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Nuclear Fuel Reprocessing
Future Prospects and Viability

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This paper analyzes the process of nuclear fuel reprocessing, where spent nuclear fuel is refined to reduce waste and provide further material for nuclear fuel. We cover reprocessing technology as well as current research and innovation in the area, as well as its environmental impact, the current policy climate in the United States, and an analysis of the economic costs and benefits of reprocessing. Overall, we find that the current state of nuclear reprocessing is not entirely viable from a political and environmental view, but new technologies show potential for the use of reprocessing in the near future.

Table of Contents

I. Nuclear Reprocessing Overview

The goal of this section is to provide a comprehensive understanding of how the reprocessing of spent fuel ties into the nuclear fuel cycle at large, as well as outlining its benefits from a purely ideal perspective. Although a wide variety of practical concerns exist which shall be addressed, it is important to first examine the scientific theory behind reprocessing to gain a better sense of what it is now, and what it can be in the future.

To produce energy, nuclear power plants engender a controlled fission chain reaction of heavy elements - most commonly U-235 and Pu-239. In fission specifically, energy released is proportional to the atomic mass of the element (the opposite is true for fusion), and is only exothermic (i.e. produces energy) if the atomic mass is greater than that of iron. In addition, very few fissionable isotopes produce enough excess neutrons to allow for a sustained reaction. Of these, uranium is naturally occurring and the most easily obtained, making it an excellent candidate. Plutonium may also be used as it remains an unavoidable byproduct of irradiated uranium.

In nature, uranium consists of ~99.284% U-238 and ~.711% U-235 with trace amounts of other isotopes. However, only U-235 will undergo fission in the presence of thermal neutrons – and thus cross-sectional energy yield per unit time in a fission reaction is governed by the ratio of U-235 to U-238. For use in nuclear reactors, uranium ore is "enriched" to about 5% - meaning that U-235 comprises about 5% of the total uranium used. This is considered low enriched, or reactor grade uranium (LEU), whereas a concentration greater than 20% is considered highly enriched (HEU) and thus is designated as weapons grade. The implications of this are clear. Whereas a fission chain reaction of HEU will result in a large energy output in a small amount of time, a chain reaction of LEU will also result in a large energy output, but over a longer period of time which allows for more control in how that energy will be managed. Obviously, we don't try and harness the power of a nuclear bomb, but it is essentially the same fission occurring at a rate which can be controlled.

The fission chain reaction itself is actualized by assembling a critical array of LEU nuclear fuel rods in the reactor core and removing the neutron capturing control rods. As

the chain reaction occurs, neutrons are either absorbed or emitted by U-238 or cause U-235 to fission releasing energy, fission products consisting of lighter mildly radioactive elements, and additional free neutrons which strike other U-235 nuclei and continue the chain reaction. It is here where the concern for reprocessing comes into play. As fuel rods burn, they will decrease in efficiency over the course of time. The cause of this is twofold. Firstly, and perhaps most intuitively, the concentration of fissile isotopes of uranium decreases. That is to say, percent enrichment decreases, and energy yield per unit time decreases. Secondly, the amount of neutron capturing fission products increases – resulting in unintentional "neutron poisoning" of the fission chain reaction. Additionally, though bearing no further consequence to the reaction the U-238 target material, upon neutron absorption, will form U-239 which rapidly decays into Pu-239. After a period of time these fuel rods are considered "spent" because of degraded efficiency. They are then removed, cooled, transmuted, and stored indefinitely in some geological repository. There are two major problems with this. Firstly, around 96% of that "spent" nuclear fuel rod is still uranium. 1% is weapon-grade plutonium and 3% are lighter elements. There are also trace amounts of other actinides such as neptunium, americium, and curium depending on the reactor but this amount is generally below a fourth of a percent. Secondly, plutonium and uranium are also actinides, so around 97% of the waste consists of actinides which happen to be highly radioactive – some of the longer lived isotopes remaining so to an order of 10^5 or 100,000 years.[12]

The goal of reprocessing is to remove a large portion of the actinides, thereby reducing the volume of the waste as well as the duration for which it remains radioactive while preserving uranium and plutonium for future use. Ideally, this is a win-win situation. In a more practical light, it presents many glaring concerns – namely costs, policy, and the fear of nuclear proliferation. An even more fundamental problem which must first be addressed exists within the technology itself. That is to say, many reprocessing technologies exist – most are still in development, and those used commercially have serious flaws. To gain a better understanding of what is available, it is relevant to examine each of these technologies in greater detail.

[1]International Atomic Energy Agency. 2007.
[2]Terminello L. J.

PUREX (**P**lutonium **UR**anium **Ex**traction).

All commercial reprocessing plants active today, as well as many which have been decommissioned, use the PUREX process. This stands for plutonium-uranium extraction, and was invented in 1947 at the University of Chicago as part of the Manhattan Project. It was first run on a large scale at the Savannah River Site in 1954, and has since been adopted by Britain, France, Russia, and Japan.[3] It is a solvent extraction technique in which the spent fuel rods are dissolved in nitric acid, leaving behind actinide nitrates, and other fission products in the aqueous nitric phase. This suspension is then mixed with an organic solvent compound of 30% tributyl phosphate and 70% kerosene which creates a solution with the aqueous nitrates, and being immiscible with HNO3 (nitric acid) eventually separates, allowing the uranium and plutonium to be extracted.

The PUREX process begins with spent fuel rods, which are dissolved in nitric acid and stored in aluminum casks to be transferred to the reprocessing site. There, the cask is dissolved in sodium hydroxide (NaOH) which reacts specifically with aluminum, leaving the aqueous nitrate solution containing U, Pu and other fission products. Before separation, this solution first undergoes a prep-phase in the "head-end" of the cycle. Here, batches of solution are simmered with gelatin – effectively removing any silica by forming extractable gelatin-silica polymers. This is done to prevent the formation of solids which can later cause emulsions in the solvent extraction equipment – a potential cause of criticality accidents. The solution is centrifuged to remove these polymers as well as other solid fission products which are stored as waste. After proper inspection, the solution is then fed into the "first solvent extraction cycle". It is important to note that at this point, the plutonium is in the oxidation state Pu (IV) and uranium is in its most common oxidation state U (VI). Both share the property of extracting into tributyl phosphate (TBP). Therefore, to separate the uranium and plutonium from other waste, the solution is combined with a 30% TBP 70% n-paraffin (kerosene) organic solvent compound. The resulting mixture is centrifuged, and forms a suspension since the TBP and paraffin are immiscible. The solvent containing U and Pu is separated and stored whereas the aqueous solution is added to the slurry of highly radioactive waste. As an aside, it is possible to extract Neptunium from this waste, but this detail is not important for the overall process. From here, the solvent stream is introduced to ferrous sulfamate, reducing plutonium from Pu(IV) to Pu(III) which does not extract into

[3]Nuclear Criticality Safety Engineering Training

TBP, effectively stripping it from the solvent into the aqueous phase. Similarly to before, the lighter U in the solvent phase is separated from Pu in the aqueous phase, and both are separately stored for further processing. Each undergoes a "second cycle" for decontamination purposes, after which the U and Pu solvents are ready to be converted to solid form. Several methods are available for this. At the SRS, for example, it was done by complexing the U or Pu solutions with a fluoride or oxalate ligand to form a precipitate which can be filtered, dried, and calcined as needed.[4]

Although PUREX is a well documented and widely used process today, it is far from perfect. Ideally, reprocessing should aim to reduce the radioactivity of waste. While PUREX accomplishes this in some regard, due to the sheer volume of solutes used the result is a much larger quantity of less radioactive waste. Another important concern is that with any buildup of uranium or plutonium there is a possibility of critical mass being attained. Although a chain reaction resulting from such a small amount of lowly enriched material would not be devastating, it could result in direct exposure of workers to high energy gamma and neutron radiation, minor concern for fallout of material into the environment, and decommissioning of the plant. The most recent example of such an accident was in 1999 at the Tokaimura reprocessing plant in Japan. The U-235 criticality achieved was a result of improperly trained workers circumventing standard mixing protocol to expedite the process. Two of the three workers responsible died from receiving a full body radiation dose ~10000 mSv (millisievert). Other workers in the plant as well as people in the surrounding area received radiation doses as well, but none of these exceeded ~50 mSv - the average lethal dose being 8000 mSv.[5] One could argue that such an accident would never occur if the facility was operated according to standard regulations, but the ability to ensure such fastidious observation of the rules in all workers is debatable.

Another pressing concern to consider is the fear of nuclear proliferation. While the uranium separated in the PUREX process is both highly radioactive and lowly enriched making it relatively useless in the production of nuclear weaponry, the plutonium is almost exclusively the fissile Pu-239 isotope. This isotope is radioactive, but only emits alpha radiation, making it safe to handle. Furthermore, due to higher neutron production in a

[4]Starks, 1977.
[5]"Tokaimura Criticality Accident"
http://world-nuclear.org/info/default.aspx?id=502

fission cross section of plutonium, a lower critical mass is required to produce a sustained chain reaction. Although one would still require considerable resources to create a nuclear weapon using this plutonium, it is nevertheless a real cause for concern, unlike the reactor grade uranium. A portion of this plutonium is generally converted to mixed-oxide fuel or "MOX", a combination of plutonium and either spent or reprocessed uranium isotopes that behaves similarly to LEU. However, the ratio of converted plutonium to stored plutonium is surprisingly low. For example, according to an Institute for Energy and Environmental Research (IEER) quoted statistic, in 1995 17 metric tons of plutonium were separated in civilian reprocessing plants, of which 8 metric tons were fabricated into MOX while the rest was stored. The largest collective civilian plutonium inventories are France with 55 metric tons, the UK with 49 metric tons, and Russia with around 30 metric tons.[6] While none of this plutonium has been reported lost or stolen, its existence alone remains a threat to nuclear proliferation.

World Mixed Oxide fuel fabrication capacities (t/yr)

	2009	2015
France, Melox	195	195
Japan, Tokai	10	10
Japan, Rokkasho	0	130
Russia, Mayak, Ozersk	5	5
UK, Sellafield	40	40
Total for LWR	**250**	**380**

[7]

Although there are problems inherent in the solvent extraction method that may perhaps never be resolved, modifications can be made to PUREX to address some of the more pressing concerns. For example, to combat the fear of nuclear proliferation the idea for UREX was developed.

UREX (**U**ranium **EX**traction)

The UREX or uranium extraction process is almost identical to PUREX except for a modification that prevents the extraction of plutonium. This is accomplished by adding

[6]Berkhout, 1997.
[7]WNA

acetohydroxamic acid (AHA) to the scrub stream, which effectively complexes Pu (IV) and Np(IV), diminishing the ability of plutonium to extract into TBP as before in the "first solvent extraction cycle". Furthermore, the complexing of Np (IV) reduces its oxidation state to Np (V) rendering it inextricable from the remaining waste raffinate. This allows for efficient recovery of uranium and technetium while rejecting the plutonium and neptunium considered viable for proliferation.[8] A UREX test done at the SRS using spent fuel from Chicago's Dresden Reactor concluded that ~99.9%of U and ~95% of Tc could be recovered while rejecting ~99.9% of other transuranic isotopes (including Pu and Np).[9]

TRUEX (**TR**ans**U**ranic **EX**traction)

Another modification of the PUREX process, TRUEX was developed by Argonne National Laboratory with the goal of improving nuclear waste management. The goal of the process is efficient separation of all transuranic isotopes from the nitric acid raffinate. This is achieved though a modification of the PUREX solvent used. Instead of pure TBP, a proportional ~12.5% of the powerful extractant octyl(phenyl)-N, N-dibutyl carbamoylmethyl phosphine oxide (CMPO) and ~87.5% TBP are combined with an isoparaffin solution (such as Isopar L instead of Kerosene). The rationale behind this modification is that other actinides, including Am and Cm, will extract into the CMPO as well as U, Pu, and Np, resulting in an overall reduction in the alpha activity of the waste – allowing for a large portion of it to be stored with ease. A much smaller portion consisting of only the actinides recovered will require further treatment, transmutation and careful storage. According to a simulated study conducted at the Idaho National Engineering Laboratory (INEL), 99.7% removal efficiency was achieved for the actinides, reducing the radioactivity of the waste raffinate from 457 nCi/g to 0.12 nCi/g thus rendering it a Class A Low Level Waste (LLW). However, one caveat is that this process increases the difficulty of stripping U(VI) and Pu(IV) from the solvent due to their high affinity with CMPO, which could be a deterrent for commercial use.[10][11]

[8]Karraker, 2002.
[9]Rudisill, et al, 2003.
[10]Vandegrift, et al, 1993.
[11]Law, et al, 1996.

Other PUREX Variants

Numerous variations of PUREX exist, by making some small modification to the overall process in order to amplify one aspect of the extraction or disposal – often times to the detriment of others. The three variations above were discussed in greater detail to illustrate the diverse motives that exist for reprocessing, and to highlight the fact that research and industry do not necessarily have the same goals. Although new technologies have been developed to minimize waste disposal and proliferation concerns, all commercial reprocessing plants continue to use PUREX because the extracted plutonium accounts for a huge portion of their revenue, and remaining waste is exported with the extracted elements back to the country of origin.

Other moderately well documented solvent extraction methods include:

DIAMEX – or "DIAMide EXtraction" developed by the CEA at the Fontenay-aux-Roses Research Centre in France using a di-methyl-di-butyltetradecylmalonamide (DMDBTDMA) reagent similar to CMPO. This process forms organic waste which contains only elements of Carbon, Hydrogen, Nitrogen, and Oxygen, thus allowing for easy disposal via burning, unlike the standard PUREX acidic waste which must be stored.

DIDPA – "DI-isoDecylPhosphoric Acid" developed at JAERI in Japan.This variant uses a solvent mixture of DIDPA and TBP, which has the benefit of reducing Np (V) to NP (IV) causing it to be easily extracted with the other actinides. A simulation of this process estimates 99.95% recovery of actinides from the waste raffinate.

TRPO – "Trialkyl Phosphine Oxide". This method developed at Tsinghua University in China uses TRPO as a solvent, which has the advantage of reversing the extraction and stripping processes.[12]

SESAME – A "back end" modification of the PUREX process developed by the CEA to selectively separate americium from the aqueous waste. This is done by introducing lacunary polyanionic ligands (LHPA) to the waste raffinate which prompts the electrochemical oxidation of Am into its hexavalent state.[13]

[12]"Partitioning and Transmutation of Minor Actinides and Fission Products"
[13]Donnet, et al, 1998.

Pyroprocessing

The one divergence from solvent extraction methods, pyroprocessing was invented at Argonne National Laboratory where it is still being developed as a part of the Integral Fast Reactor (IFR) fuel cycle. Unlike the modalities of the PUREX genre, pyroprocessing relies on high temperature pyrometallurgy and electrorefining techniques to separate actinides from spent nuclear fuel. Solvents consist of molten salts and molten metals instead of aqueous organic compounds. This rather distinct process presents a whole new set of advantages as well as challenges to be addressed apart from those previously mentioned.

In the IFR model, the process begins with direct use of the spent fuel rods. They are chopped into 6-7 mm lengths and loaded into perforated steel baskets for electrorefining. However simple modifications to the "head end" of the cycle can be made to generalize processing potential to most transmuted forms of spent fuel, including metal, oxide, graphite, hydride and cement. Aluminum presents a problem as it tends to form stable compounds with actinide elements making extraction more difficult, so aqueous solvent methods may be more appropriate in this case.[14]

Following the "head end" phase, the spent fuel is placed in an electrorefiner – a steel vessel which is sealed and prepped to contain a high-purity inert gas atmosphere to prevent combustion at high temperatures. The bottom of the vessel is covered in a 0.15 meter thick layer of cadmium, and above this is a 0.3 meter thick layer of electrolyte salt. For this procedure the eutectic system formed by LiCl and KCl is chosen to prevent unexpected or gradual solidification. The melting point for this salt mixture is 350 C, well below the operating temperature of 500 C. Once the vessel is ready, the chopped fuel containing anode basket is lowered into the electrolyte salt, with which all constituent elements come into chemical equilibrium and form metal chlorides. To be more specific, the metal phases of the constituent elements are independently in "limited" equilibrium with the same electrolyte salt, and never come into "complete" chemical equilibrium with one another. The effect of this is that elements more toward the "noble" side of the periodic table, which have lower chloride concentration, will also have a lower mass transport coefficient. However, this does not have much bearing in the interest of uranium separation, only if a complete partitioning of constituent elements is desired.

[14]Laidler, et al, 1997.

At this point, there are three distinct chemical operations which can be used to manipulate the location of the various elements in the electrorefiner – oxidation, reduction, and electrotransport. In the IFR model, and for waste management purposes in general, the third operation is most desirable. Unlike the other two, electrotransport requires no reagents and generates no waste volume. It is performed by generating an electric current in the salt to oxidize metal from an anode phase (i.e. fuel in the anode basket) into the salt in a chloride phase, as well as reduce an equivalent amount of chloride from the salt phase into a cathode metal phase. Elementary electrodynamics dictate that application of a current, and thus a voltage differential, will result in the transportation of material from the anode (positive electrode) to the cathode (negative electrode). Due to the unique thermodynamic properties of uranium, it can be exclusively collected on solid mandrel cathodes. Other actinides (including plutonium) and rare-earth metals will instead be attracted to the liquid cadmium cathode phase because the effect of the relatively negative free energies of formation of their chlorides is not reduced by intermetallic formation at solid cathodes.

In the IFR model, this is actualized in a two step electrotransport process. First, the anode basket is lowered into the cadmium pool, which forms an anode phase upon application of an electric current. It is relevant to note that cadmium is chosen because of high solubility of uranium and plutonium as well as some trace actinides and rare-earth metals at this temperature, effectively separating them from other fission products. These actinides are then electrotransported to two separate collecting cathodes, the first being a solid electrode at which only uranium is deposited, and the second being a liquid cadmium cathode at which a mixture of uranium, plutonium, other trace actinides and rare-earth elements are deposited. Liquid cadmium is chosen for the second cathode because the activity coefficients of uranium and plutonium will be identical from anode to cathode. Thermodynamic relationships dictate that under this condition only a small voltage is required for the transportation to take place, allowing for simultaneous deposition.[15]

Following electrorefining, the cathodes, which have lower boiling points than the uranium and plutonium (~800 C), can be vaporized and the respective uranium and actinide compound can be melted into ingots. These will eventually be processed and used to create new fuel rods. This conveniently leaves the option of pure uranium rods or proliferation resistant (due to radioactivity and impurity) plutonium rods being fabricated.

[15]Ackerman, 1991.

There are several other, more subtle advantages to this process to be considered as well. For example, the use of molten salt solvents instead of neutron moderating hydrocarbons reduces the risk of criticality accidents. As mentioned before, the volume of waste resulting in electrorefining is much less than aqueous methods since the highly radioactive actinides are completely removed from the solvent phase or collection equipment through vaporization, whereas PUREX produces high quantities of aqueous nitric acid waste which, although stripped of plutonium and uranium, still contains trace amounts of other radioactive actinides. Furthermore, pyroprocessing was designed for on site reprocessing in the IFR model, meaning it is a much smaller scale operation than aqueous methods which require an entirely separate reprocessing plant. Not only would this cut down on the amount of land required, it will combat the threat of proliferation during the transportation of reprocessed fuel by eliminating this step entirely.

Inherent Systematic Limitations

One major limiting factor to currently developed reprocessing technologies does not exist in the techniques themselves but in the nature of the spent fuel. As mentioned briefly in the introduction, when fuel rods burn, they decrease in efficiency due to decreasing enrichment and increasing neutron poisoning fission products. Unfortunately this is not the end of the story. Due to uranium neutron absorption and emission during fission, trace amounts of synthetic uranium isotopes are produced including U-232, U-233, U-236, and U-237 as well as a greater concentration of the naturally occurring U-234 isotope. Compared to the remaining percentages of U-235 and U-238 these trace isotopes are negligible, however they do possess certain properties which can effect the use of reprocessed uranium in standard LWRs. For example, U-234 and U-236 are neutron absorbing isotopes, imposing a compensation factor of greater U-235 enrichment to yield the same energy output. U-232 which has a relatively miniscule 68.9 year half-life decays through a series of steps to the stable nuclide Pb-208, during which it emits intense beta and gamma radiation. Although this does not have any impact if the fuel is recycled immediately, it could be a problem for handling and enrichment if stored for too long.[16] Considering these factors, there is extra difficulty presented in using reprocessed uranium rather than natural

[16]International Atomic Energy Agency. 2007.

uranium, and the decision to do so would reflect a desire to preserve the sustainability of nuclear energy rather than immediate minimization of cost.

II. Environmental Examination

Reprocessing is a very complex matter to analyze from an environmental perspective. The major obstacle is limited data. Though there are three types of reprocessing being discussed, PUREX is the only one widely used. Due to this issue, there is not very much literature about UREX or pyroprocessing. There is also an environmental record regarding PUREX accidents. The countries that currently reprocess nuclear material are the United Kingdom, France, Germany, and Japan. Though the environmental effects of reprocessing may not be directly related to climate change, they are significant. There are annual protest blockades in Germany related to the movement of reprocessed waste.

Reprocessing plants have an extensive shutdown history outside of the United States. Many plants internationally have a great deal of trouble managing coolants and other chemicals involved in the reprocessing process. The "Superphenix" reactor in France was shut down in 1987 after leaking 20 tons of sodium coolant. The "Monju" fast breeder reactor in Japan was shut down permanently in 1995. This was due to a three ton sodium leak causing the reactor to overheat and burn holes in the cooling pipes. [17]Sodium poses a very large problem in many ecosystems. The median level toxicity for mosquito fish is 125 ppm. This makes sodium moderately toxic. However, the true danger of sodium compounds it that they are extremely soluble in water, easily becoming sodium hydroxide which leaches very quickly through soil. Sodium spills are extremely expensive to contain due to their ability to find and contaminate ground water. Moderate sodium concentrations can have adverse health effects, such as irritation and coughing. Severe exposure can lead to caustic burns, difficulty breathing, and blindness.

The most extreme reprocessing disaster happened in 2005 in Sellafield, UK at the THORP plant. The problem had occurred over an unknown number of years but was not detected until 2005. Over this period of time, a massive leak of tens of tons of uranium and 160 kilograms of plutonium was generated. Though no radiation leaked into the

[17]von Hippel, 2009.

environment and no one was injured, the event was still given a 3 out of 7 on the International Nuclear Event Scale. This rating was only achieved because of the volume of the leak and the amount of time it went unnoticed. [18]

Nuclear fuel reprocessing has been done previously in the United States. The only reprocessing facility in the United States was in operation from 1966 to 1972. The reprocessing plant in West Valley, New York was closed after producing massive amounts of waste. Over the brief life span of the plant over 600,000 gallons of highly radioactive material were produced. In 2001, The GAO estimated that the cleanup would take 40 years of complete and 4.5 billion dollars. The GAO re-analyzed the incident in 2007 and estimated the project to cost over 5 billion dollars.[19]

The United States classifies radioactive wastes by the process used to produce them, and not the actual radioactivity or half-life. Reprocessing waste is designated above class C. Nuclear waste classes A, B, and C can be disposed of by shallow burying. All Nuclear waste above Class C must be disposed of in deep geological repositories by U.S. law. Wastes greater than class C are extremely dangerous to all organic life. Their aftereffects can also be detected many years into the future. Highly radioactive waste has been shown to increase cancer rates. This is mostly due to extremely long half-lives and ease with which they permeate soils to find ground water.[20]

Reprocessing results in high-level radioactive waste and large volumes of Greater than Class C waste. A study done by the Institute for Energy and Environmental Research (IEER) determined that the reprocessing performed in France would actually significantly increase the amount of waste that would need to be disposed of in a geologic repository. The U.S. Department of Energy estimates that France's combined volume of nuclear waste on a life-cycle basis is about six times the amount than the no-reprocessing approach that is currently used by the United States. Low-level waste volume and waste transportation shipments are also estimated to increase many times over when reprocessing is used.[21]

[18] IEER
[19] von Hippel, 2009.
[20] von Hippel, 2009.
[21] IEER

From an environmental perspective, reprocessing is not a beneficial practice. Reprocessing would increase the amount of waste in storage and has long record of accidents which have the potential to permanently damage and alter ecosystems.[22]

[22]Argonne National Lab, 2007.

III. Public Policy Implications

History of Nuclear Reprocessing in the United States

The reprocessing of nuclear fuel has been a key energy policy issue discussed and debated since the development of nuclear energy in the 1940s. The United States' government has taken many steps forward, as well as many steps back, in the development and implementation of nuclear reprocessing technology. Early on, reprocessing was considered necessary since the amount of uranium available was perceived to be scarce. The Atomic Energy Act of 1946 established the Atomic Energy Commission (AEC) and transferred the production and control of fissionable materials from the United States Army's Manhattan Project to the AEC, while also giving the AEC title to these materials for national security reasons.[23] Congress amended the Atomic Energy Act in 1954 to allow the AEC to license commercial reactors to private companies, while the AEC retained title to the nuclear materials produced at these licensed locations. In 1956, the chairman of the AEC, Lewis Strauss, announced a program that encouraged the private sector to reprocess spent nuclear fuel.[24]

The AEC sponsored Experimental Breeder Reactor (EBR II), at Argonne National Laboratory West near Idaho Falls, began operating in 1963. However, reprocessing and re-fabrication operations were suspended at EBRII in 1969. An operating permit was issued to Nuclear Fuel Services for the West Valley plant in New York. The plant reprocessed spent fuel from the defense weapons program (commercial spent fuel was not reprocessed at this plant) and operated from 1966 until 1972, when it closed to upgrade the plant's facilities due to stricter regulatory requirements.[25] The plant was never re-opened when it was determined that these new regulations could not be met.[26] The AEC approved General Electric to construct a spent fuel reprocessing facility in Morris, IL, in 1967. General Electric stopped construction of this plant in 1972 and decided not to pursue an operating license;

[23]CRS Report for Congress, 2008.
[24]U.S. House of Representatives, 1981.
[25]U.S. Department of Energy, 1996.
[26]Congressional Budget Office, 1977.

instead, the company applied for and received a license to store spent nuclear fuel.[27] Similarly, Allied-General Nuclear Services started building a commercial reprocessing plant in Barnwell, South Carolina, in 1970 but halted construction in 1981 when they were not able to finish without the aid of federal funding and decided that nuclear reprocessing was not practical on a commercial level.[28]

In 1974 the AEC decided that all decisions to permit nuclear fuel reprocessing would require an environmental impact statement, as called for under the National Environmental Policy Act. The AEC was split into two separate agencies in 1974: the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA). The licensing of nuclear facilities is now the responsibility of the NRC.

President Gerald Ford issued a policy statement in 1976 which stated: "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." With this statement, President Ford was effectively telling the executive branch agencies to put commercial nuclear processing on hold.[29]

The Presidency changed hands when President Jimmy Carter won the presidential election of 1976, defeating his incumbent opponent, President Ford, by a narrow margin. Early in his presidency, in April of 1977, President Carter informed the public of his decision to continue the suspension of commercial reprocessing programs and the recycling of plutonium produced in the U.S. nuclear power programs.[30] However, in 1981 this ban was lifted by President Ronald Reagan following the 1980 presidential election, when President Reagan defeated President Carter.

Congress passed the Nuclear Waste Policy Act in 1982 which outlined a plan to create a permanent underground storage facility for radioactive waste. The act was

[27]Comptroller General, 1979.
[28]CRS Report for Congress, 2008.
[29]CRS Report for Congress, 2008.
[30]Jimmy Carter Library, 1977.

amended in 1987 to designate Yucca Mountain as the only appropriate location suggested by the U.S. Department of Energy to be investigated as a nuclear waste repository.[31] In a policy statement on nuclear nonproliferation in 1992, President George H.W. Bush called for a halt in the reprocessing of nuclear weapons, but made no mention of commercial reprocessing efforts.[32] The following year, President Bill Clinton issued a policy statement which discouraged the nuclear industry from reprocessing plutonium.[33]

The National Academy of Sciences declared in 1996 that nuclear fuel reprocessing was impractical and too costly for the United States.[34] Despite this conclusion, in 2001 President George W. Bush recommended in his National Energy Policy that the United States develop nuclear reprocessing technologies.[35] In an attempt to develop proliferation resistant technologies while still expanding nuclear power both in the U.S. and around the world, in 2006 the Department of Energy announced it would begin developing UREX technology through the Global Nuclear Energy Partnership (GNEP).[36] In 2009, President Barack Obama's administration decided to cancel an environmental impact statement drafted by the Bush administration, effectively canceling GNEP. This environmental review was setting the ground for future commercial nuclear reprocessing in the United States. This was due to the Department of Energy being no longer interested in pursuing domestic commercial reprocessing, which was the main focus of the Bush administration's interest in the GNEP program.[37] In 2009 President Obama also canceled the development of the nuclear waste repository at Yucca Mountain.

Issues Affecting Policy-Making

It has been, and will continue to be, difficult for nuclear energy to become a popular energy option in the United States. Nuclear reprocessing will be an even more uphill battle as many people have preconceived notions and reservations when it comes to nuclear energy and the reprocessing of spent fuel. Fears of proliferation, terroristic threats, harm to

[31]yuccamountain.org, 2010.
[32]CRS Report for Congress, 2008.
[33]Fact Sheet — Nonproliferation And Export Control Policy, 1993.
[34]Foreign Policy In Focus, 2008.
[35]Report of the National Energy Policy Development Group, 2001.
[36]Federal Register Volume 71, 2006.
[37]Federal Register Volume 75, 2009.

the environment and exorbitant costs all play a role in shaping the public's perception of reprocessing and its role in the American energy market.

Decades of nuclear proliferation fears stemming from the Cold War era have persisted even though the Iron Curtain has fallen. In the 1950s, programs such as the United States' Atoms for Peace encouraged the United States, its Western allies and the Soviet Union to promote nuclear science and technology domestically and abroad for peaceful and civilian purposes. It also provided the United States with a way to strategically establish or strengthen alliances with developing countries for both military and industry purposes.[38] Atoms for Peace, and equivalent programs in other nuclear states, provided developing countries with nuclear technology in exchange for influence and superiority over nuclear weapons states. The United States signed nuclear cooperative agreements with Iran, Spain, South Africa, India, Pakistan and Israel, among other countries. Similar agreements were made between the Soviet Union and China and North Korea. Canada and Great Britain sold reactors to India for peaceful nuclear purposes. Many of the developing countries who were assisted through funding or training by nuclear weapons states such as the United States, Canada and the Soviet Union would later become proliferation threats.[39] Regional rivalries flourished; when one country made a nuclear advancement, their neighbors were not far behind. Instead of using nuclear power solely for civilian purposes, many recipients of training or funding for peaceful purposes went on to develop nuclear weapons.

The spread of civilian nuclear technology has given many countries the ability to develop nuclear weapons when they might not have been able to otherwise, at least not as quickly as they were able to when provided the material and knowledge from developed countries like the United States, the Soviet Union and Great Britain. For example, in 1964, China's nuclear test alarmed the rest of the world to the potential spread of nuclear weapons to other countries. Despite the 1968 Nuclear Non-Proliferation Treaty, India developed its own nuclear weapons in 1974 from nuclear material it had been given for peaceful purposes, likely to arm itself from China and its nuclear weapons. India's possession of nuclear weapons led bordering Pakistan to develop and test their own weapons as hostility in the region grew. More recently, the United States been seen to favor India by giving them exemptions to rules set by the Nuclear Suppliers Group (NSG), but has

[38]Glaser and Mian, 2008.
[39]Weiss, 2001.

not offered the same exemptions to Pakistan. The Pakistani government feels threatened by India's growing nuclear capabilities, and has, in turn, increased their own nuclear facilities[40] Proliferation as a result of the expansion of peaceful nuclear technology is a reality, and some fear that reprocessing facilities are simply making it easier for countries to obtain plutonium and manufacture nuclear weapons covertly.

The American public also fears that reprocessing will increase the risk of terrorism using nuclear weapons. When plutonium is separated from spent fuel through reprocessing, fabricated into new fuel and shipped from one place to another, the potential opportunity for this material to be seized or hijacked by terrorist groups is increased. This has not been a large threat worldwide since most countries have been storing their spent fuel on-site and have not transported it.[41] Concern over nuclear terrorism comes from projections that millions of kilograms of plutonium would be separated from spent fuel on a yearly basis. Less than 8kg of plutonium is required to make a bomb comparable to the one dropped on Nagasaki[42], meaning a significant number of nuclear weapons could be potentially made with the plutonium extracted during reprocessing efforts.

Nuclear catastrophes have caused extensive environmental and health damage across the world. Though it was not a nuclear reprocessing facility when the accident occurred, an incident at the Soviet nuclear facility Mayak showed the world the devastation nuclear disasters can cause. At Mayak, nuclear waste was improperly disposed of in a nearby river, and an insufficient cooling system led to an explosion which released large amounts of radioactivity into the environment.[43] Nearby residents suffered radiation poisoning from the radioactive cloud resulting from the explosion, and also from drinking contaminated drinking water. Over ten thousand people were evacuated from the area, though some were left behind. Little or no effort has been made to clean up the radioactive contamination.[44] The plant has continued to be used after the accident and the environment surrounding the facility remains extensively damaged. Environmental accidents such as this one, especially those that involved the health of nearby residents, allow fears surrounding nuclear facilities and their safety records to persist. Concerns over nuclear waste are

[40]Glaser and Mian, 2008.
[41]Bunn and Malin, 2009.
[42]von Hippel, 2001.
[43]Ballin, 2007.
[44]Hoffman, 1998.

growing as the developing world plans to build more nuclear plants and as more spent fuel accumulates on a global level and permanent storage options still under consideration.

Nuclear accidents can not only lead to environmental tragedy, they are costly to clean up. The GAO has estimated that the cleanup of the West Valley, New York reprocessing plant would take 40 years and upwards of 4.5 billion dollars to complete.[45] Aside from cleanup expenditures, another apprehension hindering the growth of nuclear reprocessing in the United States is the fear that associated implementation costs will be exorbitant, or exceed current costs of waste management. Some estimates claim that reprocessing will not become the cheaper option until uranium reaches a price of over $360 per kilogram[46], and that shifting to reprocessing would increase the costs of spent fuel management by more than 80%.[47] Other estimates also show that reprocessing spent fuel to be more expensive than current disposal costs, but at only an increase of 6%.[48] Such differing reports should signal to policymakers that the matter of cost needs to be evaluated further before a decision can be reached.

Government Incentives for Nuclear Reprocessing in the U.S.

As a result of the political environment and a lack of credible commitment to nuclear reprocessing in the United States, there has been little incentive to invest the significant capital required to develop it domestically. Moreover, the development of nuclear reprocessing was hindered by specific government regulations. From 1977 to 2005, government policy was prohibitive of reprocessing of used fuel in commercial reactors.[49] However, recent legislation calls for increased investment in research and development in advance fuel technology and advanced reactors in order to reduce the volume of nuclear waste and to recover the energy value of used fuel.[50] This new movement may provide an impetus for investment in nuclear reprocessing technology and presents the potential for the development of this industry in the U.S. If nuclear reprocessing does develop in the U.S., the industry could take one of two forms. Nuclear reprocessing may

[45]Government Accountability Office, 2001.
[46]Bunn, 2006.
[47]Bunn, et al, 2003.
[48]Boston Consulting Group, 2006.
[49]CRS Report for Congress, 2008.
[50]World Nuclear Association, 2010.

develop in a framework similar to the current nuclear power industry in the U.S. with private ownership of facilities and operations and significant oversight by government.[51] On the other hand, nuclear reprocessing may develop similar to the French model with government-owned and operated facilities performing nuclear reprocessing. To perceive the intricacies of these different frameworks, it is important to understand the incentives that exist in the U.S. and France with regards to both nuclear reprocessing and nuclear energy.

The American and French nuclear power industries developed along divergent paths. The U.S. nuclear power industry as a whole experienced a rapid decline beginning in the 1970's and culminating with the Three Mile Island accident in 1979 (TMI, a partial core meltdown in Reactor 2 at the Three Mile Island Nuclear Generating Station, remains as one of the most significant accidents in the commercial nuclear energy industry in the in the U.S.)[52] . Following a period from the mid-1950's to the mid 1970's when the U.S. built more nuclear power plants than any other country (231 through 1974), the U.S. only built 15 after 1974 and none after 1977.[53] This shift away from nuclear power was reversed in the late 1990's as nuclear energy was perceived as a sustainable energy solution to combat specific environmental concerns. In France, the nuclear power industry achieved a successful implementation and was prospering for many years both before and after TMI. Further, in France, nuclear power generates more than 75% of France's electricity while in the U.S. nuclear power has never accounted for more than 20% of its electricity.[54] These varying paths of nuclear power development in the U.S. and France stem largely from government's credible commitment or lack thereof to the industry. By analyzing the political and regulatory frameworks present in the U.S. and France, it is possible to gain a further understanding of the nuclear power industries in the U.S. and France, but more importantly discern the potential frameworks to develop nuclear reprocessing in the U.S.

The differentiation in the U.S. and French nuclear industries was largely based on the government's level of commitment over time. In the U.S., the government's commitment to the industry was initially strong, but abated over time, while France's government

[51]NEI, 2010.
[52]Smithsonian, (2010).
[53]Campbell, J.L. (1991).
[54]World Nuclear Association, 2010.

maintained a strong commitment over time.[55] The level of a government's credible commitment to the nuclear energy industry and specifically nuclear reprocessing will play an important role in shaping the flow of capital into the technology.[56] As the industry is currently constructed, utilities are sensitive to licensing and construction costs, which may be difficult to predict based on a government's ability to commit to the industry. Utilities must obtain construction licenses from regulatory bodies to build nuclear facilities. These investment decisions necessitate large sunk costs which must be incurred a number of years prior to operating the plant. The decision making process of the utility is ultimately influenced by uncertainty surrounding the regulatory process that can ease or complicate the process. This uncertainty increases the risk associated with these types of investments and disincentivizes investment in the technology. Therefore an "analysis of the differences in institutional environment attributes can further understanding of government's credible commitment to the industry."[57] In understanding the existing differentiation in the institutional environment for both the U.S. and France, it is possible to elucidate how these unique situations have created varying transaction costs for their respective industries.

The U.S. efforts to exploit nuclear power commercially originated as a result of the Atomic Energy Act of 1954 and specifically the creation of the Atomic Energy Commission (AEC)[58]. In 1957, the Price-Anderson Act limited utilities' liabilities regarding nuclear accidents and helped promulgate interest in the commercial use of nuclear energy.[59] This act served an important role in relaying the government's credible commitment to the nuclear industry. Initially, the U.S. nuclear industry was subject to the interaction of three groups; the nuclear/electric industry, the AEC, and the Congressional Joint Committee on Atomic Energy (JCAE).[60] In this respect, polices regarding the nuclear industry were centralized and left to the discretion of the regulators and the regulated industries themselves. This political environment fostered the expansion of the nuclear industry and investment in the technology. However, control over commercial nuclear policy became highly fragmented: By the time the JCAE was officially disbanded in early 1977, more than a

[55]U.S. Department of Energy. 1983.
[56]Byus, L., 1990.
[57]Delmas, M. and Heiman, B., 2001.
[58]World Nuclear Association, 2010.
[59]World Nuclear Association, 2010.
[60]Delmas, M. and Heiman, B., 2001.

dozen committees in the House and Senate had gained some oversight over nuclear energy policy. Once the decentralization of authority had occurred, proposals to create a single House energy committee with concentrated authority were defeated. This proliferation of oversight is far more typical of the American political system than the centralized JCAE had been.[61]

Further, during this period there was a significant rise in the number of anti-nuclear activists namely the Union of Concerned Scientist and the National Resource Defense Council.[62] These groups were able to utilize this fragmented political environment to undermine government commitment to the industry. The revived arrangement for nuclear industry oversight can be characterized by a subcommittee structure "open to competing interests, as well as vulnerable to changes in the composition of interest groups".[63] Moreover, the nuclear industry was subject to an increased volume of rules and regulations as the anti-nuclear activist groups employed the independent judiciary branch for their interests. The change in the political structure confronting the nuclear industry undermined the feasibility of credible commitment of government toward the industry. Subsequently, this helped lead to the decline of the commercial nuclear industry in the U.S in addition to the Three Mile Island (TMI) accident. This situation contrasts the environment of the French nuclear industry.

The American combination of fragmented power, little reliance on bureaucratic expertise, an independent judiciary, and opposing interest groups greatly undermines the ability of the U.S. government to credibly commit to the nuclear power industry. In France, despite substantial anti-nuclear interest groups, the impermeability of the institutional setup—no division of power, weak judiciary, and reliance on bureaucratic expertise—effectively prevents activists from influencing policy outcomes.[64]

The French exploration into commercial nuclear energy and subsequent promotion of nuclear energy was the result of "a perceived shortage of enriched uranium, a need for weapons-grade materials, and the desire for energy independence from foreign states."[65] In

[61]Jasper, J.M., 1990.
[62]Jasper, J.M., 1990.
[63]Delmas, M. and Heiman, B., 2001.
[64]Delmas, M. and Heiman, B., 2001.
[65]Delmas, M. and Heiman, B., 2001.

contrast to the U.S., the political environment in regards to nuclear energy in France has remained stable over the course of the last fifty years.

In 1955, three government organizations banded together to promote nuclear power; namely: Electricité de France (EDF—the state—owned utility empowered by the Ministère de l'Industrie et des Finances), the Commissariat à l'Energie Atomique (CEA—with a promotional mission parallel to America's AEC), and Production d'Electricité d'Origine Nucléaire (PEON—an advisory group to the CEA comprised of CEA, EDF, state, and industry representatives).[66]

The nuclear industry maintains a high degree of central planning and state integration.[67] This political environment has provided the means for credible government commitment to the industry. Though there has been strong anti-nuclear rhetoric domestically in France the well insulated governmental setup towards nuclear energy has prevented these groups access to any policy-making forum. Further, these groups are afforded less influential power toward the industry due to a weaker judiciary than is present in the U.S.[68] Therefore, the uncertainty surrounding the commitment of the government toward the nuclear industry in France is far less than in the U.S. The French political structure "can carry out a long-term policy while ignoring the fluctuations of public opinion."[69] This lack of "uncertainty" is important when we consider the effect that it has on transaction costs for the utilities attempting to employ nuclear facilities and investors realizing a return on their outlays.

The U.S. political structure has led to an increase in transaction costs for its domestic nuclear industry, while the French structure is able to mitigate similar types of increases. As a result of the political structure, transaction costs for the nuclear industry are higher in the U.S. than they are in France. In opening the policy forum to anti-nuclear interest groups, the U.S. nuclear industry experienced procedural delays and increased compliance costs for nuclear facilities. From 1954 to 1979, the average lead times, including the time from order through commercial operation, increased from 2 to 6 years in France and from 3 to nearly 13 years in the United States.[70] Further, French programs

[66]Delmas, M and Heiman, B., 2001.
[67]Jasper, J.M., 1990.
[68]Studness, C.M., 1992.
[69]Delmas, M. and Heiman, B., 2001.
[70]Nuclear Energy Agency,1991.

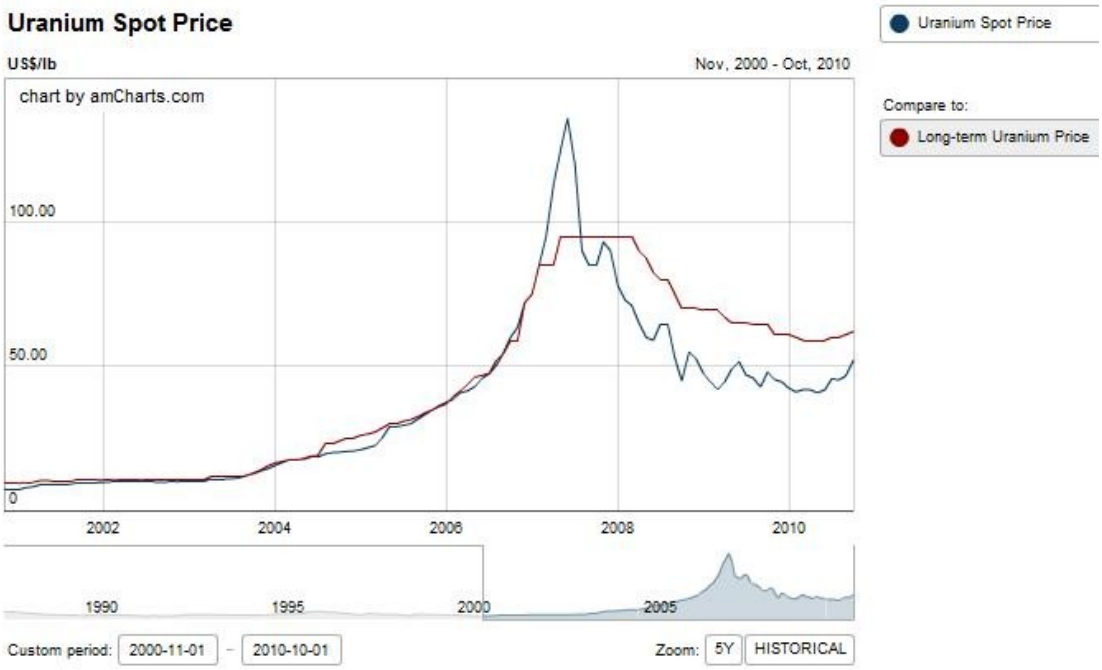
typically presented greater stability in lead times as well as fewer delays than in the United States.[71] The nuclear industry in the U.S has seen an increase in uncertainty for their transaction costs in order to protect their large sunk costs. This has resulted in an increased perception of risk on the part of investors and subsequently increased the cost of capital for the technology: "lengthening the regulatory process increases the capital costs of the plant by pushing the revenue received from operation further into the future and by adding to the total interest payments on construction loans."[72] This political institutional framework provides an understanding of the challenges which confront nuclear reprocessing in the U.S.

In understanding the political context for nuclear technology in both the U.S. and France, it is possible to estimate how the lack of government incentive could inhibit nuclear reprocessing technology in the U.S. The U.S. government has not been able to give the same type of credible commitment that the French government has toward their nuclear industry. This lack of credible commitment can increase the risk associated with and cost of investing in this nuclear reprocessing technology.[73] Therefore it may be necessary to evaluate the limitations posed by the current institutional framework to incentivize the development and subsequent growth of the domestic nuclear reprocessing industry. This is an issue not only confronting nuclear reprocessing but the industry as a whole. Although nuclear reprocessing has not achieved viability domestically, the United States has signed an agreement with India that enables Indian reprocessing of U.S. originated nuclear material in accordance with the safety provisions outlined by the International Atomic Energy Association (IAEA).[74] This agreement will facilitate the participation of U.S. firms in India's expanding civil/nuclear market.[75] Further, the U.S. also entered into agreements with Japan[76] and Italy in 2009 to reprocess its domestic nuclear fuel waste.[77] These agreements may imply that the U.S. industry and government realize that if the U.S. is to take part in nuclear reprocessing it may not be able to accomplish it internally due to domestic politics.

[71] Commission a l'Energy Atomique, 1994.
[72] Weingast, B.R., 1980.
[73] North, D., 1990.
[74] Reuters, 2010.
[75] The Economic Times, 2010.
[76] The Wall Street Journal. 2009.
[77] Ne.doe.gov. 2009.

IV. Economic Analysis

The economic viability of reprocessing fuel depends on the additional costs of reprocessing. Reprocessing adds several steps to the nuclear fuel cycle, each of which requires an initial investment and operating costs. This results in more nuclear fuel, and less intensive storage. A critical factor of this analysis is future projections: on-site storage is growing scarce in the United States, and uranium prices are prone to fluctuation and may rise as reserves diminish. At present, it is more expensive to reprocess fuel than to enrich new uranium. However, reprocessing costs have continued to decline, and uranium prices have been rising.This is expected to continue, as the long-term futures prices for uranium are higher than the current spot prices.[78]



The decreasing availability of on-site storage in the United States has also made reprocessing more advantageous, especially in combination with the end of the Yucca Mountain project. Around the world, reprocessing has been seen as short-term solution

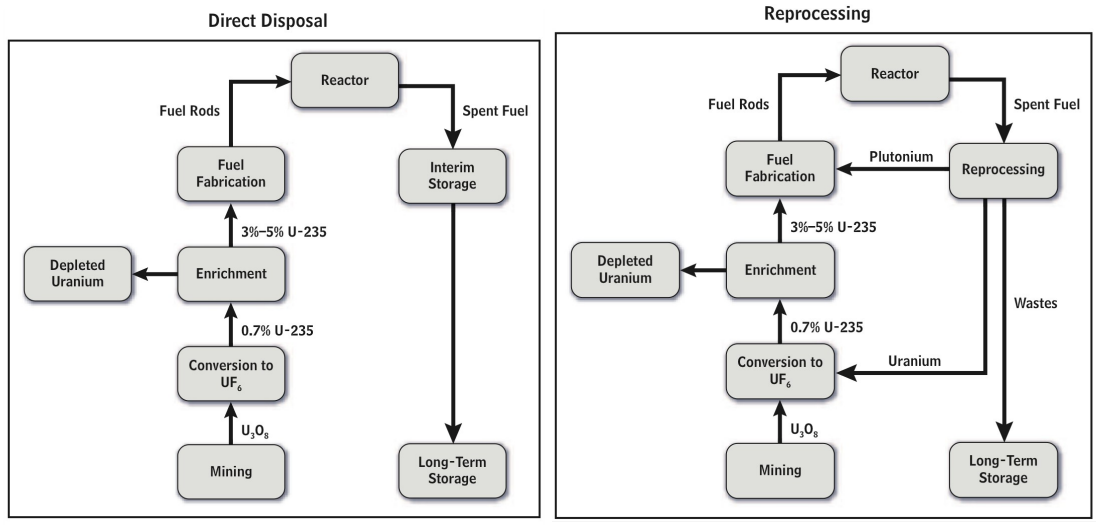
[78]http://www.cameco.com/marketing/uranium_prices_and_spot_price/spot_price_5yr_history/

given that many centralized disposal sites will not be operating for some time, as seen below:[79]

Table A-7.A.1 High-level Waste Disposal Plans of Leading Nuclear Countries

COUNTRY	MANAGEMENT RESPONSIBILITY	PREFERRED/ SELECTED GEOLOGIC MEDIUM	EARLIEST ANTICIPATED REPOSITORY OPENING DATE	STATUS
United States	DOE	Volcanic tuff	2010	Site selected (Yucca Mountain, NV); application for construction license
Finland	Power companies (Posiva Oy)	Crystalline bedrock	2020	Site selected (Olkiluoto, SW Finland) — decision ratified by Parliament in May 2001
Sweden	Power companies (SKB)	Crystalline rock	2020	Searching for a suitable site
Switzerland	Power company coop (Nagra)	Crystalline rock or clay	2020 or later	Searching for a suitable site
France	Ind. Pub. Auth. (ANDRA)	Granite or clay	2020 or later	Developing repository concept
Canada	Crown Corp. (AECL)	Granite	2025 or later	Reviewing repository concept
Japan	National agency (NUMO)	Not selected	2030	Searching for suitable site
United Kingdom	Under review	Not selected	After 2040	Delaying decision until 2040
Germany	Federal contractor company (DBE)	Salt	No date specified	Moratorium on repository development for 3–10 years

The figure below demonstrates the additional steps that reprocessing adds to the process of nuclear fuel generation. In this paper, we will quantify those *additional* costs and benefits that nuclear reprocessing adds onto the existing cycle of nuclear fuel generation. The additional costs include the cost of reprocessing fuel and the cost of storing the remaining waste. The benefits are the decreased amount of uranium that a reactor needs from mining (since it is now supplied by reprocessing), and the decreased amount of storage, as well as less quantifiable benefits such as national security.



Diagrams of the direct disposal method of nuclear fuel generation and the reprocessing method.[80]

[79]MIT

Literature Review

Many previous papers have totaled costs of nuclear reprocessing, either in addition to the existing nuclear fuel process or by finding the levelized cost of electricity for reprocessed fuel. The standardized different cost assumptions that various papers used are enumerated in the table below.

		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

[80]Congressional Budget Office. 2007.

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%

Table 1: Standardized cost assumptions across papers.[81]

The conclusion of these papers vary widely. Ramirez has estimated that it is approximately 4% more expensive to reprocess fuel than to use a once-through cycle.[82] Zagar reports a .2 cent (2009 Euros) cost per kilowatt-hour to cover the closed nuclear cycle; this is approximately $2.8/MWh.[83] Schneider breaks down the costs of the different components of a reprocessing system and finds that reprocessing costs cannot be covered by current utility charges.[84]

The Boston Consulting Group (BCG) estimated that the costs of reprocessing were similar to those of the once-through cycle; the Congressional Budget Office (CBO) reviewed this study and concluded that the low costs reported by BCG were partly attributable to the favorable assumptions they made.[85] After normalizing the assumptions made by BCG and Bunn, the CBO concluded that reprocessing would cost approximately $5.6 to $10.8 billion more than direct disposal in present-value terms with a discount rate of 3.5%. An MIT study found that reprocessing added an additional 20-34% to the fuel cycle costs of nuclear energy; this appears to be close to a median value.[86]

Utilities currently pay $1/MWh to cover storage costs for the once-through cycle; this is lower than the reprocessing costs (between $1.056 to 2.658/MWh), although this does not include the value of the recovered fuel.[87] This $1/MWh charge approximately translates to $400/kgHM for storage on unprocessed LWR waste. The Department of Energy has maintained that the currently legislated fee for long-term storage is adequate, but the actual costs estimates are reliant on a large number of economic and financial assumptions.[88] Reprocessing costs could be covered by utility charges if costs could be

[81]de Roo, et al 2009.
[82]Ramírez,et al, 2009.
[83]Žagar, et al 2010.
[84]Schneider, et al, 2009.
[85]The Boston Consulting Group. 2006.
[86]de Roo, et al, 2009.
[87]Schneider, et al, 2009.
[88]Department of Energy. 2009.

improved from the current operating and construction costs at nuclear reprocessing facilities in operation.

Costs

We consider the additional costs of the life of one reprocessing facility, which includes the construction and operating costs of a reprocessing facility and the storage costs for the remaining waste. Since the value of costs were often given in $/kgHM units, we estimate the lifetime operation of a reprocessing facility. The lifetime of a reprocessing facility ranges from 30 years to 60 years.[89] Capacity is estimated at 85% in de Roo, but the CBO notes that the current La Hague and THORP facilities only operate at 60-65% capacity. Schneider estimates the full capacity of a reprocessing facility at 900 tHM/year.

Therefore, a reprocessing facility that started operations in 2010 could potentially have the following reprocessing capacities, with a yearly cost of $1.224 billion at 85% capacity and $864 million at 60% capacity, which includes both reprocessing, transportation, and storage:

	60% capacity (CBO)	85% capacity (de Roo)
30-year lifetime (Schneider)	16,200 tHM	22,950 tHM
60-year lifetime (de Roo)	32,400 tHM	45,900 tHM

Standard Assumptions:
Full capacity: 900 tHM/year (Schneider)
PUREX reprocessing cost (inclusive of storage, transportation, construction): $1,600/kgHM (de Roo)

Disposal costs are addressed in the benefits section, since disposing of reprocessed HLW is less expensive than the once-through cycle waste. Disposal costs for reprocessed waste is $200/kgHM, or $180 million a year, but is a net benefit because it results in 50% storage savings.

Benefits

Reprocessing decreases the amount of nuclear waste that needs to be stored, so the main benefit of reprocessing is the amount of storage saved from reprocessing fuel. Bunn

[89]Schneider, 2009. de Roo, 2009

estimated that overall repository costs are decreased by around 50% with reprocessing; repository costs of $400/kgHM for the nuclear fuel cycle will only be $200/kgHM for reprocessed high-level waste. A reprocessing facility with 900 tHM/yr capacity will therefore save $180 million in annual disposal costs. In total, over $35,407 million has been paid into the national Nuclear Waste Fund up until November 2010.[90]

Uranium prices have also been rising due to increased demand, a trend that may have long-term repercussions. Identified uranium deposits can fuel existing nuclear plants for about 80 years without reprocessing. Reprocessing can extend the life of current uranium resources for an additional 15 to 20 years.[91] Total conventional uranium resources, including undiscovered deposits that are estimated using indirect geological evidence and extrapolated values, can fuel existing plants for around 200 years.[92] In the short-term, however, prices have risen sharply because of an announced increase in nuclear plants that will require fuel: China is intending to increase nuclear power as a source of national energy by 7% in the next ten years, and countries such as Russia, Pakistan, and South Korea are all building new reactors.[93] Another benefit of reprocessing is the additional plutonium and uranium recovered per kilogram of spent fuel reprocessed; this amount replaces a portion of the raw material that goes into the fuel cycle. The amount of recovered uranium is .94 kg/kgHM, and the amount of recovered plutonium is .01014 kg/kgHM.[94]

[90]NEI

[91]Žagar, p.2
[92]Žagar, Table 1
[93]Lorinc, J., 2010.
[94]Bunn, p. 91

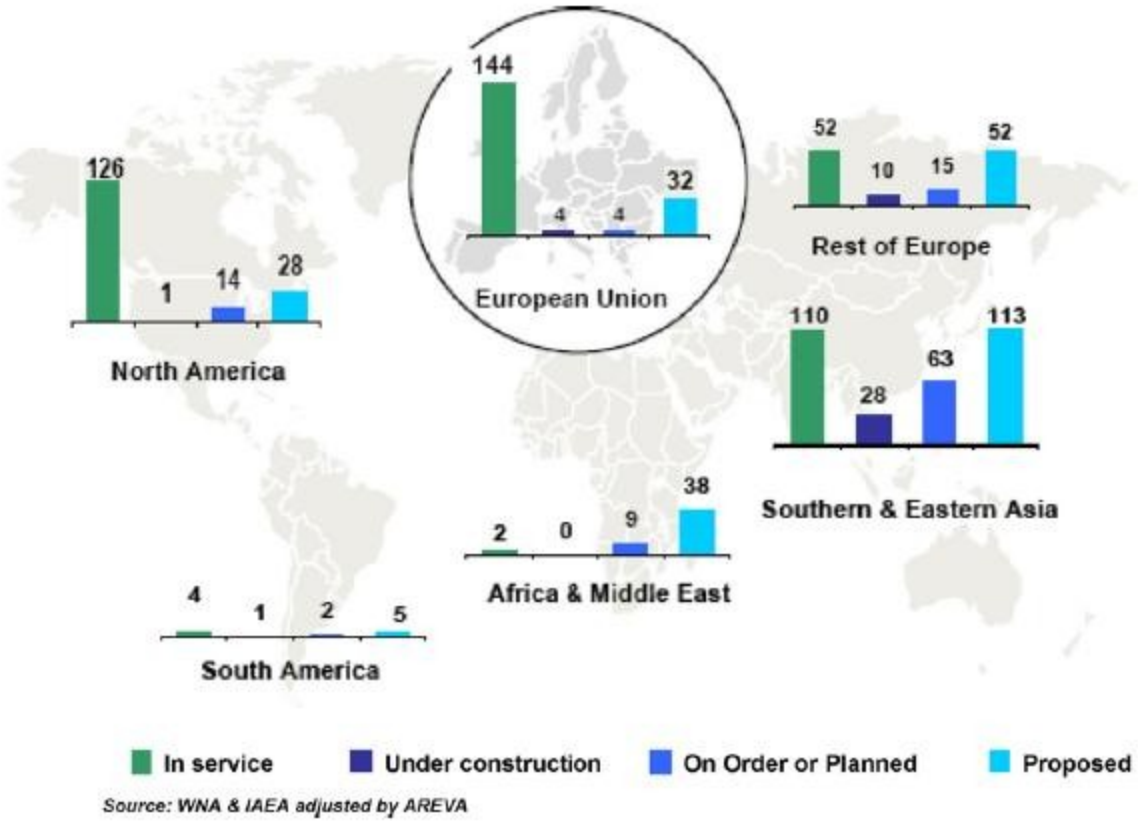


Fig. 1. Rising demand for clean energy is supporting the nuclear renaissance (end of 2008).

There are two benefits to this replacement: the fuel cycle inputs less new raw uranium, and the uranium produced from the reprocessing is already enriched. To calculate the reduction in raw uranium costs, we used the following values: a 900 tHM/year reprocessing capacity, 0.94 kg enriched U/kgHM, $60/ton of raw U, and a 14% conversion from raw to enriched uranium. These calculations are all referenced earlier in the section; our calculations showed that a reprocessing facility at this capacity would save the fuel cycle $362,571/year from less purchases of raw uranium.

This calculation also demonstrated that the 846 tons of enriched uranium that the reprocessing facility produces annually would initially have had to come from 6,043 tons of raw uranium if produced in the once-through cycle. We use this value to calculate the saved enrichment costs; the conversion ratio we use in the once-through fuel cycle is .9686 SWU/kg of raw uranium. With an average enrichment of uranium cost of $123/SWU (an

[95]Žagar

average of the costs in the table above), we calculate that reprocessing yields a savings from enrichment of approximately $720 million/year.

The table below summarizes the quantifiable benefits and costs:

Annual Costs	**Annual Benefits**
Reprocessing (lower-end): $864 million (higher-end): $1.224 billion	Uranium purchase: $362,571
	Storage: $180 million
	Uranium enrichment: $720 million
Total: $864-1,224 million	**Total**: $900.36 million

Additional Considerations: FOAKE Costs, Learning Effects, and Proliferation

One important question in price modeling is how quickly costs will decrease over time. Initial plants incur many FOAKE (first of a kind engineering) costs, such as engineering design specifications, regulatory red tape, and establishing a supply chain for materials for construction and operation. One might expect FOAKE costs to be high in the U.S., as there have been no reprocessing plants built in the country for many years. On the other hand, some of the FOAKE costs may be mitigated by transferring technology and expertise from other countries with reprocessing facilities. In order to get reprocessing off of the ground, there may be a case for government involvement in a demonstration project to overcome FOAKE costs. This would also be useful in relaxing public safety concerns and establishing a bureaucracy to deal with the regulation of reprocessing. In nuclear plants, FOAKE costs have been estimated to increase the overnight cost of the first plant by up to 35%.[96]

After FOAKE costs have been absorbed, there are additional cost decreases that can occur over time as engineers learn how to construct plants more efficiently and as companies scale up production with several of the same units at the same location. It has been estimated that learning effects result in cost decreases of 3-10 percent every time the number of plants built doubles; ultimately, this wide range reflects the difficulty of making

[96]RCF, 2004.

this assumption.[97] Scaling effects may not be quite as relevant to reprocessing plants, as there are fewer examples of multiple reprocessing units built side by side, relative to how common this is in nuclear plants.

Other unquantifiable costs include proliferation threats and environmental costs, both of which involve a great deal of uncertainty and are discussed in previous sections. In conclusion, however, most of the additional considerations of unquantifiable factors are costs, which suggests that while the quantifiable benefits above fall within the range of the quantifiable costs, the larger costs outweigh the benefits of reprocessing.

[97]RCF, 2004.

V. Conclusion

Conducting a formal cost-benefit analysis of nuclear fuel reprocessing is a difficult prospect because of the large uncertainties involved in long-term waste management and in the potential costs of reprocessing in the United States. Beyond this, there is also the question of "Whose costs, and whose benefits?" Private utilities may decide to reprocess waste or not, given the option; what we are more interested in is what government agencies should or should not do. To begin with, should the U.S. allow for the reprocessing of nuclear waste? The main argument against allowing reprocessed nuclear waste entails unacceptable proliferation risks; in the intervening years, technology has evolved to the point where this can be avoided. Our first recommendation, then, is to allow for private companies to use certain proliferation-resistant methods of reprocessing, such as UREX. However, at this point in time, it would make more sense to wait for pyroprocessing to be developed on an industrial scale. The construction of an aqueous solvent extraction plant would be out of date, especially when the more promising option of pyroprocessing is on the horizon. In comparison, to current available methods, pyroprocessing produces virtually no waste, can be done on-site, and offers the option of fabricating proliferation resistant fuel from plutonium as well as uranium.

The second question in regard to domestic reprocessing is, "how much direct involvement should the government have in the reprocessing business?" Government involvement could be justified on the grounds of the externalities present in nuclear waste disposal. This could take on a variety of forms - government research efforts, subsidizing reprocessing (or offering tax credits and loan guarantees), or even operating a reprocessing center on its own. Through its actions, the government will be able to influence the development and growth of the nuclear reprocessing industry in the United States.

These efforts in support of pyroprocessing and other advanced fuel cycle technologies represent a small portion of the Department of Energy budget - only $142,652,000 out of a total of $33,856,453,000 in discretionary funding in FY 2009, or less than half of one percent[98]. Furthermore, private companies do not have sufficient independent incentives to reduce the long-term health and environmental consequences of

[98]DOE Appropriations

nuclear waste disposal. While it is beyond the scope of this paper to present a formal cost-benefit analysis of R&D efforts, given the minimal costs and the large potential benefits, the chances of success do not need to be very high to justify continued government expenditures in this area.

It is far less clear whether or not reprocessing in its current form should be subsidized in one form or another by the federal government. Though the current technology reduces some of the long-term storage issues, it still poses substantial environmental costs. In terms of the direct options available to the government, there are several main alternatives to be considered:

1) Re-open Yucca Mountain, use it to store waste, of either reprocessed, single cycle, or a mixture; this has the advantage of not needing to implement any new technologies. This plan could be an immediate solution to our nuclear waste problem. This strategy would not incentivize research or investment in domestic reprocessing technologies. Assuming things remain the way they are, reprocessing produces six times the amount of waste produced by single cycle, and without advancement efforts in technology there would be no improvements to nuclear waste management.

2) Open a centralized reprocessing plant, and instead of using Yucca Mountain to store reprocessed waste, several smaller repositories (perhaps on-site) could be utilized. Centralized reprocessing plants could take advantage of economies of scale and advancing technologies, but as discussed earlier in the economics section FOAKE costs could be high and transportation of the waste could be both expensive and a security hazard. On-site storage, however, is a viable option for the government to consider with the incentive of subsidies or reimbursement, especially in light of the Obama administration's decision to discontinue funding for Yucca Mountain.

3) Outsource both the waste and the storage to another country, such as India, Japan, or France. This solution enables the U.S. to resolve many issues which have arisen from the current and projected domestic nuclear waste levels. As indicated before , the internal politics of the U.S. may not permit the nation to employ nuclear reprocessing as a solution to its nuclear waste. However, there may be safety concerns in allowing a third party to control all of the U.S.'s nuclear waste, as well as increasing the risk of terrorism. Further, the U.S. would be relegated to a passive role in the international dialogue for appropriate nuclear waste resolution.

4) Close Yucca Mountain, pay the Nuclear Waste Management Fund back to the utilities that contributed to it, and allow them to decide how to manage the waste their plants produce (with some regulatory oversight). Allowing the private utilities to deal with the waste would enable them to choose strategies to most efficiently manage their nuclear waste. However, this could only be possible with government oversight in order to avoid principal-agent problems. This option allows for autonomy on the part of the private utilities, which might create conflicts of interest between the nuclear industry and the government.

5) Expand on-site storage in the short-term until pyroprocessing technology is sufficiently advanced. Though current technologies are not cost-effective and have deleterious environmental consequences, waiting for pyroprocessing technology to mature may be a worthwhile option. As research into newer technologies continues, on-site storage could be expanded at lower costs. Since pyroprocessing could be performed on location,, it would be beneficial to have the waste directly on-site to process and reduce transportation of nuclear material from off-site storage (reducing transportation costs as well as diminishing the risk of accidents or the hijacking of the material en route to the plant).

Of these options, we believe that the fifth has the most promise. Nuclear reprocessing is too environmentally hazardous and expensive given current technological constraints and uranium prices, although this could change in the near future with scientific improvements. Increasing government support of advancements in reprocessing in the U.S. would encourage growth and investment in this technology. Therefore, continued government commitment to researching pyroprocessing and other advanced fuel cycle technologies is vital to the nuclear industry, especially if we envision this technology maturing internationally. As unsustainable as our current nuclear waste disposal strategies are, we believe in the current political climate, commercial reprocessing in the United States are not a viable option due to high environmental and technological costs, as well as having significant nuclear proliferation threats. However, in order for the U.S. to employ pyroprocessing in the future, the government must begin now to incentivize the technology for firms and investors. As uranium prices are expected to increase in the future, as well as an increasing concern regarding the management of nuclear waste worldwide, reprocessing may become a promising solution provided investments are made to address current challenges in the field.

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