO, through its own analyses and a common set of assumptions, ultimately concluded that the present value cost of reprocessing exceeds that of direct disposal by between $5 billion to $11 billion, depending on variability and certain assumptions. For this figure, the CBO employed a 3.5% discount rate, or interest rate used to estimate future costs, which fell between the rates used by the BCG and the Kennedy School. They also assumed that plant operating costs are 6% of plant capital costs, which is a standard number used by the Organization for Economic Co-operation and Development (OECD). The CBO also expects a nuclear plant's life expectancy to be around 40 years, which is the average of the BCG and Kennedy School studies. With respect to storage, repository costs of $1,036 per kilogram of heavy metal stored in the repository are used. Further, a densification factor, which speaks to repository storage capacity of 2.5, was applied to help model scarcity of storage (Orszag, 2007).

As is true with any study that makes vast assumptions, such as any study dealing with reprocessing, it is important to show how sensitive the bottom lines are to small changes in variable assumptions. For example, if the discount rate of 3.5% increased or decreased by 1%, the present value costs are subject to change $3 billion to $4 billion. The same is true for operating costs; however, operating costs would have to be 50% less in order for the reprocessing cost to equal that of direct disposal. As storage becomes more scarce, it seems fair to assume those costs may rise, which would affect estimates. While rising costs of long-term storage narrow the difference between the cost of reprocessing and direct disposal, these costs would have to unrealistically skyrocket in order to make reprocessing less expensive than direct disposal in the foreseeable future (Kenul et al., 2010).



The most subjective assumption when determining the present value of costs is the discount rate. When determining the rate for nuclear reprocessing, the average cost of capital for nuclear energy plant owners is used. This discount rate has a tendency to vary based on the regulatory nature of the industry. In some countries, due to government regulations, it is more difficult to open nuclear plants. These barriers result in a lower discount rate (Rothwell, n.d.). In an open market where competition is robust, a higher discount rate is given. This makes sense because in a more competitive environment, it will be more difficult for the project to generate revenue.

Some studies use a smaller discount rate because they assume this is a government sponsored project where the government is able to use the "social discount rate" or "risk-free rate," which is much smaller. In this case, the government would be able to raise capital for the project roughly at a rate of the 10-year treasury, which is currently 2.86%. However, if this were a private project, it would cost a risk-premium in order for investors to be willing to provide capital.

For the sake of our own calculation, we consider revenue constant as we compare the cost structure of a reprocessing facility versus a direct disposal plant. This makes intuitive sense as the cost of nuclear energy remains constant and we assume both plants produce as much energy. Where the difference in our calculation comes is that, through reprocessing, there is an upfront increase in capital, which is used to build the reprocessing facility. The reprocessing facility must include an extra step (refer to diagram above) in the nuclear cycle where spent fuel is converted to plutonium and enters the fuel fabrication cycle and reprocessed uranium is converted to UF_6 (Orszag, 2007). This extra step also requires increased operating costs. These operating costs are estimated to be 6% per year of the up-front capital cost. We will compare these increased costs with the costs of direct disposal, where there is an increased cost of storage and increased cost of mining uranium relative to the reprocessing method.

Through our research, we were able to form our own estimates and calculate the difference in the net present value of costs between nuclear reprocessing and direct disposal. We calculate this with an upfront cost of $20 billion for a reprocessing facility. We assume a direct disposal facility would be able to be built for 75% of the upfront cost of a reprocessing one. The annual operating cost for the reprocessing facility is estimated to be 6% while that of the direct disposal is 4% of the initial investment, $1.2 billion and $0.6 billion, respectively. Estimating the storage costs to be 10% of the annual operating costs, we get $0.12 billion and $0.06 billion. Estimating that reprocessing will result in 30% less uranium needs than disposal, we get a total of $18.6 million spent on uranium annually for reprocessing and $26 million spent in the direct disposal method ("The Economics of Nuclear Power", 2013). We use a plant's expected operating life to be 40 years, as well as a discount rate on future income streams of 3%, and calculate the annual interest payments. Given these estimates, we conclude that a reprocessing facility would have a present value cost of $11.381 billion more than a direct disposal facility.

Further, we see through the sensitivity analysis that small changes can have large impacts on our results. This is why so many different studies come to vastly different conclusions. For example, there were studies that had the discount rate at 7.5%. With this value, $12 billion to $16 billion would be added to the present value cost (Orszag, 2007). With large swings such as this, studies can be greatly biased in their assumptions to reach their predetermined conclusions. Another factor affecting variability is currency exchange rates. As the nuclear industry is effectively global, we are subject to various exchange rates, thus converting to US dollars today may be very different than next year's exchange rate. In order to give an idea of this variability, a list of various studies assumptions is in the table below (Kenul et al., 2010):

		De Roo (2009)	Shropshire (2009)	EPRI (2007)	BCG (2006)	Bunn (2003)
Front-end Fuel Costs						
Natural Uranium	$/kgHM	80	60	260	80	50
Depleted Uranium	$/kgHM	10	10	260		6
Conversion of Natural Uranium	$/kgHM	10	10	15	12	6
Enrichment of Natural Uranium	$/SWU	160	105	140	110	100
Fabrication of UOX from Natural U	$/kgHM	250	240	250	200	250
Conversion of Reprocessed Uranium		200%				250%
Enrichment of Reprocessed Uranium		10%				5%
Fabrication of UOX from Reprocessed Uranium		7%			7%	4%
Fabrication of MOX	$/kgHM	2,400	1,950	1,250	900	1,500
Fabrication of FR fuel	$/kgHM	2,400	2,100	2,600		1,500
Reactor Costs						
LWR Capital	$/kWe	4,000	2,300	2,500		1,500
LWR Capacity		85%	90%	90%		85%
FR Capital premium		20%	26%	20%		13%
FR O&M premium		20%	5%	20%		
FR Capacity		85%	82%	85%		85%
Reprocessing Cost						
UOX, PUREX	$/kgHM	1,600	2,020	1,000	600	1,000
UOX, UREX+, or TRUEX	$/kgHM	1,600	1,700	1,000		
FR fuel, pyroprocessing	$/kgHM	3,200	2,900	2,750		1,000
Waste Costs						
Interim Storage of UOX	$/kgiHM	200	120	150	150	200
Interim Storage of MOX	$/kgiHM	200	120	300		200
Disposal of Spent UOX	$/kgiHM	463	1,000		375	400
Disposal of Spent MOX	$/kgiHM	3,086			2,295	400
Disposal of HLW from UOX (PUREX)	$/kgiHM	185			96	200
Disposal of HLW from UOX (TRUEX)	$/kgiHM	185	400			
Disposal of HLW from FR	$/kgiHM	281				200
Discount Rate		7.0%	7.5%		3%	5%

Despite the countless estimates and analyses to test the feasibility for reprocessing, there still exist many unquantifiable variables that could affect the economics of the issue. One aspect to consider is to which group do these projects belong. For example, if nuclear reprocessing is conducted by a private company, it will be tremendously more expensive than a government project because of the added taxes and borrowing rates. In this case, would the government give subsidies to a private company? Would the government allow for prices of energy to increase because of the added cost of reprocessing? Another thing to consider is while it is clear that reprocessing would be beneficial in the long-term through less dependence to uranium price fluctuations, we also face an increased risk of nuclear proliferation because of the plutonium byproduct of reprocessing. With this stated risk, there would undoubtedly be increased costs in security relating to reprocessing facilities. Government subsidies and security are just two of countless complications of reaching a final conclusion on the feasibility of reprocessing. We can, however, conclude that reprocessing is more expensive than the direct disposal method and that this will be the case until uranium prices reach a certain threshold value. Implicitly, we feel that the consensus is that uranium prices will not skyrocket as literature relating to the economics of reprocessing seems dormant in recent years. This is supported by the fact that most literature on the issue was published when uranium prices spiked. We shall see if an inevitable rise in uranium price will reignite the discussion.

III. Environmental Considerations

The problem of nuclear waste has been dealt with in various ways in the past. Until 1993, it was globally acceptable to put nuclear waste in the ocean. While some of this waste was put in metal drums made with concrete and bitumen matrix, some solid and liquid nuclear waste was directly dumped into the water. Nuclear waste introduces radionuclides into the ocean, which not only affect the organisms in the water, but also those who consume or come into contact with this marine life. Nuclear waste containers often wear away, releasing their contents after they have been imbedded deep into the ocean. Many of these chemicals have been proven to be carcinogenic to humans. (Calmet 1989) Several countries that had once used this method include: Belgium, France, Germany, Italy, Netherlands, Sweden, Switzerland, the United Kingdom, Japan, South Korea, and the

United States. (Radioactive Waste Management 2013) Due to the environmental and health hazards of ocean disposal, this method of nuclear waste disposal is now banned by the London Convention Agreement (1972), Basel Convention, and MARPOL 73/78.

Alternatively, nuclear waste has also been stored on land through near-surface disposal and deep geological disposal. Near-surface disposal may be either on or below the surface of the earth: above-ground disposal involves storing the waste in vaults that are encased by an impermeable membrane and topsoil. Below surface disposal stores the waste in caverns. (RWM 2013) Near-surface disposal is currently being used by: the United Kingdom, Spain, France, Japan, the United States, Sweden, and Finland. (RWM 2013) The problem with this method is similar to ocean disposal, as none of these containers are entirely indestructible or weatherproof and leaks from these containers would contaminate the soil around the waste site.

Deep geological disposal avoids the danger of nuclear waste permeating into the soil by inserting the waste into geological earth that provides rock, salt, and clay barriers between the waste and the rest of the soil. In order to use this method, tunnels or caverns must be mined and filled with the waste that may be further encompassed by cement or bentonite as a buffer. (RWM 2013) Yucca Mountain in the US is one such considered site for nuclear waste disposal, though recent activity by the Obama administration has halted efforts to create a repository program there. (Northey 2011) While burrowing nuclear waste deep under the Earth's crust puts the problem out of sight, this method also poses several issues. The act of mining tunnels to put the waste may disrupt neighboring environments. Furthermore, while soil may not be affected, an earthquake might upset the disposal site and nuclear waste could enter the water table. (Ali 2011).

Several other options for nuclear waste disposal have been researched. Some of these options are extensions of existing methods, such as aboveground storage and boreholes, which work upon near-surface disposal and deep geological disposal. Other methods include space disposal (ejecting the waste into outer space), ice sheets (inserting heat-generating waste in containers in ice sheets), and direct injection (injecting liquid waste into a layer of rock). (RWM 2013) These alternatives themselves also pose some risks. In the event of a disaster during transportation—considering the NASA Challenger disaster in 1986—nuclear waste could spread radiation into the atmosphere and environment before the waste reaches its intended destination.

A case study of the Western New York Nuclear Service Center at West Valley ("West Valley") illustrates the problems of current nuclear waste processing and the possible consequences of keeping waste intact and standing. The pipes used in the Main Process Building of the West Valley reprocessing center operations were leaky, spreading waste into the groundwater plume underneath the facility. The plume feeds into surface water that flows into streams that eventually empty into Lake Erie. (Thier 2013) This illustrates the risk of contamination that affects areas indirectly related to the target zone. The nuclear waste not only directly ruins the water sources close to West Valley, but also risks altering the acidity of a whole lake miles away. Furthermore, the liquid waste being held by the center was being stored in underground tanks. These underground tanks have been used past their intended lifespan and are located in permeable soils with a high water table. (Thier 2013) The risk of the tanks breaking or deforming due to age is high, consequentially raising the chance that the liquid waste may enter the soil easily and contaminate the water table. Unlike Yucca Mountain, forests and fields surround West Valley; the introduction of nuclear waste and radiation into the surrounding environment would undoubtedly alter the ecosystem and endanger any species in the area.

Nuclear reprocessing, therefore, stands as the best method to deal with the waste from nuclear reactions. The previous methods suggested assume a long-standing stagnant collection of nuclear waste, which poses the obvious problem of accidentally contaminating surrounding ecosystems. Furthermore, most of these previous methods cannot usually be performed at the site of the nuclear power plant, inevitably raising the risk of accidents that could occur while transporting the waste to processing plants. As previously stated, nuclear waste contains uranium that could be used to create more nuclear energy—it logically follows that the reprocessing equipment would be on or near the actual nuclear power plant itself in order to immediately use the products of nuclear reprocessing. Therefore, the danger of exposing human beings and surrounding environments to nuclear waste and radiation decreases if nuclear reprocessing is done at or near the site. Because some of the nuclear waste is reused, the amount of standing nuclear waste at a time will be much less.

Besides dealing with nuclear waste, nuclear reprocessing reduces the amount of uranium mining required for nuclear energy. Uranium mining often uses open pit and underground mining (Uranium Mining Overview 2013), both of which take up massive amounts of land, water, and resources in order to do so. Open pit mining, besides taking up land out of an ecosystem, may expose radioactive elements, asbestos-like minerals, and metallic dust when rocks are crushed. Underground mining risks leaking minerals into groundwater, contaminating it. Furthermore, underground mining also increases sedimentation in nearby rivers and removes topsoil and seed banks; deforestation becomes an issue when removing the vegetation above the mine to prevent cave-ins. (Environmental Risks of Mining 2013) These impacts on the environment introduce hazardous material that can wipe out species living in these areas and reduce the amount of safe drinking water. By using reprocessed uranium, the need for mining decreases. According to the following graph, the use of reprocessed uranium and mixed oxide fuel reduces the amount of newly mined uranium significantly.

Estimated Savings in Natural Uranium Requirements due to Recycled U & Pu (tU)

	Use of enriched RepU	Use of Pu in MOX	Total Unat replaced
2013	1850	1220	3070
2015	1850	1260	3110
2020	1880	2140	4020
2025	1560	3200	4760
2030	1270	3650	4920

IV. U.S. Public Policy Implications
History of Nuclear Reprocessing in the United States

Since the United States began developing its nuclear program in the 1940s, nuclear reprocessing has been received in a variety of manners. In the 1940s, the practice of nuclear reprocessing was deemed necessary due to the perception that uranium resources were limited. The Cold War era, however, has created widespread fears of nuclear proliferation that have severely diminished the public and political interest in domestic nuclear reprocessing and the use of nuclear energy in general.

In 1976, President Gerald Ford issued a policy statement which declared: "the reprocessing and recycling of plutonium should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation... that the United States should no longer regard reprocessing of used nuclear fuel to produce plutonium as a necessary and inevitable step in the nuclear fuel cycle, and that we should pursue reprocessing and recycling in the future only if they are found to be consistent with our international objectives" (American Presidency Project Archives). Thus President Ford indefinitely deferred the reprocessing of spent nuclear reactor fuel until an approach could be developed which would allow nuclear power to continue without adding to the risk of nuclear proliferation (Rossin).

Following the election of President Jimmy Carter in 1976 over his incumbent opponent President Ford, President Carter continued the prohibition of commercial nuclear reprocessing programs in the United States. This decision was primarily made due to the ongoing desire to reduce the threat of nuclear proliferation and popular belief that reprocessing was not economical (Rossin). Although President Carter continued to support Gerald Ford's precedent, this "ban" against nuclear reprocessing was never penned into law. Thus, President Ronald Reagan lifted the ban in 1981, followed by his election in 1980. During the Reagan administration, Congress passed the Nuclear Waste Policy Act, which designed a plan to create a permanent underground storage facility for nuclear waste. In 1987, the amended Nuclear Waste Policy Act designated Yucca Mountain, Nevada, as the only location eligible to serve as a nuclear waste repository. This decision has been met with much controversy by the state of Nevada, which has consistently disputed the Department of Energy's claim that the Yucca Mountain would meet EPA standards as a nuclear waste repository site. Thus nuclear waste disposal in the United States has remained in limbo (Holt, 2011).

While Presidents George H. W. Bush and Bill Clinton issued policy statements discouraging the nuclear industry from reprocessing nuclear fuel, under President George W. Bush's leadership, the Department of Energy (DOE) attempted to develop UREX technologies through the Global Nuclear Partnership. Under President Bush the DOE also determined that Yucca Mountain was a suitable location and that it could begin receiving waste as early as 2020, 22 years after this goal was established by the Nuclear Waste Policy Act (Holt, 2011).

Despite his predecessor's support of nuclear reprocessing, the Obama administration canceled the development of a nuclear waste depository at Yucca Mountain in addition to the cancellation of the Global Nuclear Energy Partnership (GNEP). In order to receive backing by 2008 Senate Majority Leader Harry Reid, Obama agreed to withdraw executive support of Yucca Mountain licensing (Silverstein, 2013). Instead of utilizing Yucca Mountain, the Obama FY2012 Budget calls for long-term research on various technologies that may have the capability of reducing the volume and toxicity of radioactive waste. This strategy aims to refocus the Department of Energy away from the development of reprocessing facilities (Holt, 2011). The cancellation of the Yucca Mountain repository leaves the United States without any long-term storage site of high-level radioactive waste. While reprocessing some of the waste is a valid option, the current priority is to establish a geological repository with citizen input and approval.

Barriers Affecting Policy Making and Public Perception

The use of nuclear energy has been met with much controversy throughout the United States. The notion of nuclear reprocessing is a particularly contentious topic in recent years due to continued public perceptions and fears of nuclear proliferation, the effects of nuclear disasters such as Fukushima, and the increased economic costs of nuclear reprocessing following the recession. United States policy is highly susceptible to changes in public opinion, thus the changing public reaction to the following barriers are vital to the future of nuclear energy and reprocessing within the United States.

Nuclear proliferation fears have continued decades after the end of the Cold War era. The Nuclear Non-Proliferation Treaty, extended indefinitely in 1995, sets forth to prevent the spread of nuclear weapons and weapons technology, to promote the peaceful uses of nuclear energy, and to further the goal of achieving nuclear disarmament (UN, 1995). The spread of nuclear technology has given many nations the ability to develop nuclear weapons, much to the worry of the international community. In the case of Iran, the government has been faced with many sanctions to prevent the development of nuclear weapons. However, under the Nuclear Non-Proliferation Treaty, Iran is within its rights to research prospects in nuclear energy, prompting unease among the international community who believe the Iranian government is using this clause as a guise to develop nuclear weaponry. On November 24, 2013, a deal was struck between Iran and six world powers that slows the development of nuclear weaponry in exchange for relief of sanctions set upon their government. This six-month agreement places substantial limitations that will help prevent Iran from developing nuclear weaponry until a more permanent solution can be reached (Sciutto, 2013). In order to address the threat of nuclear proliferation, international diplomacy is a key.

On March 11, 2011, the Fukushima Daiichi nuclear power plant suffered a nuclear meltdown as a result of a massive earthquake and tsunami. As a result of poor government and institutional responses, there was a considerable release of radiation to the sea and atmosphere that continues to plague the local environment, economy, and populace (Sharma, 67). Raising questions of security and safety of nuclear power plants, the Fukushima Daiichi nuclear meltdown has severely impeded the prospects of growth of commercial nuclear energy usage in the United States (Srinivasan & Rethinaraj, 2013). Prior to the Fukushima meltdown, the United States was gradually increasing its acceptance of nuclear power. Despite this increasing acceptance, however, the United States was particularly vulnerable to the occurrence of large-scale accidents, as stated by U.S. energy policy advisors just months prior to the March 2011 events: "… new plants have safety features and designs that greatly lessen or eliminate the chance of a catastrophic accident. However, convincing the public of that fact could be extremely difficult if there is another Three Mile Island or Chernobyl" (Wodka & Zelermyer, 2010). Following the Fukushima meltdown, support for building nuclear power plants in the United States dropped significantly according to a CBS News poll (Cooper, 2011).

One of the greatest barriers for the development of nuclear energy in the United States is its high start-up cost. The EPA forecast that a cap-and-trade system among companies would have provided greater incentive for the construction of more nuclear plants had it been allowed by Congress. By using nuclear energy, companies would have been able to produce large amounts of power without over-spending their carbon "allowance" and could trade their remaining allowance to another company for profit (Smith, 2013). The Savannah River Site, a former nuclear weapons plant in South Carolina, has been renovated to reprocess nuclear waste into MOX fuel. Due to the recession limiting the amount of eligible funding, in addition to increased interest in nuclear divestment following aftermath of Fukushima, the cost of the prolonged project has increased prices to U.S. $5 billion while interest in the project has simultaneously wavered. The most likely investor, the Tennessee Valley Authority, stated that it would delay any decision until more analysis on the damage of MOX in the Fukushima Daiichi reactors. Despite Obama administration officials finding that MOX is safe, the lack of customers is creating higher costs without any current guarantee of a steady fuel supply (Becker, 2011).

Currently, nuclear energy is in direct competition with "fracking," the use of hydraulic fracturing to break open underground rock formations that hold natural gas. Fracking has lowered the cost of fuel due to the fact that gas-fired power plants are far faster and cheaper to build than nuclear plants, which take more time and can cost up to billions of dollars to construct and begin operating. Though natural gas is not carbon-free, it puts out about half the carbon emissions as that of coal. Due to such high start-up costs and lack of public approval, "fracking" is taking business away from the nuclear industry despite its more detrimental effects to the environment (Smith, 2013).

The United States, though initially a leader in the development of nuclear power, does not have any credible commitment toward its nuclear industry as a result of its susceptibility to fragmented powers and opposing interest groups. Thus, the expansion of nuclear power is dependent on public perception.

Government Incentives and Developments in Nuclear Reprocessing Abroad

The Fukushima Daiichi nuclear meltdown has influenced many countries to review their current nuclear plans. Nations such as Germany have completely withdrawn all nuclear power activities. This 2011 policy decision orders the closing of all operational nuclear power plants and places nearly 11,000 jobs at risk (Sharma, 67). Despite this reaction, many nations continue to develop their nuclear programs due to their already high dependence on nuclear energy and their commitment to nuclear reprocessing.

France, a leading figure in the development of reprocessed nuclear fuel, has faced extensive financial insecurity and uncertainty about French national utility EDF's ability to create a credible strategy in response to technical upgrade requirements as a result of the Fukushima meltdown (Schnieder, Froggat & Thomas, 2011). Regardless of such uncertainty, however, France maintains its ongoing commitment to using nuclear energy as over 75% of its electricity is derived from nuclear sources (World Nuclear Association, 2013). As a pioneer in nuclear reprocessing technologies, France's government has remained committed to its nuclear industry due to the fact that its political structure allows for lower transaction costs for the nuclear industry than in the U.S. AREVA, France's public energy conglomerate, has been influential in the expansion of the nuclear industry, having a worldwide presence in Niger, Canada, South Korea, India, Kazakhstan, China, and the United States. Although AREVA Inc. does not operate reprocessing facilities within the United States, the company is capable of providing them (World Nuclear News, 2007).

Since the development of its nuclear power program in the late 1980s, China has planned to reprocess its used reactor fuel. On April 25, 2013, France's AREVA energy company partnered with the China National Nuclear Corporation (CNNC) by supplying CNNC with a nuclear reprocessing plant that will incorporate fuel materials into MOX fuel, while waste will be compacted in a disposal facility in the Gansu province. World Nuclear News reports that by 2020, China will have amassed over 1000 tonnes of used reactor fuel with over forty operational nuclear reactors. AREVA's processing plant will be able to handle 800 tonnes of used reactor fuel each year (World Nuclear News, 2013).

India started developing its nuclear program in 1947 during its pre-independence era. Since, scientists have expanded its nuclear program into uranium mining and exploration, fuel fabrication, heavy water production, reactor design and construction, waste management, and reprocessing. Currently, India's government is expanding its nuclear program under its 12th five-year plan for 2012-17, which targets the addition of 94 GWe over the period. Nearly all reprocessing in India uses PUREX, with India's newest reprocessing plant being opened as of January 2011. India is currently capable of reprocessing 330 tonnes of fuel each year across its three reprocessing plants. Further plants are under IAEA safeguards.

Although nuclear reprocessing is not currently feasible domestically, in April 2010 the United States and India reached an agreement to build two new reprocessing plants under IAEA safeguards. In July 2010, an additional agreement was made to allow the reprocessing of fuel from the United States at one of the two mandated facilities (World Nuclear Association). However, due to dispute over India's nuclear liability law, the prospect of U.S. participation in the civil nuclear market was delayed until September 2013. As of September 2013, the United States and India have signed an additional two landmark agreements that allow for a commercial nuclear deal and for the enhancement of defense cooperation between the two nations (Dawn.com). Due to domestic politics and lack of credible government commitment, the United States is unlikely to expand its nuclear program to include nuclear reprocessing on its soil in the near future. However, the U.S.-India nuclear reprocessing deal provides an indication that the U.S. will participate in nuclear reprocessing abroad.

Necessities for Domestic U.S. Reprocessing Policy

In order to feasibly use nuclear reprocessing, some new policies must be enacted in the United States. In 1957, the Atomic Energy Commission (AEC) decided to withdraw from providing nuclear reprocessing services for spent fuel. This was a problem because section 183 of the Atomic Energy Act declared that the government would own nuclear material used or produced by licensed facilities in the U.S. Nuclear reprocessing facilities would need an operating license in order to work. In 1974, the AEC added Section 101 to the National Environmental Policy Act that decreed that nuclear fuel reprocessing companies would need an environmental impact statement. Later, the AEC was split into the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA). In 1976, concerns of proliferation halted commercialization of nuclear reprocessing; President Ronald Reagan amended this in 1981. Continued concerns of proliferation perpetuated delays in reprocessing facilities. (Andrews)

New policies that would promote nuclear reprocessing would need to clearly state the intent of reprocessing. Nuclear reprocessing would need written specific, highly regulated standards and procedures in place in order to eliminate or reduce the risk of nuclear proliferation. A board should be created in order to maintain and check reprocessing facilities for following these standards and procedures. A policy that would allow commercial reprocessing facilities to more easily navigate red tape in order to receive an operating license should also be considered: such policies might involve prerequisites and required facility reports to the aforementioned board in order to ensure the facility is following nuclear energy laws.

V. Conclusion

Technologically speaking, nuclear reprocessing is feasible and several countries in the world are reprocessing their spent nuclear fuel or are sending their spent nuclear fuel to be reprocessed. Aqueous methods have been developed that are much safer than the initial methods used. To address the fear of nuclear proliferation, Urex has been developed as a derivative of Purex, where plutonium is not extracted independently. A non-aqueous method, pyrochemical processing, has also been developed. While not as effective as aqueous reprocessing, it saves time and money and should be researched further.

From an economic standpoint, nuclear reprocessing is not feasible when compared to direct disposal. When considering the major quantifiable economic variables, such as future uranium prices, storage space, capital and operating costs, and mining costs, reprocessing yields substantially higher costs than direct disposal. Further, costs would continue to rise with reprocessing as more unquantifiable variables such as security for proliferation would become relevant. Thus, under the assumptions laid out in the economic analysis section, the United States' current process of direct disposal is economically superior to reprocessing.

From the standpoint of United States politics, nuclear reprocessing is possible but unlikely to occur domestically in the near future given the lack of current public and political support for nuclear energy. Due to the Obama administration's desire to refocus the DOE away from the development of reprocessing facilities, nuclear reprocessing will not occur domestically during Obama's presidency. However, the fact that the Obama administration has reached a deal to reprocess nuclear waste in India is indicative of a desire to expand the U.S. nuclear program to facilities abroad.

Based on the information above, the following courses of action are suggested:

1. *Creating one or more aqueous reprocessing sites in the United States.* The technology to do this exists—other countries are doing it—and there are ways to inhibit proliferation. However, upfront capital costs and operating costs for reprocessing sites would be higher than for direct disposal sites. Due to such high

costs, the United States looks more favorably upon cheaper alternatives, such as "fracking," despite the possibility of higher carbon emissions in comparison to the use of nuclear energy.

2. *Outsourcing nuclear waste.* The United States could send its nuclear waste to other countries that do reprocess. While many worry that this may increase the risk of nuclear proliferation, an accord such as the one between the United States and India can be made through which the U.S. may increase security against nuclear proliferation.
3. *Developing pyrochemical processing technology.* If pyroprocessing could be as effective at spent fuel reprocessing as aqueous methods are, it would be a good alternative. This has the benefit of being done on-site, thus making aqueous reprocessing centers unnecessary and decreasing the risk of nuclear proliferation. Still, pyroprocessing would be a capital intensive process with many upfront and operating costs to consider. Furthermore, as reprocessing is still not a very popular method politically speaking, policymakers may be hesitant in promoting or creating programs dedicated to pyrochemical processing.
4. *Opening Yucca Mountain or another site for nuclear waste disposal.* This can be done with or without reprocessing. Having a site for nuclear waste disposal would encourage the use of nuclear energy in the United States. While nuclear waste would still be a problem, the United States would benefit from a safer, greener, more independent and effective source of energy. Further, the opening of the Yucca mountain project would make space in short-term storage facilities less scarce, thus effectively eliminating storage capacity as a variable for the foreseeable future. To develop alternative strategies to nuclear waste disposal and to find another site suitable to be a radioactive waste repository, the DOE established the Blue Ribbon Commission on America's Nuclear Future (BRC). Although the BRC is committed to finding such alternatives, a nuclear repository facility (as proven by the Yucca Mountain controversy) cannot only be geologically suitable to dispose of nuclear materials but must also incorporate the input of citizens in surrounding areas.

Of these four options, option four is the most feasible and likely to come into fruition due to the fact that it supports direct disposal of nuclear waste. Option four does not include the high costs attached to nuclear reprocessing, a major barrier for U.S. policy initiatives and public will to participate in nuclear reprocessing, and scarcity would no longer be an issue for short-term storage facilities.

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