Economic Feasibility of Spent Nuclear Reprocessing in the United States

to
Dr. Aaron Hiltner

By
Logan Peterson
Tristan Wentworth
Zachary Wolf
Maggie Xu

EPD 397 Section 8
University of Wisconsin-Madison
November 26th, 2018

Executive Summary - (Group)

The United States' current method of dry cask storage to handle spent nuclear fuel is a short-sighted solution that will present severe environmental problems upon its coming expiration date. Spent nuclear fuel reprocessing offers a solution to significantly mitigate the problems associated with dry cask storage, but research on its economic feasibility is incomplete. The current method of nuclear waste disposal, known as "dry cask storage," is estimated to have a lifetime of 120 years before the fission products and other radioactive elements can no longer be guaranteed to be safely sequestered. Nuclear power has gained new light in the wake of climate change, but the problems associated with its own waste are hindering its revival. The principal form of spent nuclear fuel reprocessing is known as PUREX. PUREX, an acronym standing for Plutonium Uranium Redox EXtraction, is a method to purify the fuel and recover uranium and plutonium from the spent nuclear fuel in order to reuse these elements for nuclear power production. This process is already in practice across multiple countries including France, Britain, and Japan. PUREX would solve many of the issues pertaining to nuclear waste, but to be implemented in the industry it must be shown to be economically competitive with dry cask storage.

A common metric of dollars per kilogram was used to analyze the cost difference between dry cask storage and PUREX. Dry cask storage was analyzed based on construction of the dry cask facilities and the additional cost of buying the dry casks themselves. Data came from both academic studies as well as a real life example of actual costs at one of the United States' nuclear power plants. Breaking down the cost analysis into the lifecycle of the PUREX facilities (construction, operation, decommissioning) would give us the best approximation of the total cost. Using the United States current amount of spent nuclear fuel and projections of consumption in the future, we can model a facility capable of reprocessing all spent fuel in 60 years of operation.

In addition to assessing the economic practicality of the two methods of waste management, their effects were considered from an ethical standpoint. The effects that each method has on supply certainty of uranium, the radiological risks to the environment, and the potential of the proliferation of nuclear weapons were evaluated. While neither method poses any great ethical concerns in these areas, the adoption of nuclear reprocessing of spent fuel results in reduced risk to future generations at the cost of additional risk to the current generation.

The United States currently has nearly 90,000 metric tons of spent nuclear fuel and is producing new waste at a rate of 2,000 metric tons per year with no solution to dispose of it long-term. Although PUREX would greatly reduce the quantity of waste needed to be stored by essentially recycling our spent fuel, our cost analysis shows that it will be on the order of 10 times more expensive than dry cask storage. Current low uranium prices and high capital cost of PUREX facilities make nuclear fuel reprocessing economically unfavorable without government intervention. Since dry cask storage is an order of magnitude less expensive, we recommend that the United States not invest into PUREX heavily in the near-term as a solution to nuclear waste disposal. We do, however, recommend long-term investment into PUREX as the ethical concerns of future generations will become those of the current one.

Table of Contents

1.0 Introduction - (Zach)

The United States' current method of dry cask storage to handle spent nuclear fuel is a short-sighted solution that will present severe environmental problems upon its approaching expiration date. Spent nuclear fuel reprocessing offers a solution to significantly mitigate the problems associated with dry cask storage, but research on its economic feasibility is incomplete. The current method of nuclear waste disposal is known as "dry cask storage." While there are competing designs of dry casks, each are designed in the same way to do the same task: use concrete and steel cylinders to safely store spent nuclear fuel until a more complete and robust solution is found. The main drawback with using dry cask storage is its relatively short lifespan. The casks themselves have a lifetime of 120 years before the radioactive elements that they store can no longer be guaranteed to be safely sequestered [1].

The loading of spent nuclear fuel into dry casks began in 1986 at the Surry Nuclear Power Plant in Virginia. Its 120 year expiration date is still far away, but further procrastination on the issue may spell disaster. We must act diligently to find a better solution to the United States' nuclear waste problem as extreme regulation has been shown to significantly reduce the rate of implementation of new technology in the nuclear power industry.

One of the most promising technologies that has the potential to free the United States of its nuclear waste problem is known as spent nuclear fuel reprocessing (or just "reprocessing"). Reprocessing essentially takes the spent fuel and recycles it back into fuel that a reactor can use again. Nearly 95 percent of the uranium and plutonium left in a typical dry cask storage container is available for reprocessing. PUREX (**P**lutonium - **UR**anium **EX**traction) is the principle form of reprocessing used heavily by France (and some in other countries) and has the ability to decrease the amount of high level waste needed to be stored by a factor of 20 [2]. However, the United States nuclear energy market is mainly comprised of privatized electric utility companies who need to produce a positive bottom line in order to stay in business. Thus, despite its benefits, PUREX can only be used in the United States if it becomes less expensive than our current waste disposal method, dry cask storage.

This report will serve as an economic analysis of the two aforementioned nuclear waste waste disposal methods, dry cask storage and PUREX reprocessing. Each will be analyzed using dollars per kilogram of waste ($/kg) as a common metric of comparison. Dry cask storage costs be evaluated based on the construction costs of the dry cask facilities and the additional cost of buying the dry casks themselves. Breaking down the cost analysis into the lifecycle of PUREX facilities (construction, operation, decommissioning) would give us the best approximation of the total cost for reprocessing. Using the United States current amount of spent nuclear fuel and projections of consumption in the future, we can model a facility capable of reprocessing all spent fuel in 60 years of operation.

Finally, based on the data we find, we will state a recommendation as to whether or not the United States should pursue reprocessing as a method of dealing with spent nuclear fuel. Our recommendation will be based on two factors, the larger of which is economic costs we outlined above. We will also evaluate ethical concerns. When dealing with materials like nuclear waste, it is important to take into consideration the ethical aspects associated with each method. The main goal of this report is to analyze the economic aspects of the two methods, however any major concerns about the ethical considerations of each method will play a role in our recommendation.

2.0 Nuclear Fuel and Nuclear Waste - (Zach)

With the onset of climate change, countries are investigating more ways to significantly cut down carbon emissions across all sectors. According to the United States Energy Information Agency, 38% of all the energy used by the United States goes into generating electricity. The majority of this 38% is fueled mostly by coal, natural gas, and other carbon-emitting sources. Carbon free electricity generation, however, has started to rise in the United States. Nuclear power leads all other carbon free electricity sources combined, producing 20% of the country's electricity with 98 nuclear reactors [3]. To seriously address climate change, nuclear energy must be a mainstay in the United States energy portfolio.

The major benefit of nuclear power is that the fuel itself allows the reactors to produce no carbon for each unit of energy output. There is no carbon found in nuclear fuel; rather, it is made of uranium. Uranium is not "burned" in the conventional sense to produce its heat, but irradiated with neutrons instead. Since no carbon is burned, no CO2 is emitted. Furthermore, the energy density of uranium is 1,000,000 times greater than that of any fossil fuel, so much less is needed to produce the same amount of energy [4]. These inherent characteristics are what makes nuclear power so attractive, but its waste products have proven to be a burden of its existence. The by-products of nuclear reactions are highly radioactive. All of these radioactive elements need to be sequestered such that the public or any employees at a nuclear power plant are not exposed to high levels of radiation.

Nuclear fuel starts its life as cylindrical uranium dioxide pellets. These pellets are encased, or more often called "cladded," in zirconium alloy (zircaloy) tubes. The zircaloy tubes are then bundled together, hundreds at a time, into what's known as a "fuel assembly." There are between 100-500 of these fuel assemblies then loaded into the core of every nuclear reactor in the United States. Figure 1 shows the basic layout of nuclear fuel. After 5-6 years inside of a reactor, the fuel assemblies can no longer produce energy efficiently, and are dubbed "spent." Spent fuel is full of dangerous radioisotopes that must be handled with extreme care. Part of the nuclear reaction is the generation of fission products. These fission products are relatively lightweight and typically made of cesium-137 and strontium-90. The fission products in spent nuclear fuel only comprise 3-5% of the overall mass of the radioactive waste, but produce a vast majority of the incident heat and high level radiation. There are other elements created in nuclear reactions. These elements have a mass higher than uranium and are therefore called "transuranic" elements. Though these elements produce a negligible amount of heat, they are still slightly radioactive and take many thousands of years to decay whereas fission products do so relatively quickly [5].

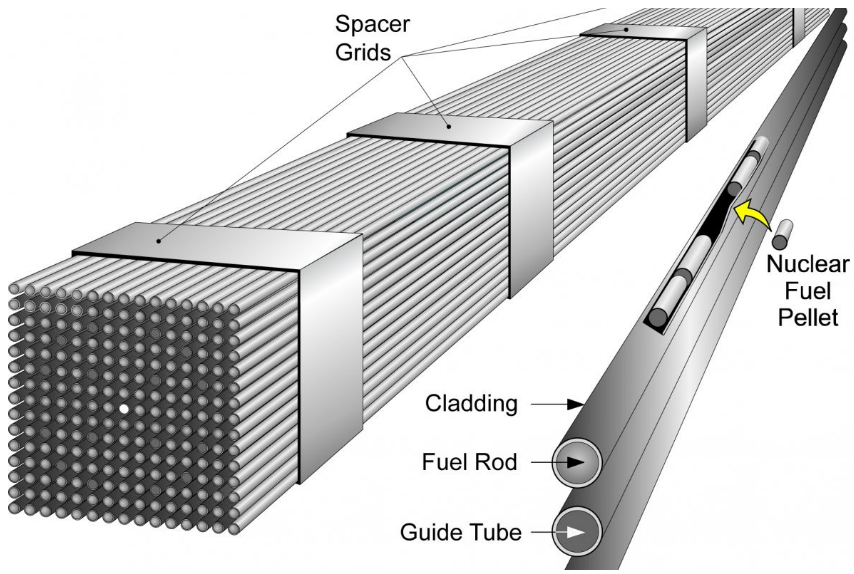

Figure 1. Nuclear Fuel Assembly Breakdown. *This figure shows the layout of a nuclear fuel assembly. Nuclear fuel pellets, roughly the size of the top segment of your pinky finger, are stacked on top of each other to a height of ~12 feet in tubes of zircaloy. Each tube, also known as a fuel pin, is assembled into a square grid, usually 14x14 - 16x16 fuel pins. Spacer grids help keep these fuel pins bundled together at all times. These fuel assemblies are then placed in the core of a nuclear reactor. A reactor core can be made of anywhere from 100-500 fuel assemblies [6].*

Fission products will keep the fuel thermally hot for years after the fuel assemblies are taken out of the reactor. To cool them down, nuclear power plants will place the fuel assemblies into large pools of water known better as “spent fuel pools.” In the early stages of the nuclear power industry, many plants kept the fuel assemblies there indefinitely. This was common practice starting in the 1960’s until the 1980’s when many of the spent fuel pools at each nuclear power plant began to fill to capacity. Since expanding the spent fuel pools was not practical, there was a large push to find a solution. Thus, the dry cask storage era had begun as a way for nuclear energy utilities to cheaply and efficiently store the spent fuel until other more complete means of disposal were developed.

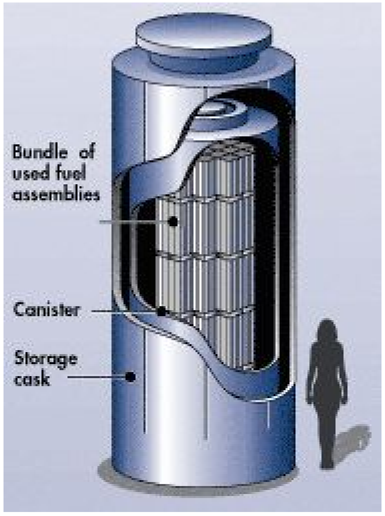

Figure 2. Dry Cask Schematic. *This figure shows the relative size and scale of a dry cask. Note the presence of the spent fuel assemblies inside. [7]*

Figure 3. Dry Casks in real life. *This figure shows what dry casks look like in real life. Often casks are stacked together like this at a nuclear power plant. [8]*

Dry casks are composed primarily of steel and concrete cylinders. These materials effectively shield and cool the spent fuel assemblies. Figures 2 & 3 shows what a typical dry cask looks like [7] [8].

Dry cask storage is not a perfect technology. It was first developed as a temporary solution to spent fuel pools filling to capacity, but is now the staple technology that the United States employs for nuclear waste disposal. According to the Nuclear Regulatory Commission, the casks are only estimated to safely contain the radioactive elements for 120 years, much shorter than even the half-life of plutonium of 24,000 years [9]. A better solution is needed for long-term disposal of nuclear waste.

Spent nuclear fuel reprocessing is a proposed long-term solution to nuclear waste disposal. PUREX (**P**lutonium and **U**ranium **R**ecovery by **EX**traction) is the principal process used by France today for the country's fuel reprocessing needs. The main process of PUREX is to first mix the spent fuel that contains the useful uranium and plutonium and other unneeded elements with a strong acid. Then the mixture that contains a special molecule, TriButylPhosphate, acts like an enzyme is added to trap the uranium and plutonium in the kerosene. Later this kerosene can be drawn off from this acid bath and plutonium and uranium in it can be separated and purified. Other forms of reprocessing such as UREX, TRUEX, and DIAMEX are all derivatives of PUREX and do essentially the same job, but for more specific needs. Above all, PUREX is the most widely used.

The U.S. at one time had one reprocessing plant that used PUREX in the late 60's to early 70's: the Western New York Nuclear Services Center. However, with mounting regulation requiring modifications to the plant it was deemed uneconomical to keep operating after recovering ~2000 kg of plutonium and over 6000 metric tons of uranium. The plant was then shut down in 1975. In 1977, the United States declared all civilian reprocessing plants illegal. PUREX inherently has the ability to extract trace amounts of plutonium from spent nuclear fuel. Though this plutonium is not the correct isotope to be used in nuclear weapons, there are clever ways of engineering your way out of the problem. Consequently, these reprocessing sites can be used to make nuclear weapon proliferation easier. As a result, passing a law banning all civilian reprocessing plants was the United States' way of showing the world it was making strides to limit its nuclear weapons arsenal, even though only 0.9 metric tons of highly enriched uranium was ever produced by the plant. Nonetheless, four countries in the world today use some form of nuclear fuel reprocessing: Japan, India, France and Russia [10].

Though illegal in the U.S. today, reprocessing has been brought back to the surface by academia and nuclear energy utilities as a legitimate solution to the ongoing nuclear waste problem. In an interview with Darius Ahrar, reactor supervisor at Xcel Energy, he stated that the entire U.S. nuclear fleet would benefit from investment into PUREX. With new technology and the rising issue of climate change, nuclear power has once again gained traction among U.S. public opinion. The United States nuclear energy utilities are putting the Trump Administration under heavy pressure to find a better and more complete solution to our current methods today; including repealing the moratorium that banned reprocessing in the first place. We have seen examples of other countries performing reprocessing in the world today, but these markets have a large socialist structure where the government pays for much of the reprocessing cost. In the United States, we believe it will be unlikely that the government will intervene on this issue in the near future as each utility currently pays for its own dry cask storage.

3.0 Costs of Dry Cask Storage - (Zach)

Dry cask storage is not a new technology in the United States. A high-demand market has created a robust and well understood technology that serves as a cheap interim solution for dealing with nuclear waste. Since our research question tasks us to figure out which method of dealing with spent nuclear fuel is the least expensive, we must create a model that can accurately predict the costs of each method. To best evaluate and answer the proposed question, we will have to first lay out the underlying assumptions of our cost model as it pertains to dry cask storage. We will employ the following assumptions in this section:

1. The cost of dry cask storage will include only the construction of a dry cask facility and an additional per-kg cost
2. There is no foreseeable geologic repository for spent nuclear fuel to come online in the next 30 years. Thus, no transportation costs of delivering spent fuel to a large repository are needed.
3. The only operating costs of a dry cask facility is the security personnel needed to maintain the license of the facility

3.1 Dry Cask Facility Construction Cost

Estimates of the capital costs needed to implement a dry cask facility on-site have been anywhere from \$8-\$12 million in 1998 dollars. These costs are mostly independent of the size of the plant (and therefore the amount of waste generated) [11]. Using [12], the inflation-adjusted cost of constructing a dry cask facility at a nuclear power plant in the United States is between **$12.5-$19 million** in 2018 dollars. For simplicity's sake, we will use these values as bounds to the total upper and lower costs of dry cask storage for later comparison.

To obtain these costs in our chosen metric, $/kg, we must further manipulate our data. A typical reactor size in the United States is 1000 MWe. There are 98 nuclear reactors operating in the United States at 60 different plants for an average of 1.63 reactors/plant. Each 1000 MWe reactor uses approximately 27 metric tons (27,000 kg) of fuel per year, or 44,100 kg of fuel per year per plant [13]. Since each plant will be assumed to operate for its full 40 year initial license, plus an additional 20 year license, it is a good assumption that each plant will operate for 60 years. Thus, at 44,100 kg/year, over the course of its life a nuclear power plant in the United States will use *on average* 2,646,000 kg of fuel.

Dividing the construction cost by the total amount of fuel used during the lifetime of the plant, we can see that construction costs of the dry cask facility is between **$4.7-$7.2/kg** in 2018 dollars.

The costs are assumed to be accurate in today's world due to the relative simplicity of the dry cask facilities. At most nuclear power plants, this facility consists essentially of just a large concrete slab for casks to sit on as well as fencing for added security. Though construction regulations for the building of new nuclear plants has changed since the time of the report, [11] , specific regulations for the construction of dry cask facilities have *not changed in a significant way* because of the extreme simplicity of the facilities. Since we don't expect these simple construction costs (just concrete and fencing) to change significantly with time, we assume that this cost hasn't changed, other than from inflation, since the report, [11], was established in 1998.

3.2 Cask Cost

The cost per cask was found using estimates from a real nuclear power plant in the United States. Darius Ahrar, reactor supervisor at Xcel Energy, said in an interview that one of their nuclear power plants, Prairie Island, will pay upwards of $4 million per cask. Each cask there can hold 40 spent fuel assemblies. With each assembly having a mass of 400 kg, this translates to roughly **$250/kg** to dispose of spent fuel via dry cask storage.

Prairie Island is a 2 unit plant (there are 2 reactors at the plant). Each unit uses an industry standard 14x14 fuel pin assembly. Since the fuel assembly design is used by nearly the entire nuclear power industry, it is sufficient to say that most of the industry will see approximately the same cost. Thus, we will use **$250/kg** as the cost of purchasing and loading the cask.

3.3 Operating Costs

The operating costs of maintaining a dry cask site are only due to the security of the site that's required to maintain its operating license. These costs are largely independent of the plant's size and are estimated to be on the order of $1.1 million per year, or $66 million over the lifetime of the plant in 2018 dollars [11]. Again, assuming that each plant uses *on average* 2,646,000 kg of fuel during its life, we calculate that the operating costs over the course of its life are **$25/kg.**

3.4 Total Cost of Dry Cask Storage

The total cost of dry cask storage is simply the sum of the facility construction, cask, and operating costs. Thus, the total cost of dry cask storage is **$279.70-282.20/kg.** It is interesting to note that the vast majority of the cost is from the casks themselves. Both the capital and operating costs are essentially negligible.

4.0 Cost of PUREX Reprocessing - (Logan)

The United States does not currently have an operational facility capable of PUREX reprocessing or storing the small amount of spent nuclear waste that results from this process, so the majority of the cost associated with PUREX reprocessing can be attributed to building the facilities capable of doing so. Therefore we will break down the cost elements as it pertains to the lifecycle of these facilities. This will be separated into three categories, construction, operation, and decommissioning. Then using the current amount of spent nuclear fuel in the United States we will create an estimate as to how large these facilities will have to be and how long they will be operational until they are eventually decommissioned.

According to the Center for Arms Control and Nonproliferation, the United States currently has nearly 90,000 metric tons of spent nuclear waste and are producing nearly 2,000 metric tons each year [11]. This means we need to build a facility that is capable of not only reprocessing the spent fuel that we currently have but also the new fuel waste we will produce up until the plant is decommissioned. Now using other existing reprocessing plants as a baseline, it takes 10 year to build these facilities and they are operational for roughly 60 years. Totaling the amount of spent nuclear fuel in need of reprocessing at 230,000 metric tons, which needs to be done at a rate of 4,000 tons per year, which is more than any reprocessing plant in existence.

4.1 Construction Costs

The best way to determine construction costs is to take examples of existing reprocessing plants and extrapolate the costs to match the capacity of the needed new facility. According to a paper published from the Harvard Kennedy School on the prospective cost of reprocessing in China [14] we can use something similar to *equation 1* to best extrapolate these figures. The equation takes the proportion of capacity (M/M_o), raises it to a scaling factor (y) based off of that proportion, and multiplies that by the example capital costs (C_o) in order to get the capital cost (C) of a new facility.

Equation 1 $$C/C_O = (M/M_O)^{\gamma}$$

The defined capital cost used in the equation includes the largest expenses that are incurred during construction including things like cost of materials, land, labor, and nearly all other things needed to build a reprocessing facility. The scaling factor is determined by the proportion of capacity (M/M_o), if M/M_o is between 0.5 and 2 we set y = 1, if M/M_o is greater than 2 but less than 50 we set y = 0.65.

There are only a handful of reprocessing plants in the world, most of which were constructed over 50 years ago, therefore we will use the most recently constructed reprocessing plant in Japan at Rokkasho in order to get the most accurate estimates. Rokkasho has a capability to reprocess up to 800 (= M_o) tons of heavy metal each year, and after adjusting initial estimates of construction cost for inflation, the total capital cost behind building this facility comes out to nearly 23.3 (= C_o) billion dollars. Thus we get the following equation:

$$C/C_O = (M/M_O)^{\gamma}$$
$$C = 23.3 * (4{,}000 / 800)^{0.65}$$
$$C = 66.3 \text{ billion dollars}$$

This ultimately amounts to **$302 per kg of heavy metal** reprocessed solely coming from just the construction of the facility in which the reprocessing is being done. Now this figure can vary significantly and may very well be on the optimistic side of an estimation, as most nuclear reprocessing plants have a tendency to quickly go over budget and push back deadlines due to strict regulations and extremely thorough safety practices. Rokkasho alone has been a nightmare, as the timeline of completion has been pushed from 1997 to 2021 and the final budget has nearly tripled since the original estimates.

4.2 Operation Costs

Once the facilities are built and we enter into the 60 year time period of operation, the majority of the costs associated with this timeframe can be attributed to things such as the cost of actual reprocessing, transportation of spent nuclear fuel, long term storage of spent nuclear fuel, and refurbishing/upkeep of the facilities. Where the largest portion of this piece will be the actual reprocessing cost itself, as it makes up nearly 90 percent of the total operating costs.

In accordance with law, the Japan Atomic Energy Commission (JAEC) [15] provided an estimation of all future operational costs at Rokkasho once it becomes fully operational. Since this plant operates in nearly the same fashion that an United States facility would need to operate, we can take the numbers JAEC provides and apply the same equation used in construction cost in order to extrapolate the numbers to meet our capacity requirements. JAEC estimates that using the PUREX reprocessing method will cost nearly 1.53 billion dollars annually. They also provide a comprehensive overview of the transportation costs throughout the nuclear fuel life cycle, which comes out to be nearly 51 million dollars annually. Lastly JAEC estimates that the cost of long term storage of the spent nuclear fuel that results from the PUREX process costs about 119 million dollars annually. The one thing that JAEC failed to include in their estimations would post operational refurbishment costs that usually occur throughout the lifetime of the facilities operation. British Nuclear Fuels Limited [16], a former builder of a similar reprocessing plant in britain estimated that it would cost nearly 1.5 billion dollars in the lifespan of the plant (25 million annually) to keep it operational. In summation of all of these factors, the annual cost of operation at Rokkasho is nearly 1.725 (=C_o) billion dollars, if we plug this value into the previous *equation 1* we get:

$$C/C_O = (M/M_O)^{\gamma}$$
$$C = 1.725 * (4{,}000 / 800)^{0.65}$$
$$C = 4.91 \text{ billion dollars annually}$$

This adds an additional **$1225 per kg of heavy metal** reprocessed that can attributed to the operation of the facility.

4.3 Decommissioning Costs

Decommissioning cost has the highest variation of these three categories as there has not been a fully operation reprocessing plant that has gone through the decommissioning process and provided a full financial report post completion. Therefor most of the estimations could vary significantly, yet by today's estimates decommissioning will be the least costly process of the three so it wont dramatically change the financial picture. Again according to Japan Atomic Energy Commission [17], full decommissioning of the plant at Rokkasho and site restoration will cost roughly 16 billion dollars (= C_o).

Once again we can use the extrapolation *equation 1* in order to adjust these figures to a PUREX reprocessing plant in the United States.

$$C/C_O = (M/M_O)^{\gamma}$$
$$C = 16 * (4{,}000 / 800)^{0.65}$$
$$C = 45.54 \text{ billion dollars}$$

Converting this to a usable measure, decommissioning costs **$207 per kg of heavy metal** reprocessed.

In summation, the cost of PUREX reprocessing will be nearly **$406 billion dollars total** throughout the complete lifecycle of the reprocessing facility and it will cost about **$1,734 per kg of heavy metal reprocessed.**

5.0 Ethical Considerations - (Tristan)

When comparing the two methods of once through nuclear power and reprocessing, the differences can be seen when comparing them in the short and long term. In general, once through nuclear power has more advantages in the short term, while reprocessing seems to be the better option in the long term. Considering the ethics behind this then, we must decide how much weight we place on minimizing risk in the future, at the expense of increasing the risk to the current generation.

5.1 Supply of Nuclear Fuel

The first factor that we need to consider regarding the short and the long term is the supply of uranium that we can use to generate nuclear power. In 2006, the Nuclear Energy Association estimated that we have 85 years’ worth of uranium available for a once through process [18]. After use, the leftover fuel would be stored in the dry casks, meaning it would be still available for retrieval. Sustainable uranium collection is being researched which would allow us to have a much larger supply. For instance, uranium has been successfully separated from seawater with high percent yield. The Earth's oceans contain over 4.5 billion tons of uranium, distributed at 3 micrograms per liter of seawater. If we were able to extract even a thousandth of that total, we would double the amount of available uranium globally [19].

PUREX has the advantage of being able to use more of the available fuel with less waste. If the US were to use PUREX repressing, it would have 2,500 years' worth of nuclear power [18]. The closed fuel cycle guarantees a much longer lasting supply of fuel, however advances in technology may reduce the need for the current supply of nuclear fuel to last that long.

5.2 Radiological Risks

The two methods proposed have different risks associated with them in terms of radiological impact. Dry cask storage has shown to be very reliable for the short term. In 2014, the Nuclear Regulatory Commission concluded that nuclear waste could be safely contained in the casks for the better part of a century [20]. Also, in 2014, the NRC published an environmental impact statement for spent fuel storage that evaluated impacts on environmental factors. It was found that the effect on soil, air quality, aquatic impact would be minimal for a period of at least 160 years after the life of the license of the reactor [21].

After uranium goes through the enrichment process to produce energy, 90 percent of the ore is left over. Just storing the waste in dry casks creates a greater risk for the future, it may need to be contained for hundreds of thousands of years before it decays back to a normal radiation level [21]. After going through the PUREX process and having the uranium and plutonium separated from the waste, whatever is left behind is trapped in glass for disposal [18]. This is called vitrified waste and will decay to the radiation level of uranium in 5,000 years, 40 times sooner than if it were the original spent fuel. PUREX reprocessing is better for the environment long term, because it reduces the both the volume and toxicity of the waste.

The radiation exposure to both the public and the plant workers is minimal and safe for both types of fuel management. However, they differ in the importance of mining new uranium. Reprocessing could reduce the need for mined uranium by 21 percent, reducing miners' exposure to radiation [22]. PUREX reprocessing has a slight advantage on reducing radiological exposure to humans in the short term. Long term, all the ore may be mined anyway creating the same amount of overall exposure.

5.3 Nuclear Proliferation

One of the biggest concerns about the PUREX process is its ability to produce weapons grade plutonium. When it was developed in the 1950s, this was its original purpose. If the plutonium is used in the reactor for a long enough time, the isotopes become too high to be usable in a weapon [21]. The plutonium fuel would have to be discharged early, an improper use of the reactor, in order to obtain the correct isotope for a weapon. However, only eight kilograms would be enough to create a bomb comparable to the one that was dropped on Nagasaki [18]. Any plutonium gained from the PUREX process would need to be treated with caution in order to prevent misuse or theft.

Separating the plutonium from the waste now creates the issue of securely storing and disposing of the plutonium, but it eliminates the potential for those in the future to recover the dangerous material from once through waste. If left in waste in dry cask storage, malicious groups could recover is with the intention or making a nuclear bomb or a dirty bomb. Terrorists in connection with al-Qaeda have been arrested both in the US and Britain while trying to acquire radioactive materials [23]. Terrorist groups have an interest in acquiring this type of material. It cannot be used directly for a nuclear weapon and would still need to go through a very intensive process in order to retrieve weapons grade plutonium, such as PUREX. This radioactive waste from the dry casks could also be used in a radiological dispersion device more commonly called a dirty bomb. In a dirty bomb the radioactive material is blown up, spreading the contamination over a larger area [23]. The radius and impact are not as large as a nuclear bomb but is still harmful.

Managing the products of PUREX reprocessing presents a more present and larger threat in terms of potential harm than storing the waste in dry casks. In either case, these types of threats can be accounted for. Safeguards such as regular inspections, strict regulations, and high security expectations could be put in place to eliminate these types of threats for either type of waste management.

It seems like neither waste management method, in terms of supply certainty, radiological risks, and safety, has any large ethical advantages over the other. The largest differences appear to be the supply certainty and safety. PUREX reprocessing has a much longer supply certainty, while at the same time presenting larger security risks in the present. Dry cask storage on the other hand, currently has an 85-year deadline on supply certainty, while proving to be extremely safe. Technological advancements such as uranium extraction from seawater, as well as the ability to retrieve the fuel for PUREX reprocessing in the future make the supply certainty of uranium in a dry cask storage system less of a concern. Dry cask storage is ethically the more attractive option because it is safer to present humans and still allows the possibility of fuel resources in the future.

6.0 Conclusion and Recommendation - (Wanyue)

The cost for dispose of spent fuel via dry cask storage is **$279.70-$282.20/kg**. For PUREX, it is **$1734/kg**. By doing the division, it shows that the cost for reprocessing is around six times as much as the cost for using the dry cask storage. Since now the United States is using dry cask storage and there is currently no infrastructure for the PUREX facilities, everything would need to start from square one if PUREX become the choice. The facilities need to be built and transportation costs that take the fuel from the storage to the processing plants also need to be taken into account. We estimate the total cost for building the facility for PUREX will be $66.3 billion in the next 10 years. Just by simply comparing the costs for both construction and operation, PUREX is not a wise choice for the current situation.

Beside the low cost, dry casks are guaranteed to be safe and will not leak in at least the next hundred years. Therefore, in the short term, the radiation exposure to both the public and the plant workers is minimal and safe for both types of fuel management. However, since spent fuel need hundreds of thousands of years before it decays back to a normal radiation level but the lifetime for dry cask is only a hundred year, in long term, PUREX will be the choice. For operation safety, the US is currently using the dry casks and no leaking events has happened. Also, four other countries are currently using some method of reprocessing process and no accident had ever happened either. So both methods satisfy the operation safety. But when considering the security risk, PUREX will increase the risk that the radioactive materials may be stolen by the terrorist groups for making threaten weapons. And this is the main reason why the US stop doing reprocessing since we want to prevent those materials being reached by the terrorist. Therefore, in the short term, dry casks storage is also a better choice when consider the safety aspect.

The management policy for the spent nuclear fuel should satisfy the aspects of high safety, economical, long-term beneficial, and low environmental impact. By considering all four aspects, there is not reason for us to use PUREX in the short term(at least in the next few decades before the dry cask reaches its lifetime). Since dry cask storage will still be the best recommendation for the current few decades, more studies about dry cask storage in details are needed. Such as its exact lifetime need to be found out so we can be prepared to take the next action before they might leak. Also, any potential future harm that dry cask storage may have to both the environment or the public will need to be studied. For example, whether the chemical inside will corrode the casks and cause them to leak when they reach their lifetime? What possible solutions do we have in order to handle this kind of accident when this really happen in the future?

The current usage of the dry cask storage in the US satisfy the low cost and safety for the current few decades, which however is not a sustainable solution and the casks may leak the dangerous waste after hundred years. Therefore, some actions must be taken in the future when those dry casks reach their lifetime and PUREX technologies may be considered as an alternative choice for handling the spent fuel in the US at that time. The main disadvantage of PUREX is its high cost of reprocessing and recycling that will increase billions of dollars of management fees in the US, an additional cost that will either comes from the government supports, or from forcing the private utility companies to build and operate the uneconomic reprocessing facilities. However, both methods of getting this extra reprocessing fee need the formation of new policy and require a long time of implementation and improvement. Therefore, to be prepared to have PUREX replace the dry cask storage in the future, it is important to discuss whether the government or the utility companies should take the responsibility of this extra cost. We suggest that the government should pay for the cost by citing the recent stangnate of the reprocessing plants in Japan as an example.

Japan is one of the country that is currently doing the reprocessing, but recently, their reprocessing plant had faced a hard time. In Japan, the utility companies are the one that are in charge of building the facility and running the whole reprocessing process. In 2016, 10 utilities that operate the nuclear power plants in Japan stopped funding the reprocessing program due to the high reprocessing cost that they need to afford [24]. This will effect Japanese recycling policy and they may need come up with a new way to handle the spent nuclear waste.

Compared to Japan, the reprocessing plants in European countries are under the management of the government, who can operate the reprocessing plants at low interested rate while perform the project that is complex and at high risk [25]. The cooperation from the government reduce the fees that individuals need to pay which ensures the reprocessing plant can be operated successfully and durably. Since the expense of building the reprocessing facilities is more expensive than the value of the plutonium produced by the reprocessing process, without enough support from the government, individual utility companies will have less enthusiasm to pay for the reprocessing process. When comes to long-term action and impact, the government, who is also the only one that can overcome any issue caused by the politics, should be ultimately responsible for the spent fuel a hundred years later [25]. If PUREX has been decided to be the replacement of the dry cask storage in the future, more study of how to divide the responsibility between the government and the utility companies will be needed.

Since there are still a hundred years till the dry casks to reach their lifetime, this actually leave our options open and give us time to do more research on it. As the technology become more advanced as well as the politic environment evolve in the next few decades, we should keep study to find out better solutions other than PUREX with lower cost and higher safety to take over the dry cask storage.

Word Count: 6897

7.0 References

[1] "NRC: Spent Fuel Storage in Pools and Dry Casks - Key Points and Questions & Answers." [Online]. Available: https://www.nrc.gov/waste/spent-fuel-storage/faqs.html#18. [Accessed: 10-Oct-2018].

[2] M. Abdallah, H. M. Chang, D. Hampton, A. Mahmood, F. Mahmood, and C. Wong, "CLOSING THE NUCLEAR FUEL CYCLE: REPROCESSING," p. 52.

[3] "What is U.S. electricity generation by energy source? - FAQ - U.S. Energy Information Administration (EIA)." [Online]. Available: https://www.eia.gov/tools/faqs/faq.php?id=427&t=3. [Accessed: 26-Nov-2018].

[4] N. Touran, "Computing the energy density of nuclear fuel." [Online]. Available: https://whatisnuclear.com/energy-density.html. [Accessed: 11-Oct-2018].

[5] "NRC: Backgrounder on Radioactive Waste." [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/radwaste.html. [Accessed: 25-Nov-2018].

[6] "Yucca Mountain," *Energy.gov*. [Online]. Available: https://www.energy.gov/photos/yucca-mountain. [Accessed: 26-Nov-2018].

[7] "NRC: Typical Dry Cask Storage System." [Online]. Available: https://www.nrc.gov/waste/spent-fuel-storage/diagram-typical-dry-cask-system.html. [Accessed: 18-Nov-2018].

[8] J. Dillon, "Vermont Yankee Buyer Says Success Here Could Mean Big Business Elsewhere." [Online]. Available: http://digital.vpr.net/post/vermont-yankee-buyer-says-success-here-could-mean-big-business-elsewhere. [Accessed: 14-Dec-2018].

[9] "NRC: Spent Fuel Storage in Pools and Dry Casks - Key Points and Questions & Answers." [Online]. Available: https://www.nrc.gov/waste/spent-fuel-storage/faqs.html. [Accessed: 25-Nov-2018].

[10] "Key Issues: Disposal of High-Level Nuclear Waste." [Online]. Available: https://www.gao.gov/key_issues/disposal_of_highlevel_nuclear_waste/issue_summary. [Accessed: 11-Oct-2018].

[11] A. Macfarlane, "The problem of used nuclear fuel: lessons for interim solutions from a comparative cost analysis," *Energy Policy*, vol. 29, no. 15, pp. 1379–1389, Dec. 2001.

[12] "1998 dollars in 2018 | Inflation Calculator." [Online]. Available: http://www.in2013dollars.com/1998-dollars-in-2018. [Accessed: 26-Nov-2018].

[13] "How uranium ore is made into nuclear fuel - World Nuclear Association." [Online]. Available: http://www.world-nuclear.org/nuclear-basics/how-is-uranium-ore-made-into-nuclear-fuel.aspx. [Accessed: 18-Nov-2018].

[14] M. Bunn, H. Zhang, and L. Kang, "The Cost of Reprocessing in China," p. 96, 2016.

[15] Atomic Energy Commission Bureau, "Estimation of Nuclear Fuel Cycle Cost at Rokkasho," 26-Nov-2018.[Online].Available: http://www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf. [Accessed: 27-Nov-2018].

[16] *The Economic and Commercial Justification for THORP*. British Nuclear Fuels, 1993.

[17] Atomic Energy Commission Bureau, "Estimation of Nuclear Fuel Cycle Cost at Rokkasho," 26-Nov-2018. [Online]. Available: http://www.aec.go.jp/jicst/NC/about/kettei/seimei/111110_1_e.pdf. [Accessed:

27-Nov-2018].
[18] B. Taebi and J. L. Kloosterman, “To Recycle or Not to Recycle? An Intergenerational Approach to Nuclear Fuel Cycles,” *Sci Eng Ethics*, vol. 14, no. 2, pp. 177–200, Jun. 2008.
[19] X. Wei *et al.*, “Efficient removal of uranium(VI) from simulated seawater using amidoximated polyacrylonitrile/FeOOH composites,” *Dalton Trans.*, vol. 46, no. 45, pp. 15746–15756, Nov. 2017.
[20] B. Richter, R. Budnitz, J. Long, P. Peterson, and J. Schori, “California’s Energy Future - Powering California with Nuclear Energy,” p. 43.
[21] W. H. Hannum, “Modern and future nuclear fuel cycles and the relationship with nuclear waste management,” *Wiley Interdisciplinary Reviews: Energy and Environment*, vol. 3, no. 4, pp. 323–329, 2014.
[22] OECD and NEA, *Radiological Impacts of Spent Nuclear Fuel Management Options*. OECD Publishing, 2000.
[23] “NRC: Backgrounder on Dirty Bombs.” [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/fs-dirty-bombs.html. [Accessed: 14-Dec-2018].
[24] “Japanese utilities ended funding for nuclear fuel reprocessing in 2016, putting MOX program in doubt | The Japan Times.” [Online]. Available: https://www.japantimes.co.jp/news/2018/09/03/national/japanese-utilities-ended-funding-nuclear-fuel-reprocessing-2016-putting-mox-plans-doubt/#.XBPfG2hKg2w. [Accessed: 14-Dec-2018].
[25] N. R. Council, *Nuclear Wastes: Technologies for Separations and Transmutation*. 2001.