Nuclear Fuel Reprocessing

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Executive Summary

A nuclear reprocessing facility takes the spent fuel from nuclear power sources and regenerates the fuel into a usable form once again. There is not a nuclear reprocessing facility currently operating in the United States. However, countries such as France and Japan are developing more and more dependence on reprocessing cycles. With foreseeable increases in the nuclear power market over the next few decades, it will become imperative that the United States develop a spent fuel reprocessing infrastructure. Most reprocessing today uses the PUREX process. This process can be inefficient at times. Another drawback is that it produces high levels of potential weapons grade material. Because of this, it is proposed that a new and more efficient process can be developed for nuclear reprocessing cycles.

In order to facilitate the need for a new reprocessing technique, crown ethers were evaluated for their economic feasibility as well as their overall nuclear fuel reprocessing capabilities. Through the use of experimental data, it was determined that crown ethers were indeed capable of extracting uranium out of the spent nuclear fuel. An analysis was done using various crown ethers while varying the hydrobromic acid concentration. Once this data had been evaluated, it was determined that the Dibenzo-24-Crown-8 crown ether with a hydrobromic acid concentration of 7.5M was optimal for the extraction of uranium from the spent fuel. Once the organic phase containing the uranium had been separated from the rest of the fission products, it is shown that using a hydrobromic acid concentration of .45M is optimal for stripping the uranium away from the crown ether.

With the type of reprocessing method now determined, a site location and economic analysis was needed. Based on current storage numbers of U.S. spent fuel and projections for the coming years, it was estimated that a reprocessing facility with a 7500 metric ton/yr capacity was needed. The site location was determined by analyzing the locations and amount of spent fuel produced by all nuclear power plants in the United States. From this, an idealized location was determined to exist in Metropolis, IL. A rudimentary cost analysis was performed on the proposed reprocessing facility in Metropolis, IL. The estimate placed the total capital investment for the plant at approximately \$50 billion. The yearly operating costs were estimated to be at approximately \$1100/kg of spent fuel reprocessed. This equates to around \$3.3 billion yearly.

Table of Contents

List of Illustrations

Figures

Tables

Equations

I. Introduction

a. Problem Statement

Current U.S. policy dictates that long-term storage methods are more economically feasible than nuclear spent fuel reprocessing. However it is estimated, with the continual rise in oil prices and the concerns surrounding global warming, that nuclear power could grow exponentially from the 20% energy market share it has now in the United States [3]. If this does happen, the need for spent fuel reprocessing will become necessary. One of the main drawbacks to reprocessing, besides its costly nature, is that fact that it often leaves the reprocessed fuel in state such that it can be easily converted in to a weapons grade material. Because of this, there is a need for new reprocessing techniques which provide safe and economically viable methods of spent fuel regeneration.

b. Background

The process of nuclear fission involves striking or bombarding an atom with neutrons. This bombardment of the atom causes its nucleus to “fissile” and split into smaller nuclei. This phenomenon was first studied by Enrico Fermi in 1934. While his research never fully unlocked the realizable extent of nuclear fission, it paved the way for those who followed him to harness the energy produced [3]. Further research showed that nuclear fission could spark a chain reaction of sorts in certain atoms. Namely ^{235}U and ^{239}Pu, certain particles can undergo spontaneous fission, releasing neutrons into a controlled environment. These neutrons then spark a chain of reactions, impacting other fissile particles. A ^{235}U isotope, when undergoing nuclear fission, breaks down into two smaller atoms while producing 3 additional neutrons. Because more neutrons are produced than atoms, the chain reaction is more conducive to continue. A ^{238}U isotope on the other hand produces fewer neutrons while undergoing nuclear fission. It breaks down into numerous other elements including lead. Lead can act as a barrier in the sustainable fission process preventing the chain of reactions from continuing. Because of this, ^{238}U is not utilized by itself as a weapons grade energy source. The ^{238}U isotope can however be broken down into ^{239}Pu isotope, which is a fissile isotope [3].

Nuclear energy is produced via a nuclear reactor. Most nuclear reactors are used as a source of electricity, though some are used to produce weapons grade nuclear material. The nuclear reactor harnesses the energy produced by nuclear fission and uses it to power turbines. The turbines in turn produce electricity to power communities. Most nuclear reactors today use a sustained fission reaction. A nuclear reactor utilizes continual, controlled fission reactions as its source of energy. The reaction takes place within a reactor vessel. This, along with the pressurizer, localizes the energy produced and uses it to produce steam from a continual water supply. The steam then proceeds to drive large turbines which in turn produce the desired electricity.

Nuclear fission can also be used to form weapons grade uranium and plutonium. With the advances made in technology over the past two decades, concerns have arisen around the increasing access and availability of these materials. Nuclear proliferation, as it is called, has led to more governmental regulations and less incorporation of nuclear power into countries such as the United States. Nuclear proliferation is a term used to describe the efforts made in preventing the spread of weapons grade and fissile materials. A nuclear power plant has not been built in the United States since the mid 1980's. There however has been a renewed interest in nuclear power over the past decade due to the environmental concerns and rising costs of the oil industry. The "Nuclear Power 2010 Program" was initiated by the U.S. Government in 2002 to address the projected growing energy demands using nuclear power. The program is aiming to renew interest in nuclear power and identify sites for nuclear reactors to be built in the future.

As a result of nuclear proliferation, along with long term storage concerns, more attention has been given to nuclear reprocessing in recent years. While very expensive, nuclear reprocessing may provide a solution to these growing problems. Research is being done to further develop recycling processes that convert spent nuclear fuel into a reusable energy source while at the same time removing elements of the fuel that make it easily converted into a weapons grade material. Solutions such as these may prove to be the long term answer in providing a safe and effective method for handling nuclear waste.

II. Nuclear Fuel Cycle

The process to prepare uranium for use as an energy source involves numerous steps. Initially, the uranium is mined from the earth as an ore. This ore only contains small trace amounts of the desired uranium oxide, U_3O_8 typically in the range of 0.05 to 0.3 wt%. Of this uranium oxide, two different isotopes exist. One isotope is ^{235}U which leads to the process of nuclear fission. The other isotope found is ^{238}U which during nuclear fission undergoes a transformation into plutonium and members of the actinide group. The amounts of the two isotopes found in this uranium oxide ore are approximately 0.71% ^{235}U and 99.29% ^{238}U [3]. Once removed from the ground, the ore undergoes a milling process to strip the uranium oxide from the surrounding rock. This process is typically referred to as chemical leaching. Chemical leaching is a process whereby a highly selective solvent is used to remove a metal from its ore. The solvent breaks down the ore, and selectively isolates the metal, in this case the uranium. Now isolated, this uranium oxide resembles a yellow solid slurry and is known commonly as “yellow cake” [3].

Figure 1. Uranium Ore/Yellow Cake

Uranium enrichment is the next step in the nuclear fuel cycle. Enrichment increases the percentage of ^{235}U in the yellow cake. This step is site dependent; meaning the amount of enrichment undergone depends on the needs of the nuclear reactor. A common enrichment process is the conversion of uranium oxide to uranium hexafluoride (UF_6). In this process, U_{235} increases from .71% to 3.5% in the isolated uranium compound. One other process is enrichment through uranium dioxide (UO_2). The now enriched uranium is formed into small pellets. These pellets are then placed into fuel rods. A fuel rod is a stainless steel and zirconium casing containing these small pellets of enriched uranium. The nuclear fuel rods are what actually make up the core of a nuclear reactor. They are arranged into fuel bundles, a grouping of 6 to 8 individual fuel rods. Each fuel bundle has a life span of 2 to 6 years within the reactor. There are numerous fuel bundles within the core of the reactor. The core is cycled every 12 to 18 months, with spent fuel rods being removed and new ones integrated [1].

III. Storage Method

a. Storage Devices

After the basic nuclear cycle is completed, the spent fuel is removed and placed in a spent fuel pool. It is here that the nuclear waste is allowed to cool down over a considerable period of time. Typical operations place spent fuel rods in these pools anywhere from 1 to 5 years. There are certain operations requiring upwards of 10 years in wet storage. In each case, the design for the specific pool is unique to each reactor site. This is due in part to each reactor's consumption methods and capacity to produce spent fuel. A typical nuclear facility will undergo turnaround every 12 to 18 months with portions of the nuclear core being replaced and sent on to the spent fuel pool.

Due to the immense amount of heat and radiation generated by these now-spent rods, the process is generally automated and occurs in a very controlled environment. The pools are typically 30 to 100 ft deep, providing adequate safety precautions (the Nuclear Regulatory Commission dictates approximately 10 ft as a safe distance below the surface). The pools are filled with water for the cooling process. To prevent the water from heating to a point of vaporization, a cooling process runs continuous to the spent fuel pool cycle. Here, the water is circulated continuously through an extensive system of heat exchangers maintaining a relatively cool environment within the pool while extracting the heat generated by the fuel rods [8].

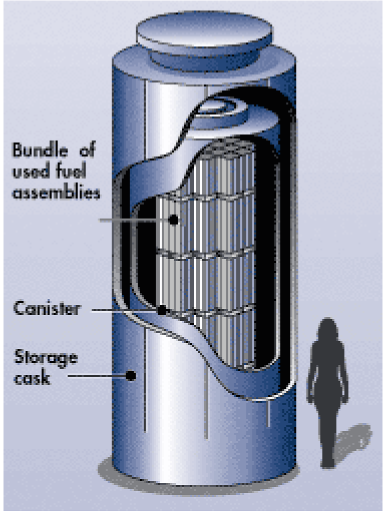

Figure 2. Dry Cask Storage

It estimated that space at existing spent fuel pools will reach maximum capacity within the next two decades. Because of this, new measures were instilled to counteract this impending problem. One such method was to cycle the fuel rods from the spent fuel pool after the cool down period and store them in what are termed "dry cask storage devices". These are large tanks wherein the fuel rods are stored in an inert, gaseous environment. Encapsulating the spent fuel rods and inert gas are layers of steel and concrete to prevent radioactive emissions from the storage tanks. Each tank can hold anywhere from 2 to 6 dozen fuel rods. Even still, questions continue to arise concerning the lack of space for spent fuel storage. The surrounding areas of nuclear power facilities were not originally designed to accommodate these dry cask storage tanks. A movement has been underway to take the storage tanks from each facility and locate them at a single depository, Yucca Mountain [8].

b. Yucca Mountain

Current U.S. policy dictates that spent fuel storage rather than spent fuel reprocessing is the most logical choice given our current infrastructure. Further, U.S. policy has evolved to believe that as we become more dependent upon nuclear power as an energy source for the future, a single depository site is necessary for all spent waste to be stored. Currently, over 126 separate storage facilities are located across the country. As the demand for energy continues to drive expansion within the field of nuclear energy, more and more changes must be made at existing facilities. It has been proposed that in the future, the costs of evolving each site separately will far outweigh that of one national depository.

Yucca Mountain resides on a tectonic ridgeline in the south-central region of Nevada on the land surrounding the Nellis Air Force Range [4]. It is here that the proposed national depository for all U.S. nuclear waste and spent fuel has been developed. The Yucca Mountain Project started in the early 1980’s when the government commissioned a study on the feasibility of a single depository site for all the spent nuclear fuel in the United States. The reasoning at the time was that a single storage facility would be much cheaper than maintaining hundreds of separate storage facilities at each of the nuclear plants across the country. Originally, 9 sites were commissioned for study. Slowly, sites were eliminated after being deemed unfit for the proposed facility. Not without opposition, the Yucca Mountain site was selected as the national nuclear depository for all spent fuel including that from the weapons program [4].

Yucca Mountain is proposed to begin full operation in the year 2017 [3]. Spent waste from facilities all across the country will be sent to the mountain for storage. An extensive tunnel system has been developed to accommodate the spent fuel. Branching out from each tunnel are individual alcoves. It is within these, 1000 ft below Earth's surface, that the spent fuel will be stored. The means of storage (dry cask storage) will be similar to what is currently being used where the only difference is that it is located in the depths below Earth's surface. A schematic for Yucca Mountain's operation is detailed in Figure 3 below.

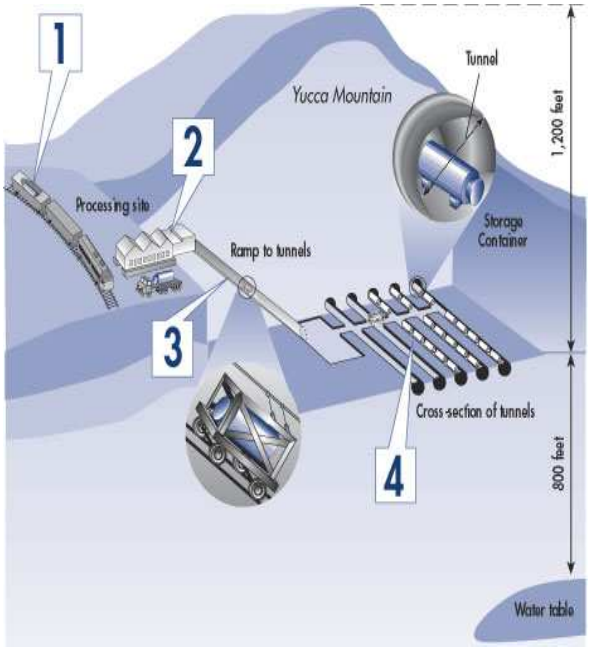

Figure 3. Yucca Mountain

Yucca Mountain has been met with strong opposition at the local, state, and national levels. Locally, concerns as to whether the facility is safe for nearby residents continues to be an issue. About a 1000 ft below the spent fuel depository is a water table which provides water to much of the surrounding area. Government experts feel this is a non-issue as the water table is at a level well below that of the maximum projected run off should leakage occur. Statewide, citizens oppose the project because the state of Nevada has no great dependence upon nuclear power as an energy source. Not a single nuclear power plant facility lies within state boundaries but yet they must store the waste from other states who do utilize this resource. Nationally, much debate has taken place concerning the exorbitant funding of the Yucca Mountain Project. Estimates have shown that approximately $10 billion has been spent to date with upwards of another $100 billion to be spent before the project even reaches full operational capabilities. Needless to say, Yucca Mountain has become the most studied geographic area on the face of the earth [3] [4].

Results

a. PUREX Process

The recent interest in nuclear fuel reprocessing has set in motion the eventual replacement of the current reprocessing technique. Although reprocessing-used nuclear fuel had been originally carried out by several commercial facilities, reprocessing of used nuclear fuel has been banned in the United States since the mid 1970’s [3]. The main reason why commercial reprocessing was eventually banned, through a presidential directive, was increasing concern over nuclear proliferation. In the past, commercial reprocessing facilities reprocessed used nuclear fuel from nuclear power plants to extract out the un-used uranium and any other valuable fission byproduct. Although at that time a small portion of the materials extracted out of used nuclear fuel was used for medical purposes, it was the ability to extract weapons grade plutonium that created increasing concern for the security of the United States and eventually led to reprocessing permanently being banned.

As previously mentioned there has been recent interest in reprocessing used nuclear fuel. The reason why nuclear fuel reprocessing has been brought to the forefront again is the overwhelming success of next-generation nuclear reactors (mainly CANDU type reactors that have the capability of using uranium from used nuclear fuel). Previously built reactors were only capable of using uranium that had been properly put through the enrichment process. This was done to increase the wt% of U_{235}, which is the isotope of uranium that under goes nuclear fission [12]. Natural uranium that is mined out of the ground is typically .71 wt% U_{235} and must be enriched to a U_{235} wt% of approximately 3.5 to 5 wt% [12]. Although nuclear fission is very efficient, there is typically un-reacted U_{235} that can be extracted from used nuclear fuel.

Originally CANDU reactors were designed to use natural uranium that is only .71 wt% U_{235}. After repeated successes, the idea was proposed to reprocess currently stored used nuclear fuel and use this uranium in CANDU-type reactors. What makes this idea of reprocessing so promising is the fact that most used nuclear fuel is .9 wt% U_{235} due to the above mentioned incomplete nuclear fission. In theory, this reprocessed uranium can potentially work better in the CANDU reactors than mined uranium. Naturally, this increased interest in used nuclear fuel drove the nuclear industry to reevaluate the current method of reprocessing.

Although not used in the United States, the PUREX Process has been used and perfected in various reprocessing facilities throughout the world. As can be seen in Figure x below, the PUREX process is capable of reprocessing used nuclear fuel while extracting out its two most valuable components: uranium oxide and plutonium oxide.

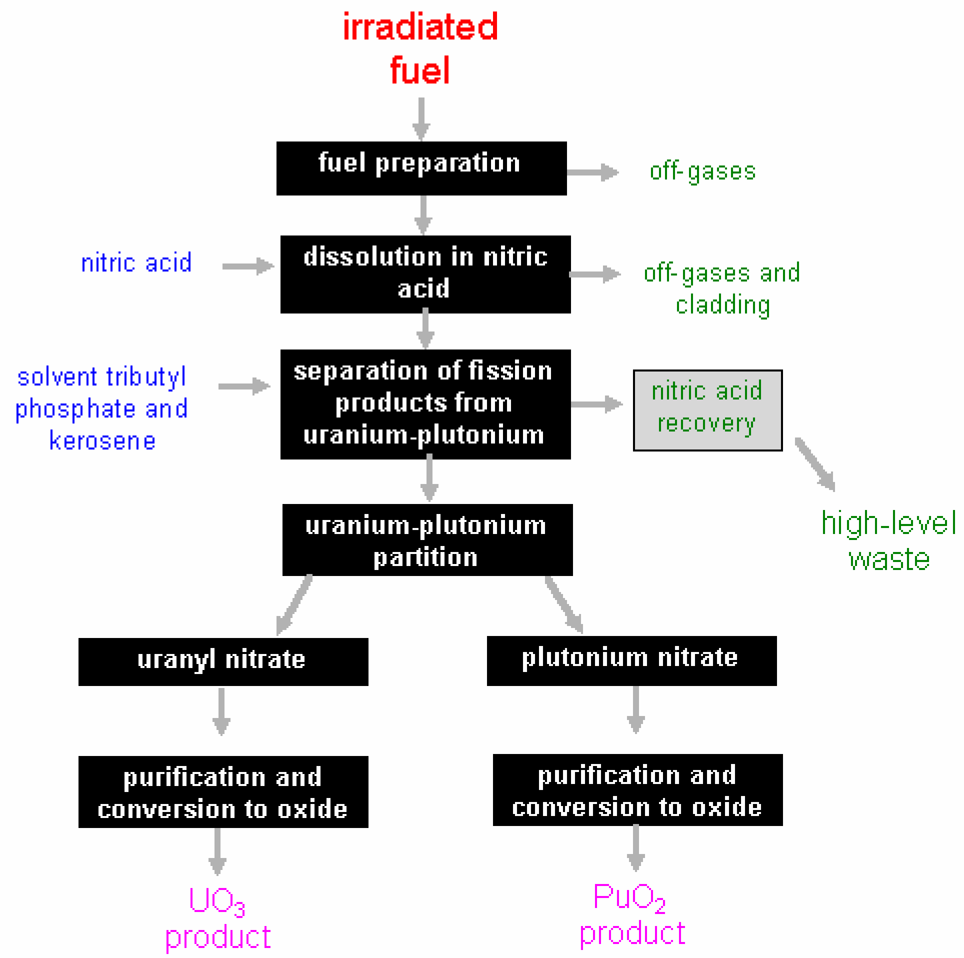

Figure 4. Purex Process [9]

The PUREX process is currently the most common technique used in nuclear fuel reprocessing. This technique is capable of extracting out uranium and plutonium. PUREX stands for “Plutonium and Uranium Recovery by Extraction”. Essentially, the

PUREX process recovers the plutonium and uranium from spent fuel via a liquid-liquid extraction. The spent fuel is exposed to highly concentrated nitric acid solution forcing dissolution from insoluble solids. If not otherwise removed, these solids could prevent the liquid-liquid extraction from proceeding. The next step involves the separation of the fission products from the uranium and plutonium. Here, a tri-butyl phosphate and kerosene solvent interacts with the prepared spent fuel to recover the uranium and plutonium from the spent fuel. The remaining nitric acid/actinide solution goes on to processing as high level waste. Finally through a liquid-liquid extraction, the plutonium and uranium are separated into plutonium nitrate and uranium nitrate where each undergoes one last purification step into their oxidized forms, UO_3 and PuO_2 [9].

The most important reason why nuclear fuel reprocessing was banned in the 1970's was primarily due to the concern over nuclear proliferation. This is the key problem with the above mentioned reprocessing technique. Although the PUREX process has the ability of extracting out uranium, it only separates the plutonium away from the rest of the fission products. Once this plutonium is separated from the other fission products, it is capable of being manipulated into a "crude" nuclear weapon that could eventually be used in a terrorist attack. It is this newly developed use for un-reacted uranium, along with the long held belief of nuclear proliferation, which has recently pushed for a completely new reprocessing technique.

b. The Solution

The approach that was taken to facilitate the current need for an alternative reprocessing technique was to look at exactly what element has to be extracted out of the used nuclear fuel. Nuclear fuel that has been removed from a reactor consists of mostly uranium and a recognizable amount of other elements. These range from zinc to the major actinides. This is unique because the only element that goes into making nuclear reactor fuel is uranium; the other elements are created during the actual fission process. While the chemistry is quite complex, the only thing that needs to be extracted with this proposed method is the uranyl ion [UO_2^{2+}]. Unlike the Purex process, the newly proposed method leaves the plutonium in with the other fission products, thereby eliminating the concern over nuclear proliferation. Additionally, it fulfills the need for a safe extraction technique that is capable of selectively extracting the un-reacted uranium from the used nuclear fuel.

In searching for a technique that was capable of extracting individual cations (such as [UO_2^{2+}]) from an aqueous solution, it was determined that the best method for doing this was through the use of crown ethers. An example of a crown ether is shown below in Figure 5.

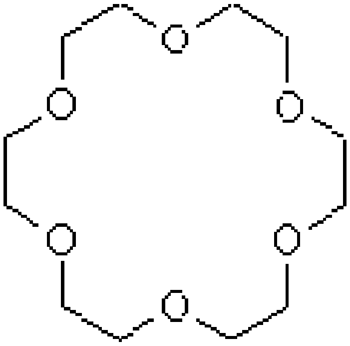

Figure 5. 18-Crown-6 [11]

The primary characteristic of crown ethers that allow them to be used for this very specific purpose is there high affinity for cations. This high affinity is accomplished through the strong electron density that exists in the inner portion of the crown ether ring due to the lone pair of electrons on each of the oxygen atoms [5]. Along with having a strong attraction for cations, another favorable characteristic of crown ethers is there ability to be synthetically developed to only have an attraction to very specific cations [5]. This is typically done by adding substitutes such as cyclo-hexane rings to the crown ether as shown below in Figure 6:

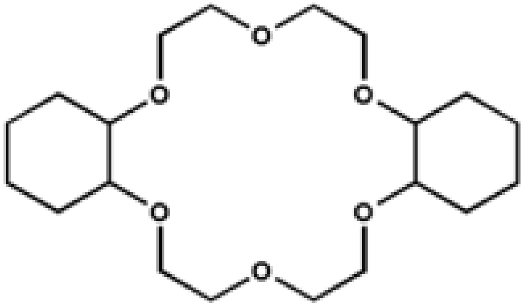

Figure 6. Dicyclohexano-24-Crown-6 [11]

However, the most important feature of crown ether selection for a specific cation is the size of the ring. Simply put, the size is determined by the number of oxygen atoms in the ring. The size of the ring determines which element the crown ether will extract out of the aqueous solution. As shown below in Figure 7, the crown ether with eight oxygen atoms should extract out cations that have atomic diameters close to 3.5 angstroms. This is approximately the atomic diameter of uranium so in theory any crown ether that has eight oxygen atoms should work better than different-sized crown ethers.

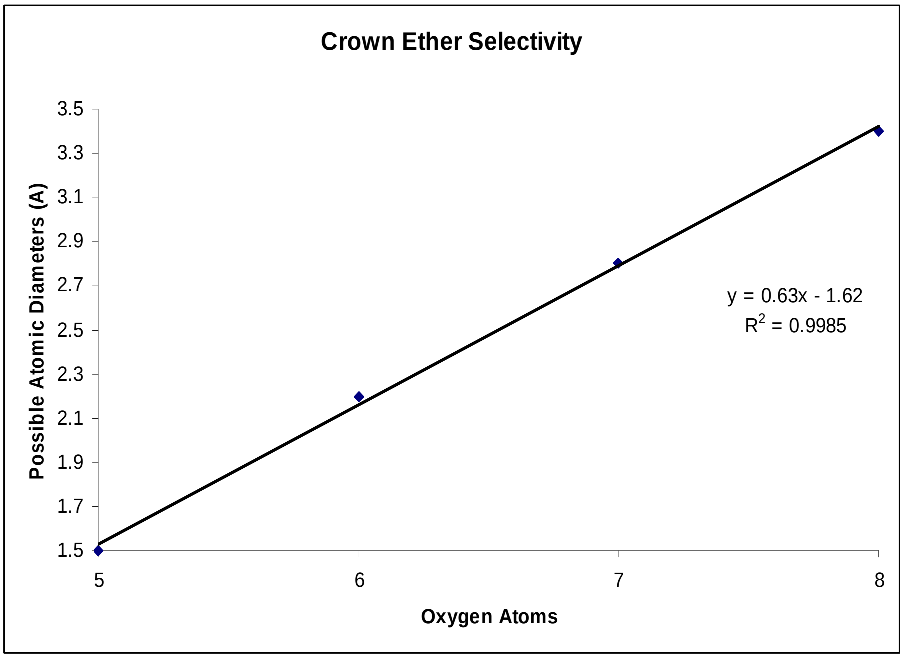

Figure 7. Crown Ether Selectivity

Although crown ethers with eight oxygen atoms should work better, there are many steps to undergo to determine the ideal crown ether for extraction. For the determination of which crown ether will work best in the extraction of a uranyl ion, there were several that were evaluated with varying ring sizes. These crown ethers varied in size (from five to eight oxygen atoms) and also with different substitutes. The specific types of crown ethers analyzed were 15-Crown-5, Benzo-15-Crown-5, 18-Crown-6, Dicyclohexano-18-Crown-6, Dibenzo-18-Crown-6, Dcyclohexano-24-Crown-8 and lastly Dibenzo-24-Crown-8. For this experimental data, all crown ethers were evaluated at .01M in a nitrobenzene dilutent.

Once it was decided upon the crown ethers to be evaluated, it was necessary to figure out how to determine which of these crown ethers will work best for the extraction of the uranyl ion out of an aqueous solution.

When dealing with a two-phase solution, there is one fundamental equation that is used for extracting a solute from one phase into another phase. This equation is known as the partition coefficient [k] as shown below in Equation 1.

$$K = \frac{[\mathit{Concentration}\ \mathrm{Solute}]_{\mathrm{Organic}}}{[\mathrm{Concentration}\ \mathit{Solute}]_{\mathit{Aqeous}}}$$

Equation 1. The Partition Coefficient

As in the PUREX process, the experimental data that was obtained used a strong acid to dissolve the nuclear fuel [2]. To accomplish the job of dissolving the used fuel, hydrobromic acid was used in the place of nitric acid. Additionally, nitrobenzene was used to dilute the crown ether in the organic phase. Shown below in Figure 8 is the percentage of uranium extracted with each crown ether and taken in respect to the concentration of the hydrobromic acid.

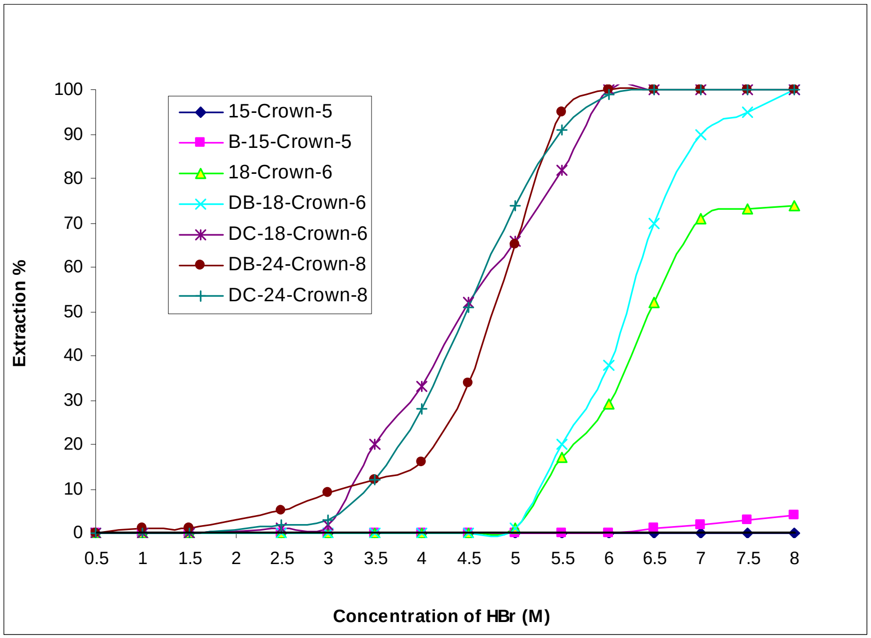

Figure 8. Crown Ether Effectiveness vs. [HBr][6]

Although the above figure would suggest that there are several crown ethers that are capable of extracting uranium out of used nuclear fuel, it only tells part of the story. It was necessary to use the above mentioned partition coefficient to determine how well each of the crown ethers actually worked when varying the hydrobromic acid concentration. Starting with the smallest crown ether (which is the 15-Crown-5), it is shown below in Table 1 that there was no extraction of the uranium into the organic phase. This can be determined because the partition coefficient [k] did not change with a change in hydrobromic acid concentration.

15-Crown-5		*Varying the concentration of HBr		
HBr				
Nitro-Benzene				
Conc.: HBr*[mol/l]	$[\text{Conc.}]_{aq}$	$[\text{Conc}]_{org}$	Partition Coef: K	log[HBr]*[mol/L]
0.5	4.2012E-07	0	0	-0.301029996
1	4.2012E-07	0	0	0
1.5	4.2012E-07	0	0	0.176091259
2	4.2012E-07	0	0	0.301029996
2.5	4.2012E-07	0	0	0.397940009
3	4.2012E-07	0	0	0.477121255
3.5	4.2012E-07	0	0	0.544068044
4	4.2012E-07	0	0	0.602059991
4.5	4.2012E-07	0	0	0.653212514
5	4.2012E-07	0	0	0.698970004
5.5	4.2012E-07	0	0	0.740362689
6	4.2012E-07	0	0	0.77815125
6.5	4.2012E-07	0	0	0.812913357
7	4.2012E-07	0	0	0.84509804
7.5	4.2012E-07	0	0	0.875061263
8	4.2012E-07	0	0	0.903089987

Table 1. 15-Crown-5

The 15-Crown-5 crown ether did not extract any of the uranium regardless of the hydrobromic acid concentration. Although surprising, this result was expected due to the fact that the 15-Crown-5 ring is theoretically too small to extract the uranyl ion.

As mentioned above, there can be substitutes added to the actual crown ether that will improve its extraction capabilities. As shown below in table 2, if there is a benzene ring added to 15-Crown-5, then a limited extraction of uranium out of the aqueous phase takes place.

Benzo-15-Crown-5		*Varying the concentration of HBr			
HBr					
Nitro-Benzene					
Conc: HBr*[mol/l]	$[\mathrm{Conc}]_{aq}$	$[\mathrm{Conc}]_{org}$	Partition Coef:-K	log-K	log[HBr]*[mol/L]
0.5	4.20117E-07	0	0	N/A	-0.301029996
1	4.20117E-07	0	0	N/A	0
1.5	4.20117E-07	0	0	N/A	0.176091259
2	4.20117E-07	0	0	N/A	0.301029996
2.5	4.20117E-07	0	0	N/A	0.397940009
3	4.20117E-07	0	0	N/A	0.477121255
3.5	4.20117E-07	0	0	N/A	0.544068044
4	4.20117E-07	0	0	N/A	0.602059991
4.5	4.20117E-07	0	0	N/A	0.653212514
5	4.20117E-07	0	0	N/A	0.698970004
5.5	4.15916E-07	4.20117E-09	0.01010101	-.996	0.740362689
6	4.11715E-07	8.40234E-09	0.020408163	-1.69	0.77815125
6.5	4.11715E-07	8.40234E-09	0.020408163	-1.69	0.812913357
7	4.07513E-07	1.26035E-08	0.030927835	-1.51	0.84509804
7.5	4.03312E-07	1.68047E-08	0.041666667	-1.38	0.875061263
8	4.03312E-07	1.68047E-08	0.041666667	-1.38	0.903089987

Table 2. Benzo-15-Crown-5

Similar results are realized for each of the crown ethers that were evaluated. Adding substitutes to the crown ethers continuously improve its extraction capabilities. Theoretically, the best crown ethers for the extraction of uranium from the aqueous phase should contain eight oxygen atoms in its ring. Although there was improved extraction as the ring size increased up to eight oxygen atoms, it is clear in Figure 9 below that the best extraction was realized while using the Dibenzo-24-Crown-8 crown ether.

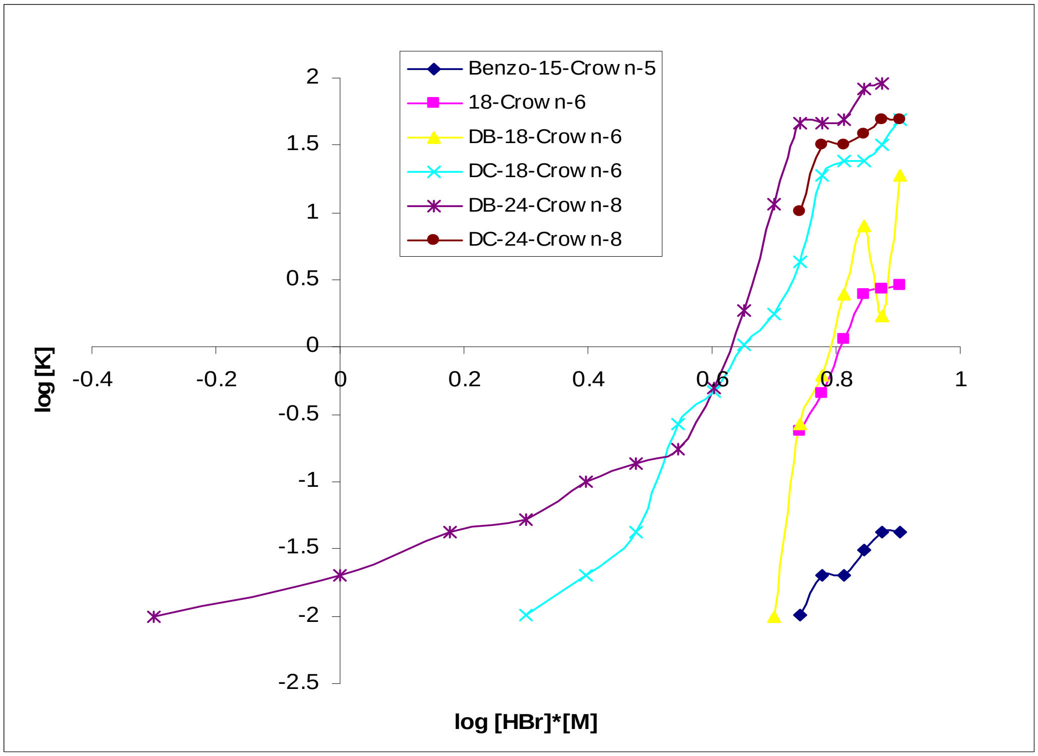

Figure 9. Crown Ether Extraction vs. [HBr]

There are two very distinct reasons why the DB-24-Crown-8 works best for the extraction of uranium from an aqueous solution: 1) as the value of the partition coefficient [k] increases, the ratio of uranium in the organic phase to the uranium in the aqueous phase increases as accordingly. Essentially this correlation states that as the partition coefficient increases, the overall separation efficiency of the crown ether increases. 2) It is important to use the crown ether that allows for the stripping of the uranyl ion away from this crown ether after the extraction process has been carried out. As can be seen in Figure 9, the Dibenzo-24-Crown-8 starts to extract the uranium out of the aqueous phase at the lowest hydrobromic acid concentration. Going back to the idea of the partition coefficient (which is essentially the equilibrium constant for this process) it will be possible to strip the uranyl ion away from the crown ether by simply lowering the hydrobromic acid concentration. Ultimately, when attempting to extract the uranyl ion out of the aqueous phase, it will produce optimal results when the process is carried out with a hydrobromic acid concentration of 7.5M. This corresponds to a partition coefficient [k] of 82.3. Conversely, when trying to strip the uranyl ion out of the crown ether, it is best to carry out the process with a hydrobromic acid concentration of .427 M.

The last thing that was evaluated to show that Dibenzo-24-Crown-8 was indeed the best crown ether to use for the extraction process was concentration. Its concentration was varied holding the acid concentration constant at 7.5M. Shown below in Figure 10, it is seen that the overall extraction of the uranyl ion increases with an increase in the concentration of the crown ether. Ultimately, this overwhelming result shows that the Dibenzo-24-Crown-8 works best for the extraction of the uranyl ion out of an aqueous solution.

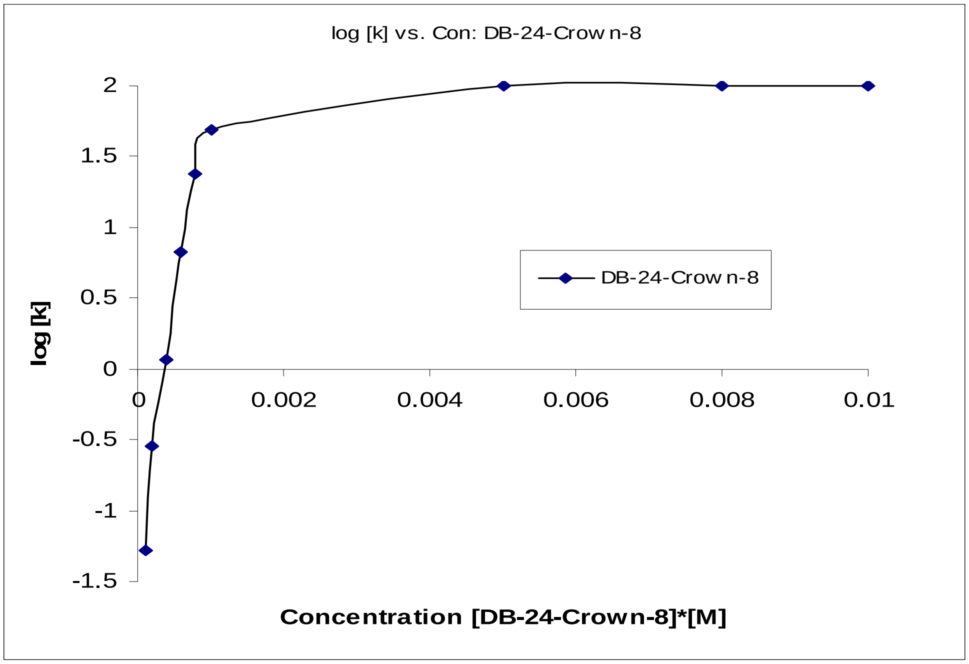

Figure 10. Varied Crown Ether Concentration

V. Site Selection

a. Selecting a Location for Reprocessing Facility

Several factors were instituted in order to select an idealized location for the proposed nuclear reprocessing plant. These included population, population density, location to a continuous water source, location to a major thoroughfare (i.e. an interstate), and location to a railroad system. Along with these, the most important factor analyzed was location to the nuclear power facilities in the United States. The costs associated with transporting spent fuel have reached exorbitant levels, prompting the nuclear reprocessing plant to be located in close proximity to power plants.

A weighted order was established to select the site location. The first factor analyzed was the number of nuclear process plants in the United States and the amount of spent fuel that each generates on a yearly basis. These nuclear power plants tended to exist in large clusters within various regions. The amount of spent fuel produced by each of these nuclear power plant clusters was used to give a weighted order in the selection process. An example of this selection process is outlined in Figure 11 below.

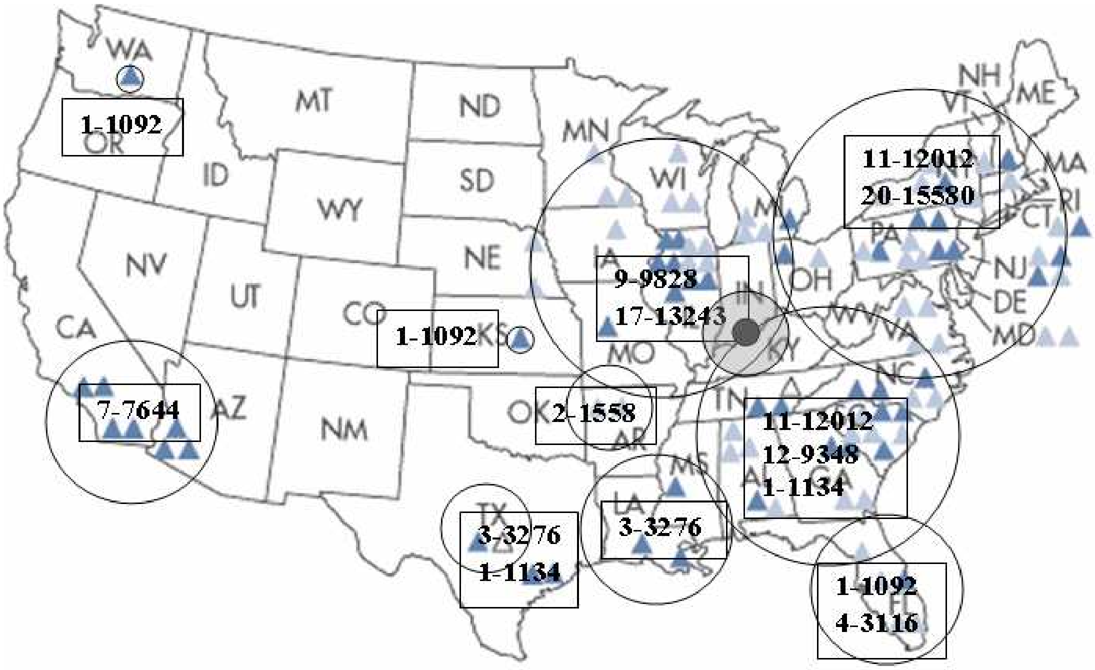

Figure 11. Selection Process [8]

A weighted area was generated for each cluster of nuclear power plants and their associated production levels of spent fuel. Referencing Figure X above, the numbers on the left within each defined area signify the number of plants while the numbers on the right signify the average amount of spent fuel generated by the plants in (MDC). From this, a centralized region was generated wherein the proposed nuclear reprocessing plant could be located. This region incorporated parts of Kentucky, Illinois, and Indiana.

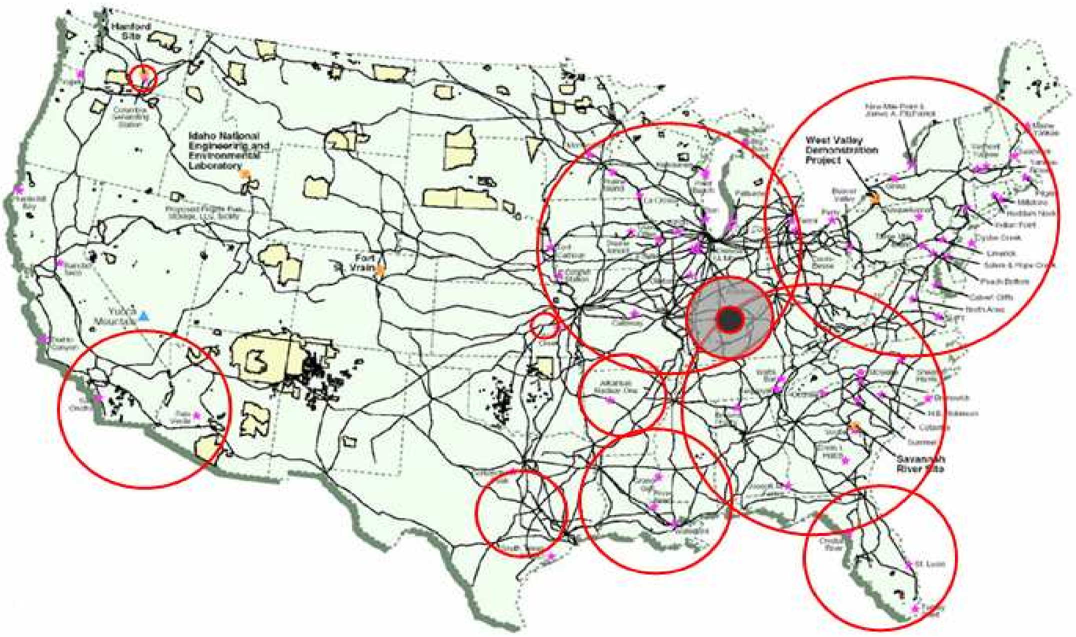

Figure 12. U.S. Railroad System [3]

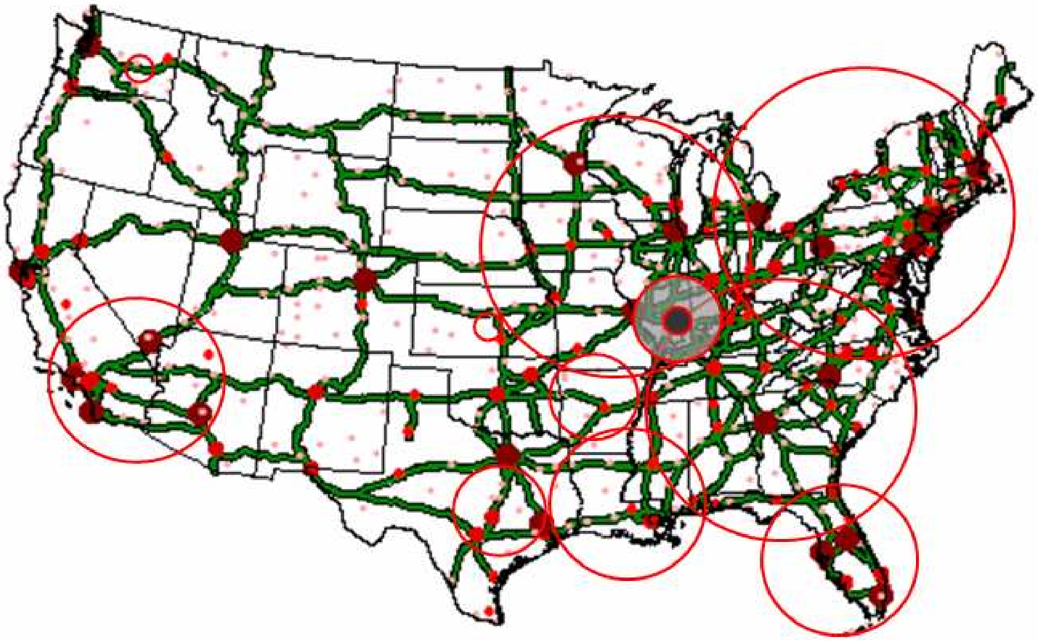

Figure 13. U.S. Interstate System

The next step in the selection process was to analyze the interstate and railroad system running through the centralized region where the nuclear reprocessing plant was to be located. United States' railroad and interstate maps were used in this analysis, the results of which are shown in Figure 12 and Figure 13 above. This region became a clear choice after analyzing the encompassing interstate and railroad infrastructure, as it is the most densely grouped region in the country. This is due in part to the development of St. Louis as the "Gateway to the West" during the 19th century where U.S. expansion westward occurred at an exponential rate. Because of this, along with its proximity to the Mississippi River, the region's infrastructure has grown at a much faster rate than the rest of the country.

With the region's viability to house a nuclear reprocessing plant no longer in question, the analysis took more of a micro-approach where an exact location was selected.

b. Metropolis, IL

After extensive analysis, a region approximately 10 miles northeast of Metropolis, IL was selected. This region has many favorable traits for the placement of a nuclear reprocessing facility. These include it being a sparsely populated area, having only a population of approximately 10,000 within a 20 mile radius. Additionally, it is located just miles from Interstate-24 (which leads straight into St. Louis) and also the Ohio River (a major feeder into the Mississippi River). See Figure 14 below for the exact location of the proposed nuclear reprocessing facility.

Figure 14. Metropolis, IL

This area has an extensive railroad system leading from regions across the Southeast and into St. Louis making transportation relatively safe and simple. The most cost effective methods of transportation are going to lie in the trucking and rail system.

c. Public Opposition

One of the key factors affecting the Yucca Mountain storage site has been the opposition from the Nevada government and citizens. The main complaint, outside of safety issues, is that Nevada houses no nuclear power plants within state borders. Nevada argues that they should not have to house nuclear waste when they have no nuclear power plants to sustain.

In the case of the proposed site outside of Metropolis, IL, it is expected that some opposition will be met both locally and statewide. As is the case with any type of nuclear-related proposition, many feel that it increases danger-risk of the area in which it resides. While this can be true, nuclear power has proven thus far, throughout the United States and the rest of the World, to be a safe method of energy production. However, there is the undeniable fact that Illinois has more operational nuclear reactors than any other state in the U.S. It has even been referred to by many as "Nuclear America" (http://www.neis.org/literature/Brochures/npfacts.htm). The fact that so many people live within a nuclear energy-dependent state supports the location of reprocessing facility in Illinois.

XI. Costs Associated with Nuclear Fuel Reprocessing Facility

It is difficult to precisely estimate the cost of the proposed spent fuel reprocessing facility. There are so many factors that influence the cost of nuclear facilities. Constant regulations placed on the design and implementation of these facilities has forced prices to sky rocket over the past two decades. Nuclear ratcheting, the term used to describe government imposed sanctions and regulations which drive the price of nuclear facilities upwards, has directly influenced the economic feasibility of a nuclear reprocessing facility. A reprocessing facility has not been built in the United States since the mid 1970’s. There have, however, been several built in other parts of the world. Most today use the PUREX process to reprocess spent fuel. The most prominent and well-known reprocessing facility is in La Hague, France [6]. The facility first came into operation in 1976 with a reprocessing capacity of under 1000 metric tons per year. Facility upgrades have since pushed the spent fuel capacity to over 1700 metric tons per year, making the facility the largest of its kind in the world. It was estimated that approximately $14 billion in total capital investments have been placed into the facility over the course of its upgrades and expansions [6].

The newest and most technologically advanced facility to be built is in Rokkasho, Japan. The Japanese, in the past, have outsourced most of their reprocessing to other countries such as France and England. The Rokkasho reprocessing facility marks a turn in local reprocessing. The plant has a maximum spent fuel capacity of 800 metric tons per year. Construction on the Rokkasho plant facilities were completed in 2005 for approximately $11 billion. However, stringent governmental constraints have pushed backed the fully operational date to late 2007, and increased the total capital investment to over $21 billion.

It is because of these continual constraints and upgrades to the facilities that makes an estimation difficult. Because a single reprocessing facility is being proposed to handle the spent fuel capacity for all of the United States, estimations can be done based on proposed capacity and spent fuel reserves that are expected to exist for the U.S. The projections for spent fuel in the United States are as follows: 63.86 metric tons by 2010, 74.34 metric tons by 2015, and 82.71 metric tons by 2020. Based on these projections, it estimated that the U.S. would need a plant with a maximum capacity of approximately

7500 metric tons/yr. This number would prepare for the expected increase in nuclear energy over the next few decades while reprocessing the spent fuel already held in long term storage. The estimations for a nuclear reprocessing facility built in the United States today are shown in Table 3 below.

Total Capital Investment **(7500 metric ton/yr capacity)**	
Direct Costs	**$31,434,562,500.00**
Purchased Equipment/Instrumentation & Controls	$39,250,000.00
Installation	$13,125,000.00
Building/Piping/Insulation	$28,050,000,000.00
Electrical	$876,562,500.00
Service/HBR holding facilities	$2,454,375,000.00
Land ($2000/acre) (625 acres)	$1,250,000.00
Indirect Costs	**$12,207,327,500.00**
Engineering and Supervision	$2,805,000,000.00
Legal Expenses	$15,605,000.00
Construction expense and contractor's fee	$4,511,722,500.00
Contingency	$4,875,000,000.00
Fixed Capital Investment	**$43,641,890,000.00**
Working Capital	$6,015,630,000.00
Total Capital Investment	**$49,657,520,000.00**

Table 3. Total Capital Investment

As is evidenced by the table above, the majority of the costs associated with building the nuclear reprocessing facilities like in the building, piping, and insulation category. Because of the stringent regulations on radioactive control, the walls and insulation of the facility must be extremely reinforced and be able to withstand nuclear penetration. These extra precautions drive the costs of construction skyward. The equipment costs along with instrumentation and controls were estimated by comparing to plants of similar size, not necessarily in the nuclear reprocessing field. The equipment is not nearly of large of an influence on the total capital investment as the building and structural costs. In many cases of past nuclear facilities, nearly half of the investment has come after the structure was completed. The continual modifications and regulations imposed drive these costs upward. As far as operating costs are concerned, a 2006 Congressional Subcommittee hearing determined that a nuclear reprocessing facility built in the United States would cost anywhere between \$1000/kg and \$3000/kg of spent fuel that runs through the facility [7]. The lower number is the estimate for a government funded facility while the higher number is for a privately funded facility. These estimates were based on a reprocessing with a 2500 metric ton/yr capacity. In the case of a 7500 metric ton/yr capacity reprocessing facility, this equates to approximately \$3.3 billion/yr in operating costs for a government subsidized facility. For a privatized reprocessing plant, operating costs could reach upwards of \$10 billion/yr.

XII. Recommendations

It is apparent that the nuclear energy sector must become a more economically viable option before it can develop into a leading source of energy for the United States. The current constraints placed upon the nuclear energy sector limit privatization. However, with initiatives such as the “Nuclear by 2010 Program”, development and growth are on the horizon. It is due to this growth that spent fuel reprocessing facilities will become more prevalent worldwide and outpace long term storage. While U.S. policy currently dictates long term storage as the most economically viable option, future oil prices could drive the demand for nuclear reprocessing to increase. Because of this potential, it is proposed for future work to be performed in the field of crown ethers and their use in spent fuel reprocessing. Specifically, it is desired to explore different crown ethers, different acids, and their interactions to promote an idealized reprocessing technique. It is further recommended that more work be done in the design and economic aspects of the crown ether reprocessing technique.

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