ENERGY AND ENERGY POLICY

CLOSING THE NUCLEAR FUEL CYCLE: REPROCESSING

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1. INTRODUCTION

EXECUTIVE SUMMARY

The energy industry today faces significant challenges in meeting rising global demand, fuelled by economic growth in China and India, and in mitigating the effects of global warming. To date, nuclear energy constitutes about 70% of clean energy generated in the United States and represents an important option for the energy market in a low-carbon world. Further, in recent years, projections for nuclear-power growth have increased dramatically and construction of new plants has accelerated particularly in China, India and South Korea. While the recent disaster that occurred in Fukushima forced a reassessment of the safety of nuclear plants, nuclear power is still very much considered a strong candidate for the long-term development of a sustainable clean source of energy. In light of the rising popularity of nuclear power and recent technological advancements, it would be meaningful at this particular juncture to conduct an evaluation of the feasibility of various nuclear reprocessing technologies as a means of closing the fuel cycle.

Apart from giving an overview of the five major forms of nuclear reprocessing that we believe hold the highest potential for industrial implementation, this paper will also assess the viability of these particular processes. It is hoped that this study might inform future decisions on whether nuclear reprocessing should be pursued as an alternative to direct disposal in closing the back-end of the nuclear cycle, and if so, which technologies would be most desirable.

The five technologies that this study investigates are PUREX, UREX, NUEX, COEX and pyroprocessing. UREX, NUEX and COEX are derivations of PUREX technologies, which each differ from its parent process in the sense that they do not produce pure plutonium streams, thereby representing an amelioration of the older process. PUREX and pyroprocessing are two particular technologies that have been studied extensively and used in various countries such as France. As such, they are considered viable options should the US decide to pursue nuclear reprocessing.

As insufficient data and literature exist on the economic feasibility of COEX, UREX and NUEX, the cost-benefit analysis conducted in this paper only examines PUREX and pyroprocessing in depth. The analysis proceeds by quantifying costs and benefits of each reprocessing technology as applied to a single first-generation nuclear plant. Costs studied include the capital costs of building the plant, costs of operation and maintenance, as well as cost of refabrication of spent nuclear fuel. Benefits considered include savings from reduced nuclear fuel usage as well as savings from reduced storage needed to contain spent nuclear fuel.

Our analysis then revealed that the net effect of implementing either PUREX or pyroprocessing was a net loss, which can be attributed in part to depressed costs of direct disposal and of uranium. Pyroprocessing was the more expensive of the two, suggesting that PUREX is the more economically viable option. However, in evaluating the various processes, other factors such as environmental concerns and proliferation risks were taken into account. In general, UREX, NUEX and COEX might be more expensive options, due to the higher level of sophistication in chemical processes involved, but they mitigate proliferation risks, which can be considered a significant benefit in assessing the best option for nuclear reprocessing.

Upon taking into account further qualitative factors, and weighing the advantages and disadvantages of each of the five technologies, this report recommends COEX and NUEX as technologies with the highest potential for future implementation, subject to the expectation that costs of fossil fuels and of storage might increase in the future, and that sufficient research is conducted to render these technologies implementable on an industrial scale.

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2. THE APPEAL OF NUCLEAR ENERGY

GROWING ENERGY DEMAND

The world today faces significant challenges in meeting its growing energy demand, even as researchers continue to test and explore the sustainability of various energy sources, ranging from fossil fuels to renewable energy (wind, solar, biomass and hydroelectricity) to nuclear power. Between 1980 and 2007, total world primary energy demand grew by 66% and is projected to grow by 40% from 2007 onwards to 2030. Electricity demand, however, is projected to grow at almost twice this rate at 76%, averaging almost 2.5% per year (WEO, 2009), and the challenge to meet this demand is heightened by the investment needed to replace aging power sector infrastructure. Part of this increase in energy demand can be attributed to a bludgeoning world population, which is predicted to grow from 6.6 billion in 2007 to 8.2 billion by 2030 (United Nations, 2009), and also to increasing standards of living in developing countries. Further, growth in oil consumption in emerging economies, particularly for transport in China, India and the Middle East, more than outweighs reduced demand in the OECD, pushing oil use steadily higher (WEO, 2012). In order to meet this growing demand for energy, it is crucial that new sustainable methods for generating more electricity are developed, especially given the scarcity of natural resources left on the planet.

Climate change mitigation is another pressing issue that the global energy industry faces today (WEO, 2012). Fossil fuels remain the main source of energy, but the carbon dioxide emissions that accompany its use are causing global warming and will pose a significant environmental threat over the next century, should fossil fuel use persist at its current levels (WEO, 2012). As such, there is an urgent need to find an alternative source of energy that is clean (i.e. does not emit carbon dioxide as a by-product) and sustainable in the long run. Renewables might be clean sources of energy, but the intermittent nature of these sources makes it difficult to increase their overall energy capacity.

THE ROLE OF NUCLEAR ENERGY

Given the current issues facing energy generation today, nuclear power appears to be a viable solution that could alleviate the problem of global warming and produce large quantities of energy to meet increasing energy demands. Relative to other forms of generation, nuclear power has high capacity and is also energy-dense. Further, its use does not generate any carbon dioxide emissions, making it a clean source of energy. In fact, every 22 tons of uranium used saves one million tons of carbon dioxide relative to coal (WNO, 2012). Uranium, the main raw material for generating nuclear power, is also relatively abundant and can assure energy security (as opposed

to imported oil and gas) (MIT, 2011). Finally, even if nuclear power involves high capital costs, it is projected to be cost effective on the margins in providing clean power, particularly where there is little or no access to low-cost fossil fuels. In the longer-term, since a large proportion of costs are in the capital cost of nuclear plants, final electricity production costs will generally be stable, offering a means of stabilizing overall energy prices.

DEVELOPMENTS IN NUCLEAR ENERGY

As most nuclear plants in the United States run on a once-through nuclear cycle, generating a growing amount of nuclear waste, recent studies have attempted to address the question of closing the nuclear fuel cycle (MIT, 2011). However, due to complexities in public policy and scientific uncertainty, research scientists have not been able to determine a best option for managing spent nuclear fuel. Currently, two broad strategies exist to address this problem: waste disposal and nuclear reprocessing. Waste disposal involves establishing a large geological repository that would be able to contain the growing amount of spent nuclear fuel and provide permanent geological isolation for the long-lived components of the nuclear waste (MIT, 2011). To date, this option has met with significant political and economic impediments, rendering further research necessary to evaluate the viability of this solution. On the other hand, various technologies for nuclear reprocessing exist, but its further development is currently hindered by the question of economic feasibility as well as proliferation concerns.

3. ISSUES ASSOCIATED WITH SPENT NUCLEAR FUEL

COMPONENTS OF SPENT NUCLEAR FUEL (SNF)

Before discussing reprocessing in detail, it is important to first understand SNF, which is after all the raw material for reprocessing. Dealing with SNF is a complicated problem, because the different constituents in SNF pose different challenges for disposition. The table below shows the composition of SNF and the issues associated with each constituent.

Table 3.1

Constituent	Composition %	Issue	Disposition Path
Uranium (U)*	95-96	Energy resource	Separated uranium could be recycled as fuel in reactors
Plutonium (Pu)*	1	An energy resource, but also the major contributor to long term radio-toxicity (and heat-load) of the waste. Separated Pu constitutes a major proliferation concern	Separated Pu could be recycled in reactors as fuel. Proliferation concerns could be reduced by not separating pure Pu.
Minor Actinides (MAs) primarily Np, Am, and Cm	0.1	Important contributors to long term radio-toxicity and heat source of the waste. Proliferation concerns exist concerning separated Np	MAs can be burnt alone or in combination with Pu in fast reactors.
Stable or short-lived Fission Products (FPs)	3-4	Some FPs such as Cs and Sr are the primary contributors to the short term radio-toxicity and heat source in the waste. Other FPs, e.g. noble metals, could be valuable	Storage of high level waste (HLW) for a few hundred years or separation of Cs and Sr for separate disposal after a few hundred years storage. Separated Cs has industrial applications
Long-lived fission products (LLFPs), Tc and I	0.1	Contributors to the long term radio-toxicity of the waste	No industrial process to limit the problem has been developed

**U and Pu are termed major actinides in the nuclear industry*

FUEL CYCLES AND STRATEGIES

In general, there are three nuclear fuel cycles, each of which handles SNF in a different way. These cycles can be classified in the following manner:

1. Direct Disposal / Once-through: In this fuel cycle, there is no reprocessing, only direct disposal of SNF
2. Limited Recycle: In this fuel cycle, there is limited separation of the constituents of SNF, and recycled fuel is only used once
3. Closed / Full Recycle: In this fuel cycle, there is complete separation of the constituents of SNF, and iterative recycling in reactors

Currently, direct disposal is the fuel cycle of choice in the USA. Countries such as France, Russia, India and Japan have adopted differing versions of the Limited Recycle fuel cycle. The Closed / Full Recycle fuel cycle is a long term aspiration, and requires further research and development before it can be implemented on an industrial scale.

Concerns about proliferation mean that the isolation of Pu is not desirable in any recycling process. Consequently the limited and full recycle fuel cycles have developed strategies that prevent the isolation of Pu. Reprocessing technologies available today can be classified under three broad fuel recycling strategies:

1. U and Pu recycling: U and Pu are co-extracted to improve the proliferation resistance of SNF.
2. Heterogeneous Recycling: MAs are extracted separately from U and Pu to reduce heat and long term radio-toxicity of waste.
3. Homogeneous Recycling: co-extraction of MAs, U and Pu to improve proliferation resistance. Homogeneous recycling is not expected to be deployed on an industrial scale before 2025.

4. AN OVERVIEW OF DIRECT DISPOSAL

BRIEF TECHNICAL BACKGROUND ON DIRECT DISPOSAL

In order to successfully manage spent fuel, direct nuclear reactor managers use disposal methods. Once the fuel is spent, the managers need to store it safely. The most common method is to store it immediately into Light Water Reactors (LWR) on-site. In these LWR, the spent fuel is transferred immediately from the reactors so that radiation and heat levels are reduced. The IAEA commonly sites that the initial storage time in these pools could take around 9-12 months. (IAEA, 2006) Depending on storage capacities, the spent nuclear fuel will be left in these pools. Once the SNF is sufficiently cooled, they are transferred to dry cask storage facilities nearby. In these storage facilities, SNF is placed in steel containers fortified with concrete walls. These walls contain some air vents to ensure cooling. In other countries, such as France, these storage methods are treated only as interim storage methods before being transferred to a centralized storage facility, often a geological repository. In the US, no such facility exists or functions (IPFM, 2011).

SPENT FUEL INVENTORIES

The United States currently has the largest inventories of spent nuclear fuel. As of 2010, the US total stockpile of spent power-reactor fuel was at 64,500 tons, of which 15,350 tons were stored in dry casks (IPFM, 2011).

According to the 2006 International Atomic Energy Agency (IAEA) figures, one third of the 276,000 metric tons of heavy metal (tHM) is reprocessed, and around 190,000 (tHM) is left in spent fuel in storage facilities. Most of these spent fuels come from uranium. (IAEA, 2006)

The table below shows spent fuel inventories (measured in tHM) across different countries and shows what spent fuel policy each country has in place.

Table 4.1

Country	Spent fuel inventory (tons of heavy metal) (tHM) end of 2007	Spent fuel policy
Canada	38,400	Direct disposal
Finland	1,600	Direct disposal

France	13,500	Reprocessing
Germany	5,850	Direct disposal (now)
Japan	19,000	Reprocessing
Russia	13,000	Some reprocessing
South Korea	10,900	Storage, disposal undecided
Sweden	5,400	Direct disposal
United Kingdom	5,850	Reprocessing but future unclear
United States	61,000	Direct disposal

Source: IPFM, 2011

INTERIM STORAGE METHODS

1. *Light Water Reactors (LWR)*

   Light Water Reactors (LWR) is the most common type of reactors by which spent nuclear fuel is stored in cooling pools. With these LWR however, issues of overheating may cause the release of radioactive fission products. This happens when some reactor managers overstore some SNF by packing it closely together in order to make more efficient use of storage space inside the pools. This may be avoided by transporting the SNF into dry-cask storage directly after the 9-12 month interim storage time, instead of storing it on-site in the pools for years as commonly practiced (IPFM, 2011).

2. *Dry Cask Storage*

   Dry cask-storage occurs on-site at reactors or in nearby storage facilities. In these storage facilities, SNF is placed in steel containers fortified with concrete walls. These walls contain some air vents to ensure cooling. According to the IPFM, about half of the US' inventory is in dry cask storage, and of the 65 existing sites 54 had either built or are in the process of building facilities that accommodate for dry cask storage (IPFM, 2011).

   Figures provided by the US Nuclear Regulatory Commission (NRC) show that these dry cask storage facilities have the ability to store SNF for up to the next 60 years. Given that the operating lifetime of reactors is at 60 years currently, this means that interim storage in these facilities could last up to 120 years (IPFM, 2011).

3. *Storage Transport*

A committee in US National Academy of Sciences (NAS) concluded that risks to the safety of transport of spent fuel are minute. Some scientists, however, argue that they did not consider the possibility of transport casks being exposed to the threat of terrorist attacks (IPFM, 2011). While no case has occurred, the concern is rooted in the fact that most casks are transported via large trucks on public expressways. These concerns on possible terrorist attacks make the transport of spent fuel an issue of national security. For this reason, the Department of Energy (DOE) and the Department of Transportation (DOT) have created resolutions that require their approval before nuclear material is transported off-site. Pending decisions on final disposal may, however, create costs beyond those that have already been incurred in designing and building a permanent storage facility (IPFM, 2011).

4. *Geological Repositories*

Most countries have long-term plans to store High Level Waste (HLW) in geological repositories. These repositories are hundreds of meters deep and serve as natural barriers to radioactivity leakage. The objective of these repositories relies on isolating the wastes from the environment (IAEA, 2006). It is believed that the repositories could prevent leakages for up to thousands of years (IPFM, 2011). However, uncertainties remain on issues of long-term containment of long-lived radioisotopes in geological repositories.

According to the IAEA, these geological repositories should be designed to store the SNF in canisters with long expected lifetime. In addition, these canisters must remain in operational condition for a long time in conditions that have very limited ground water movement (that could allow for the corrosion of the canisters), in areas that have stable geochemical conditions, so that the canisters remain intact and effective (IAEA, 2006).

CURRENT STORAGE STRATEGY IN THE US

The majority HLW in the US and spent fuel are in on-site interim storage facilities. HLW from the production of plutonium is being stored at production sites after being mixed into glass before awaiting deep geological repository disposal. The waste is mixed with glass in a solidification process called vitrification. With this process, the waste is solidified with the glass and incorporated into its structure (IAEA, 2006). Naval spent nuclear fuel and HLW waste obtained from stored naval fuel are currently stored at the Idaho National Laboratory, also awaiting deep geological repository disposal. By 2035, in agreement with the state of Idaho, the waste is meant to be removed.

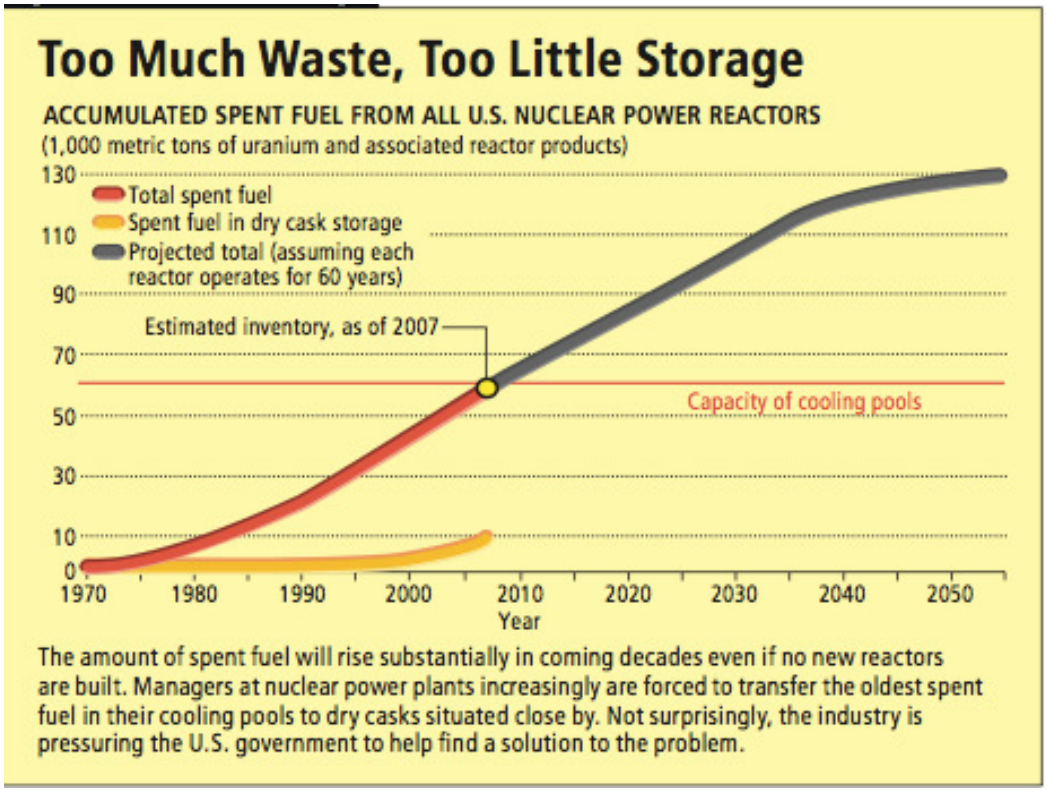
1. *US Stance on Direct Disposal*

In 1982, the Nuclear Waste Policy Act mandated the DOE to select three repository sites. By 1987, Yucca Mountain in Nevada was chosen for this site. The DOE spent approximately $15 Billion preparing for a license application and for the technical basis, but in 2010, in response to strong opposition from the Nevada state government and its Congressional representation, the Obama Administration called a halt to the project (IPMF, 2011).

In 2011, The Obama Administration formed a Blue Ribbon Commission to produce a report and in January 2012 their report made several key recommendations on the future of US policy towards nuclear waste management. The Commission suggested amendments to the already existing Nuclear Waste Act and suggested that the US move to a consent-based approach to open a new geological repository, which would be managed by a new independent waste management organization. The Commission also came to a consensus that the US should develop consolidated storage facilities and eventually move to using a geological repository (BRC, 2012).

Although interim storage techniques are economically competitive and feasible for the coming decades, the US is nearing its technical capacity (Figure below). Researchers have therefore come to a consensus that a move to a long-term waste management method must be adopted. The most popular long-term storage technique has been to store spent nuclear fuel in geological repositories (MIT, 2011). However, using geological repositories alone does not solve the nuclear waste problem and therefore some scientists have suggested that the US adopt nuclear reprocessing.

Figure 4.1



The figure shows the inventory and capacity of cooling pools and dry cask storage in US plants as of 2007. It does not keep into consideration the 120,000 ton capacity of Yucca Mountain geological repository.

Source: Von Hippel, Frank N. "Rethinking Nuclear Fuel Recycling." Scientific American May (2008): 88-93. Print.

5. AN OVERVIEW OF SPENT NUCLEAR FUEL REPROCESSING

ISSUES ASSOCIATED WITH REPROCESSING

The motivations for reprocessing are manifold. This section discusses the potential pros and cons associated with reprocessing, without rigorous analysis. In our subsequent cost-benefit analysis, these issues are utilized as metrics for evaluating reprocessing technologies.

The first and perhaps foremost issue that we address in this section is that of Economics. As seen in Chapter 3, reprocessing allows us to obtain not only U and Pu to be reused in reactors, but potentially other commercially valuable products such as Cs and noble metals as well. Conservation of natural resources constitutes a directly quantifiable benefit here. Additionally, reprocessing can help optimize waste management and SNF disposal. Current SNF has a level of radio-toxicity that is estimated to last into the next 1 million years, a time frame that immediately removes any degree of confidence in planning for its management. By removing U, reprocessing immediately reduces the volume of waste we have to deal with. By removing Pu, the radio-toxicity falls to a natural level in 10,000 years – a daunting but much smaller number. Finally, by removing the MAs, radio-toxicity falls further, while the reduction in heat levels allows for higher waste packing density and hence a reduction in repository space demand. The table below compares the waste flows generated from the different fuel cycles, and illustrates the above benefits. Note here that the table assumes full technological capability: a Full Recycle fuel cycle requires an integrated reprocessing plant and fast reactor, for example.

Table 5.1

Fuel Cycle	High-Level (m^3/TWh)	Low-Level, Short-Lived (m^3/TWh)	Low-Level, Long-Lived (m^3/TWh)
Once-through	4.1	15	0.3
Limited Recycle	0.7	17	1.9
Full Recycle	0.2	7	3.3

On the other hand, reprocessing introduces additional steps into the current Direct Disposal fuel cycle that will result in additional costs. These include early cycle costs associated with planning, R&D and licensing; as well as life-cycle costs such as capitalized and annualized costs. Other costs are also involved that are not so easily quantifiable. These include the issue of environmental externalities in the form of radioactive and chemical discharge. While the continued operation of industrial scale reprocessing plants over the past few decades have allowed for substantial reductions in radiological discharges, no amount of discharge is

acceptable within the public discourse. Environmental externalities and disutility from public rejection of reprocessing plants thus bear examining. These issues are analyzed in detail in our cost-benefit analysis section.

The second issue that inevitably arises in discussing reprocessing is that of nuclear proliferation. This is a critical issue which arises from the risk of diversion of separated SNF constituents which can be possibly misused for non-peaceful ends. As we will see in the next chapter, proliferation concerns were the main reason why the USA moved to a direct disposal fuel cycle. There are currently some methods to address this. For example, the Rokkasho-Mura plant in Japan mixes some U with the Pu at the end of the reprocessing cycle so no pure plutonium exits. The homogenous recycling fuel strategy also addresses proliferation since the presence of MAs makes the reprocessing product much harder to handle and hence divert. Nonetheless homogenous recycling is not expected to be industrially deployable in the next 2 decades.

The issue of reducing proliferation risk is a multi-faceted one. The IAEA describes two categories of risk reduction measures: intrinsic features and extrinsic measures. The first category consists of analyzing the mass flow of the SNF in the reprocessing cycle to determine its relative attractiveness for manufacturing nuclear explosive devices, as well as looking at reprocessing plant design. Specific metrics are highlighted in our cost-benefit analysis. Extrinsic measures include national and international safeguards to prevent proliferation.

REPROCESSING TECHNOLOGIES BY STAGES OF MATURITY

In this section, we review the various types of reprocessing technologies currently available and in development, organized by their respective stages of maturity. All reprocessing technologies aim to separate SNF into its various constituents; chemistry-wise, they differ in the separation pathways used and the intermediate products. Consequently there are different pros and cons to each technology, which are analyzed in detail in our cost-benefit analysis.

Any analysis of mature reprocessing technology invariably begins with the (1) Plutonium-Uranium Extraction (PUREX) process. PUREX was first utilized in the Savannah River Plant in the USA in 1954, and is still being used in all commercial reprocessing plants currently operating. Decades of commercial experience with PUREX have allowed it to develop into a mature technology, and it is hence at the top of our list. The rejection of PUREX technology in the USA is a complicated issue, which we explore in detail in the next chapter.

Nonetheless there remain many incentives for improvements on top of PUREX technology, since PUREX does not yet allow us to deal with all the issues arising from the various constituents in SNF. Many alternative R&D efforts have however failed to extend to the industrial stage, due to

the relative success of PUREX, and also because of the failed commercialization of fast reactors (which would have been able to use recycled fuel from other methods of reprocessing).

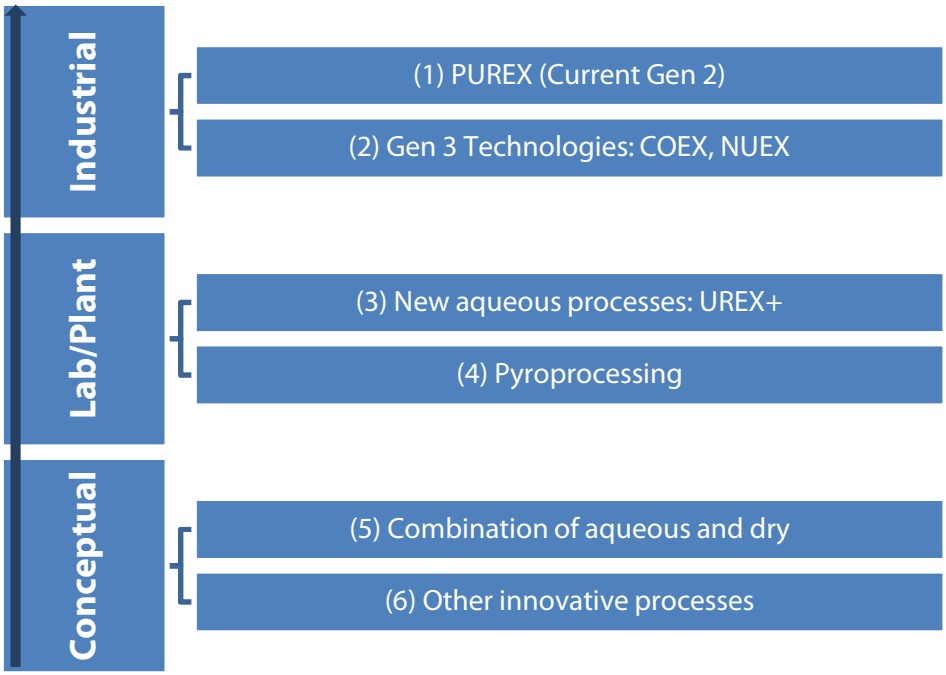
That said, there are some aqueous technologies that have been successfully tested, which constitute the second tier of reprocessing technologies. These include processes such as (2) COEX (France) and NUEX (UK). These enhance proliferation resistance by ensuring there is no pure Pu separation, unlike PUREX. They also create MOX fuel that be used in both light water and fast reactors. These technologies produced recycled fuel that can be used in Generation III reactors, and are hence ready for industrial implementation.

The third tier of reprocessing technologies are (3) new aqueous processes that use new extractant molecules. The extractant molecules allow MAs to be separated, allowing either the heterogeneous or homogeneous recycling strategies to be implemented. These include processes such as DIAMEX-SANEX (France), NEXT (Japan) and the UREX+ suite of processes (USA).

The fourth tier is (4) pyroprocessing. Pyroprocessing is fundamentally different from the three tiers of technology described above, because it is not an aqueous technology. Rather it uses inorganic media (and is hence a "dry" method), which allows for many more possibilities in reprocessing. Because of its potential, pyroprocessing is a method that we will discuss in detail in this paper.

The fifth and sixth tiers of reprocessing technologies are conceptual and are hence only covered in brief here. Scientists are postulating a (5) combination of aqueous and dry processes to maximize the advantages of both process. Some other (6) innovative processes include the use of supercritical CO_2 or Freon fluid.

Figure 5.1



The purpose of listing these technologies by their stages of maturity is to highlight that the way forward in reprocessing is to build on the successes of the well-established PUREX process and technologically mature aqueous processing methods. In the longer term, with the development of advanced reactors such as Generation IV, pyroprocessing and the other conceptual processes may become favorable.

Consequently in our paper, we will focus on analyzing PUREX, UREX, COEX, NUEX and pyroprocessing. A technical overview of these processes is presented in Chapter 6.

6. HISTORY OF REPROCESSING IN THE UNITED STATES

REPROCESSING FOR MILITARY PURPOSES

Nuclear reprocessing initially began in the United States and abroad for military purposes. Reprocessing is the product of the United States' efforts to create the atomic bomb in World War II. When Plutonium is extracted from Uranium, the product, high-grade plutonium, can be used of nuclear weapons. The United Kingdom, France, and Russia also initially reprocessed nuclear fuel as a part of their military programs. Amid proliferation concerns and the expansion of nuclear fission as a power source, military plants were converted for commercial use, and new plant were built. Nuclear reprocessing has been indefinitely phased out in the United States, but continues outside of the U.S., most notably in France.

When the United States entered the Second World War, the government put considerable resources towards experimenting methods of plutonium separation and how to used nuclear material for a large-scale nuclear weapons The latter was performed in Los Alamos, while the separation techniques – unknown to many of the scientists doing the research – were explored in Tennessee and Illinois. Most of the plutonium separation was conducted at the X-10 pilot plant in Oak Ridge, Tennessee, which made its first shipments of plutonium from Oak Ridge to Los Alamos in February of 1944 (ORNL Review). The first process used a bismuth phosphate separation process, and was quickly able to recover 90% of the plutonium in the radioactive slugs (ORNL Review). By early 1945, when X-10 ceased production, 326.4 grams of plutonium had been extracted (ORNL Review). A full-scale reactor was built in Hanford, Washington using lanthanum fluoride.

After the war, nuclear reprocessing for military purposes continued, both in the United States and abroad. America's first new reprocessing plant prior to the war was the Savannah River Site. It was constructed in the 1950's to produce tritium and plutonium-239 to support the needs of U.S. defense programs (SRS). The French also constructed reprocessing plants as a part of their defense program, commencing construction of the Marcoule plant in1955, and La Hague in 1961("AREVA Marcoule: Industrial Operator."; "History"). The United Kingdom and Russia also built reprocessing plants to fuel their military efforts. The UK built the Sellafield site in 1945, and Russia began construction of the Mayak Production Association in the same year ("Solution"; Standring).

MOVING INTO COMMERCIAL REPROCESSING

After military plants came online, plants were built for commercial uses, and many defense-oriented facilities were converted to produce residential and industrial energy. This phase was jump-started by President Dwight Eisenhower's "Atoms for Peace" program, which sought to divert nuclear research and production from military to commercial use (Andrews, 2008). With the government's blessing, companies began to invest more in nuclear energy and in 1960 Westinghouse developed the first fully commercial pressurized water reactor, a type of reactor still commonly used (Andrews, 2008). In 1966 the first permit for commercial reprocessing was awarded to a site outside of Buffalo, NY, the West Valley Demonstration Project (West Valley Demonstration Project). The facility was made to reprocess fuel used in nuclear weapons in order to diminish the US stockpile (West Valley Demonstration Project). One year later, the AEC permitted General Electric Co to build a reprocessing plant called the Dresden Generating Station in Morris, IL (Andrews, 2008). It was the first full-scale commercial nuclear power plant to be privately financed ("Dresden Generating Station.").

Major facilities abroad were also converted to produce commercial power generation, most notably in La Hague France. The facility produces approximately 1,700 tons per year, and has been operating at full capacity since 1995. The site recycles 96% of the fuel, producing only 4% waste, and has provided power generation to France for decades ("Nuclear Power").

GROWING PROLIFERATION CONCERNS

In the 1970's India indicated that it was capable of building nuclear weapons through reprocessing, causing the United States to take a deeper look at the proliferation concerns that reprocessing poses (Perkovich). The United States ultimately decided to discourage nuclear reprocessing, and President Gerald Ford issued a statement, saying: "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"(Gerald R. Ford). After Ford's public condemnation of nuclear reprocessing, President Carter indefinitely suspended support for reprocessing (Andrews, 2008). The President hoped that the United States would take the lead against nuclear proliferation by halting its reprocessing operations and encouraging other nations to do the same.

This resulted in a wave of plant closures in the U.S., but reprocessing continued outside of the United States. General Electric saw that the direction of nuclear policy in the US was not in its favor, and therefore halted construction on the Morris facility. Instead, GE sought to license the site as a storage facility. Another victim of the move against reprocessing, the West Valley Plant, was permanently shut down in 1976. In 1981, President Reagan sought to rejuvenate nuclear reprocessing in the United States by "lifting the indefinite ban which previous administrations

placed on commercial reprocessing activities in the United States" (Andrews, 2008). Reagan's initiative, however, was to no avail. The National Defense Act for Fiscal Year 1991 praised the States' stance against plutonium production and condemned the Soviet Union for operating their nine reactors for plutonium production. H.W. Bush and Clinton pushed back against nuclear reprocessing, nullifying any of Reagan's efforts. Like Reagan, George Bush encouraged more development and research for nuclear reprocessing, but his efforts were defeated as well. In June of 2009, President Obama cancelled the environmental review that was to be the first step in America's resumption of commercial nuclear reprocessing ("Adieu to Nuclear Recycling").

Nuclear fuel has not been reprocessed in the United States since 1964 (Andrews, 2008), however, America maintained once-through nuclear power generation, in which spent fuel is not reprocessed, but disposed of in pools. The US is currently the world's largest nuclear power producer, with 104 reactors generating 807 billion kWh in 2010 alone ("Mixed Oxide (MOX) Fuel."). Nuclear energy is a major power source in the United States, yet the spent fuel is not reprocessed and there are no permanent storage facilities. This leaves over 45,000 tons of spent fuel in "wet storage" (cooling pools) or dry casks. Yucca Mountain was the single potential permanent storage facility, but President Obama halted the program 2010 (White, 2010).

In 1982 the NWPA created a fund to solve the spent fuel storage problem. Utilities companies have contributed approximately $750 million per year, for a total of about $25 Billion. This fund is meant to go towards building a permanent waste storage facility, however, no progress has been made in using these funds for such a purpose ("Blue Ribbon Commission").

THE MILL FUND

In 1982 the U.S. enacted the Nuclear Waste Policy Act, which requires that the Federal government provide a site for the permanent disposal spent nuclear fuel and other radioactive waste. The Act set up a fund, funded by utilities, to raise money for the construction of a nuclear waste depository. The fund is raised through an initial one-time fee, followed by an annual fee of one mill ($0.001) per kWh. The revenue of the fund has been accumulating in the Treasury. As of May 2011, the "Mill Fund" has accumulated $24Bn of accrued interest and fees, increasing by approximately $2Bn annually. Despite the funds considerable surplus, the budget structure and procedures limit the funds effectiveness and efficiency (Hezir, 2012).

7. TECHNICAL OVERVIEW OF SELECTED TECHNOLOGIES

PUREX

As we saw in the previous chapter, the USA has rejected PUREX due to proliferation concerns. However it is the only commercially implemented reprocessing technology to date, and hence remains an important point of reference due to the surplus of data available on PUREX. In this section we will elaborate on the chemical processes involved at every stage in a typical commercial PUREX cycle. Given that UREX, COEX and NUEX are also aqueous reprocessing methods, this will make it easier to project the monetary costs of these technologies in our cost-benefit analysis.

PUREX is an aqueous chemical process that separates plutonium and uranium from nuclear fuel. This is done by dissolving nuclear matter in nitric acid and mixed with a solvent. The uranium and plutonium are then concentrated by evaporation and stored in tanks to be vitrified. The solvent still contains some fission products and actinides, and those must be extracted..

Once the uranium and plutonium is fully separated, the uranium is purified and stored. After the uranium is stored it can be sent to join the fuel cycle all over again. The left over solvents are then recovered from purification cycles and decontaminated to be recycled. Finally, uranyl nitrate is transformed into uranium nitrate. The separated plutonium is converted into a powder, plutonium oxide, through a process of calcination. The powder is then stored in stainless steel, plasma arc welded boxes. These containers are then sent for MOX fuel fabrication.

UREX

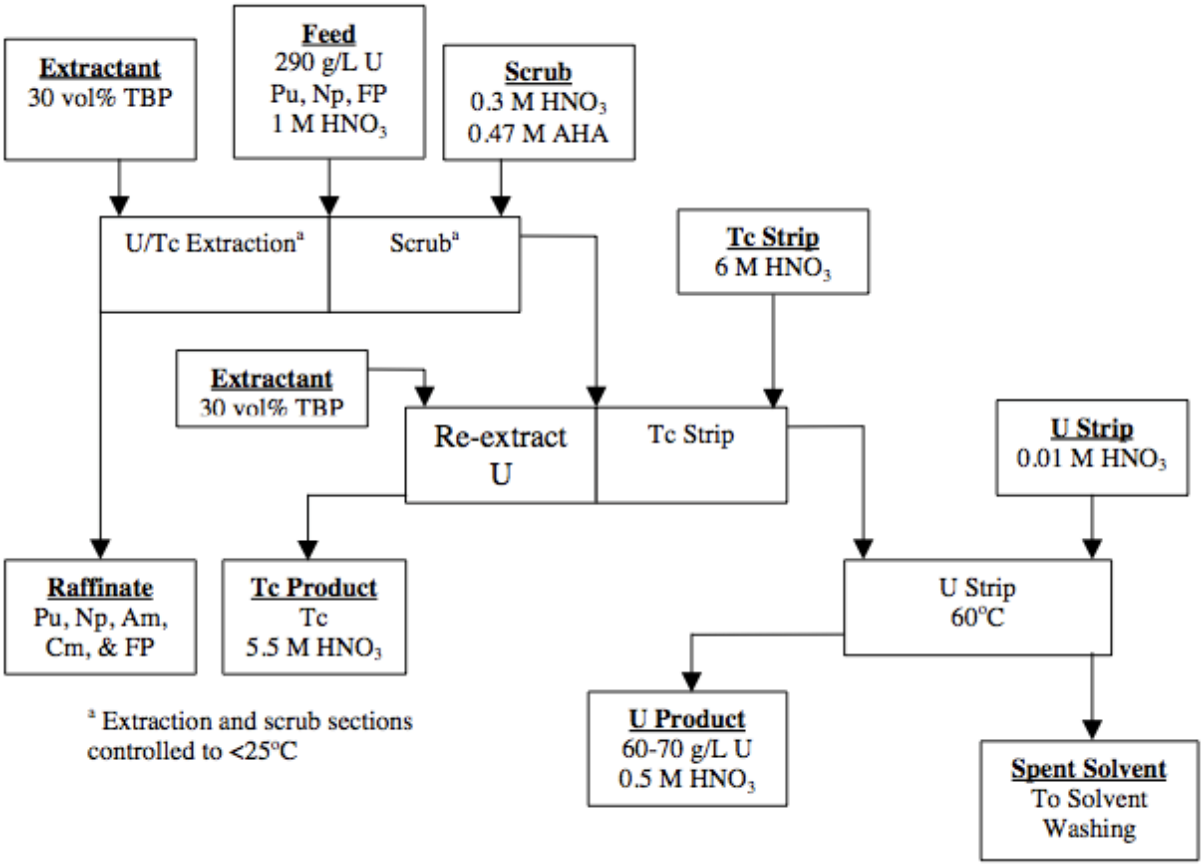
UREX, uranium extraction process, is a solvent extraction process that extracts uranium and technetium from spent nuclear fuel while leaving the plutonium to waste with the fission products and higher actinides. PUREX, plutonium and uranium extraction process, recovers plutonium and uranium whereas UERX is a slight variation on this process such that only uranium and technetium are recovered and the transuranic isotopes go to the aqueous raffinate along with fission products. Since UREX does not recover or separate plutonium, much of the proliferation risks associated with PUREX are alleviated (Thompson, 2001).

The uranium from UREX is converted into uranium trioxide and the raffinate that is produced is evaporated and calcined to produce oxide products. These products are then additionally treated by pyrochemical processing to separate the transuranic isotopes from fission products. The raffinate can be potentially sent to other aqueous processes that recover neptunium and

plutonium. The technetium is recovered from the solution and converted into an irradiation target (Thompson, 2001).

The UREX process is to recover over 99% of the uranium and 95% of the technetium in different product streams; the process should also reject over 99% of the transuranic isotopes to the raffinate. Additionally, the uranium product meets the Class C requirements for waste for not only the fission products but also the transuranic waste (Thompson, 2001).

Figure 7.1



COEX

In the COEX process used nuclear fuel is separated into three streams: Uranium-plutonium, uranium, and fission products and minor actinides. Pure plutonium is never separated out and thus the risk of proliferation is reduced. The entire process is split into two collocated processes: the treatment process and the mixed oxide fuel fabrication process (Hylko, 2008).

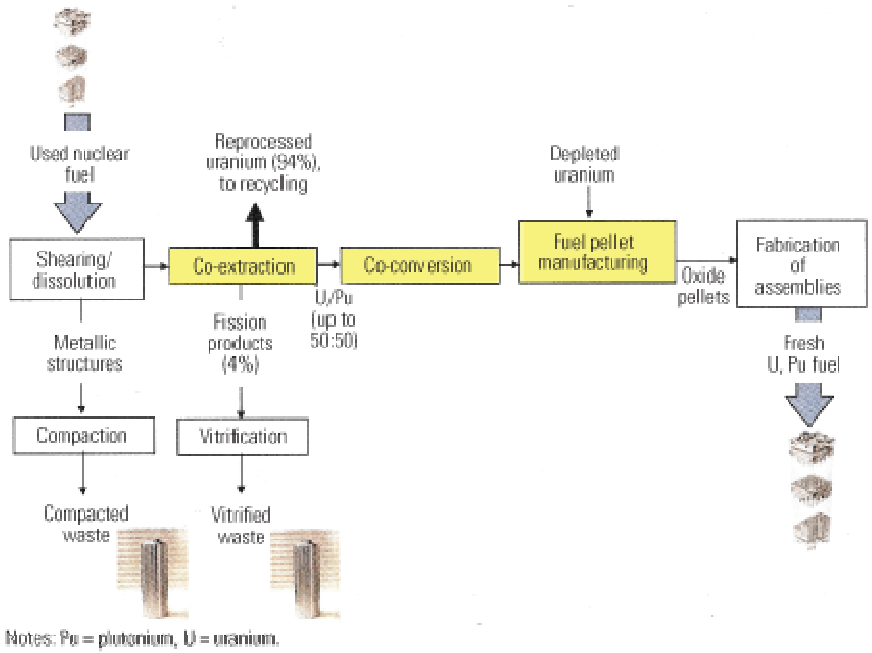
The spent nuclear fuel that is separated into the uranium-plutonium stream is extracted and then turned into MOX fuel for use in light-water reactors. The uranium stream is sent to a separate facility for purification, conversion and re-enrichment and conversion into added recycled fuel. The fission products and minor actinides stream is vitrified into glass logs and stored on site as high-level waste before being disposed of (Hylko, 2008).

The main differences between COEX and PUREX are:

- No separation of plutonium in the separation stage
- The concentration of (U, Pu) solution before conversion
- Storage of concentrate (U, Pu) solutions
- Use of co-conversion process, to product (U, Pu)O_2 solid-solid solution
- Direct feed of mixed oxide from conversion to MOX fabrication (Drain, 2008)

The implementation of COEX is aimed at the minimization of plutonium in solid form and the integration of reprocessing and recycling facilities on a single site, in this case a light-water or fast reactor. This is to prevent the risk of proliferation and to alleviate concerns regarding the safe transport of spent nuclear fuel to reprocessing plants (Drain, 2008).

Figure 7.2



NUEX

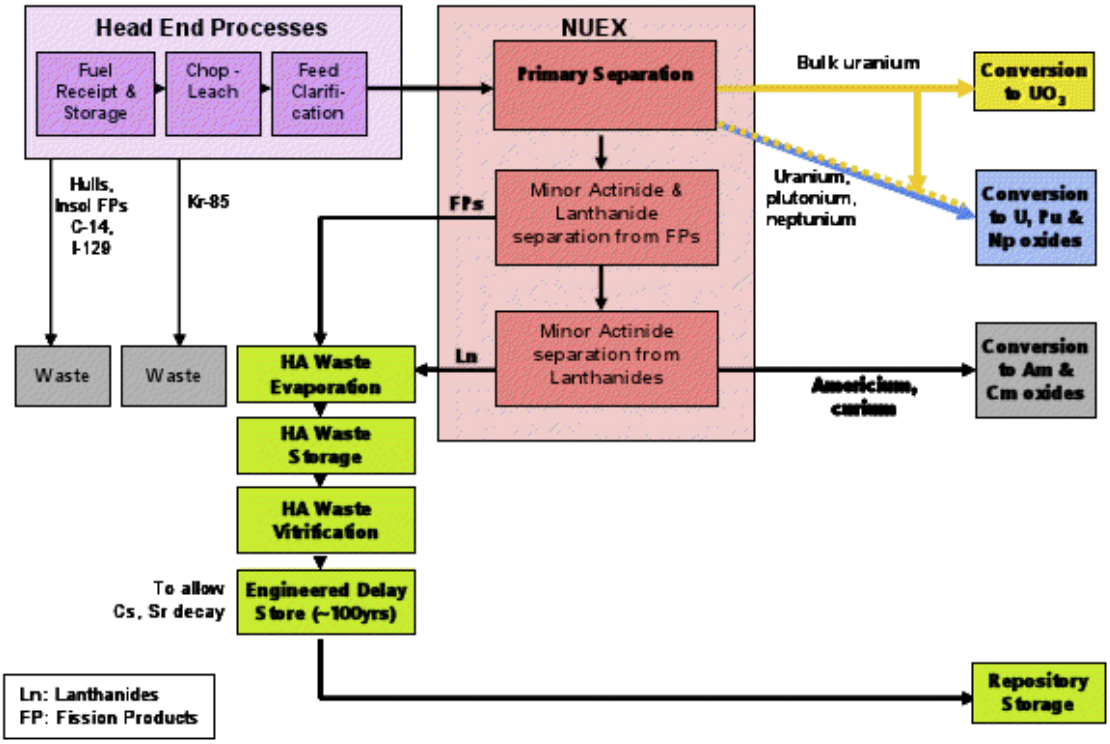
The NUEX process begins with a primary separation stage during which the spent nuclear fuel is dissolved nitric acid and then the uranium, plutonium and neptunium are extracted together into the solvent tri-butyl phosphate dissolved in kerosene. This is followed by the Strip stage during which all of the plutonium and neptunium, as well as some of the uranium, are co-stripped from the solvent and into a different aqueous solution. The quantity of uranium that is co-stripped can be changed by adjusting the redox and strip chemistry such that the required uranium to plutonium ratio necessary for the MOX fuel is produced. Additionally, uranium can also be blended further into the mix later on at the oxide powder stage so that the precise blend compositions can be obtained and so that depleted uranium stocks can be utilized (Hesketh, 2009).

The primary separation process of NUEX produces a mostly uranium stream as well as a mixed uranium-plutonium-neptunium stream. Each stream is purified in secondary stages, with the bulk uranium stream being mainly purified from technetium and the more mixed stream being purified mainly from ruthenium. This stage also provides the potential to remove the neptunium if it is not required for the MOX fuel. The mixed stream of uranium-plutonium-neptunium provides proliferation resistance because of a variety of reasons:

- The presence of uranium requires for a chemical separation step to recover plutonium
- The uranium increases the volume of the co-product and so a larger mass would be required for use in weapons
- Recycling the neptunium reduces the long term radioactivity of the high-level waste in the repository (Hesketh, 2009)

The process equipment for NUEX has been well proven; it is a chemical modification to the current reprocessing technologies in use in France and requires no further development (Hesketh, 2009).

Figure 7.3



PYROPROCESSING

Pyroprocessing, as developed by Argonne National Laboratory for fast reactors, takes place in highly shielded hot cell to provide self-protection for the fuels. The process begins with the removal of individual spent fuel rods from nuclear reactors. The individual fuel rods are then cut down into shorter segments and loaded into steel baskets after which they are placed in an electrorefiner and undergo the step called electrorefining (Laidler, 1993).

Electrorefining involves the recovery and separation of actinides from the fission products that are present in the spent fuel rods. The process begins with the placement of the spent fuel rods into steel baskets and lowering the baskets into an electrolyte salt layer consisting of LiCl and KCl. $CdCl_2$ is added to the electrolyte, and oxidizes a certain quantity of the elements in the spent fuel to their chlorides. This process creates a sufficient enough concentration of actinide ions in the electrolyte layer to sustain electrotransport; this is followed by the application of a potential of one volt between the cathode and anode (Laidler, 1993).

Uranium is electrotransported to the solid cathode and is collected in the form of a dendritic deposit that contains minute amounts of electrolyte salt. Plutonium cannot be deposited on the solid cathode because the chlorides of plutonium and uranium are in equilibrium. For plutonium

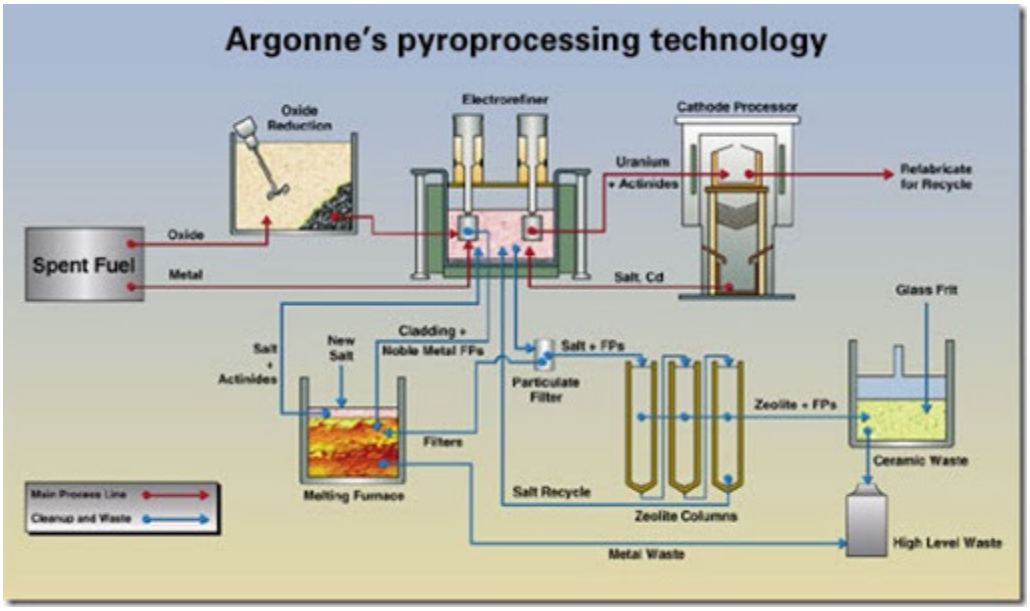
to be collected, the activity of plutonium is reduced by increasing the Pu:U concentration ratio in the electrolyte to a value greater than 2-3, followed by the electrotransport of Pu and the minor actinides to a liquid cadmium cathode. The Pu and minor actinides then form intermetallic compounds with cadmium (Laidler, 1993).

Virtually pure uranium is collected at the solid cathode and a mixture of plutonium, americium, neptunium, curium, uranium and rare earth fission products are collected at the cadmium cathode that is suspended in the electrolyte salt. These deposits are then recovered and sent to cathode processors where they are consolidated by melting and volatile materials that are present are removed by vaporization. The distillates are then transported to the condenser region of the cathode processor to be recycled for the electrorefining step (Laidler, 1993).

The resulting metals then undergo the injection casting step of Pyroprocessing. Injection casting functions to create the appropriate blend of uranium, plutonium, minor actinides and zirconium and then to case the resultant fuel alloys into slugs for new fuel rods. The fuel batch is induction-melted under vacuum and homogenized, followed by pressurization and the injection of the fuel alloy into closed-end molds. This process ends with the rapid cooling of the fuel alloy. The molds are sent to the fuel pin processing step where the molds are removed and the fuel slugs are inserted into new fuel pin cladding. Fuel pins that pass inspections are then loaded into bundles and placed in new fuel subassembly hardware and eventually inserted into the reactor (Laidler, 1993).

The majority of long term radioactivity from nuclear plants and waste generally comes from the actinides in spent fuel. Pyroprocessing removes the actinides, compacting the waste and producing less dangerous by-products. The actinides that are produced by this recycling process are used again as nuclear fuel rods, but many require fast breeder reactors to achieve the greatest potential efficiency (Laidler, 1993).

Figure 7.4



This initial pyroprocessing process has been altered and improved on by Korea's Atomic Energy Research Institute with US assistance. This more advanced process involves separating uranium, transuranics including plutonium, and fission products including lanthanides. This process utilizes a lithium-potassium chloride bath from which uranium is recovered electrolytically to concentrate the actinides, which are then removed together. The actinides are then fabricated into fast reactor fuel without further treatment (Yoo, 2008).

The most recent development in Pyroprocessing is the Advanced Recycling Center proposed by GEH (GE Hitachi Nuclear Energy) along with IBM and Lockheed Martin. The ARC combines Pyroprocessing and fast burner reactors in one location and produces power using the spent nuclear fuel from other nuclear reactors. ARC begins with the separation of spent nuclear fuel into:

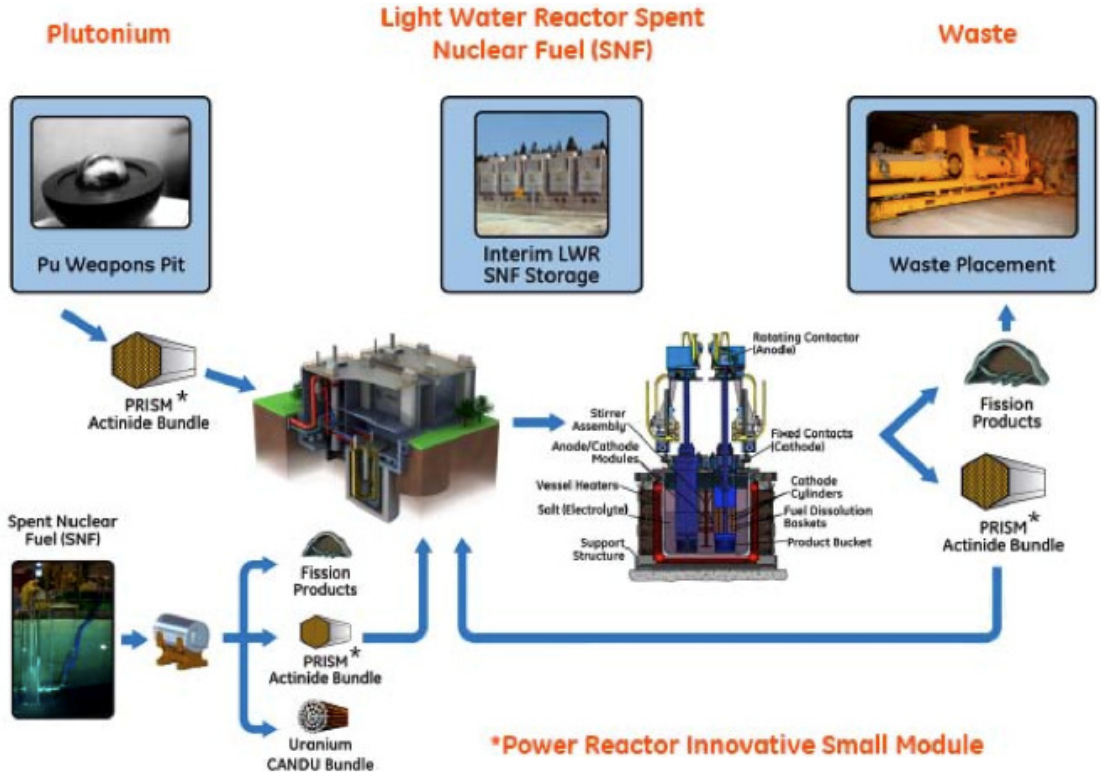
- Uranium that can be used in CANDU reactors or re-enriched for use in light-water reactors
- Fission products that are stabilized for geologic disposal
- Actinides which are used as fuel in the Advanced Recycling Reactor (GE Hitachi, 2012)

As with the ANL pyroprocessing technology, this separation is proliferation resistant because pure plutonium is never generated and this separations technology is widely used in the aluminum industry and has been demonstrated time and again in US National Laboratories and various other research institutes (GE Hitachi, 2012).

The actinide fuel that is separated is used in GEH's PRISM advanced recycling reactor to produce electricity. PRISM uses liquid sodium as a coolant which allows the neutrons to have higher energy and thus drive the fission of the actinides, converting the actinides into shorter lived fission products. The result is the production of heat energy, which is promptly converted into electrical energy in a turbine. Sodium cooled reactors operate in many sites around the world (GE Hitachi, 2012).

The ARC produces carbon-free base load electrical power and consists of a pyroprocessing plant and three power blocks of 622 MWe each for a total of 1,866 MWe. For the current load of spent nuclear fuel being produced in the United States by the 100 nuclear power plants in operation, a total of 26 ARCs will be required to process all of the spent nuclear fuel. Each would produce approximately 50,000 MWe per year and prevent the emission of 400 million tons of carbon dioxide yearly (GE Hitachi, 2012).

Figure 7.5



8. COST-BENEFIT ANALYSIS

COST-BENEFIT ANALYSIS METHODOLOGY

Now that we have presented a technical overview of the technologies, we will perform a cost-benefit analysis on them and attempt to choose the most suitable technology for the United States. It is emphasized here that our analysis is neither comprehensive due to the lack of data nor as mathematically sophisticated as we would like it to be. Nonetheless, we have attempted to present as useful a picture of our chosen reprocessing technologies as possible.

We divide our analysis into a quantitative component which applies discounting methods to monetized costs and benefits, and a qualitative component which provides a static analysis of non-monetized costs and benefits. We then discuss the issue of proliferation resistance, as well as other issues that we did not cover in our analysis. Our cost-benefit analysis methodology can be summarized in the following matrix:

Table 8.1

QUANTITATIVE ANALYSIS	
Benefits 1. Recycled Fuel Savings 2. Storage Savings	Costs 1. Cost of building plant 2. Cost of Operation and Maintanence 3. Cost of Refabrication

QUALITATIVE ANALYSIS	
Beneficial characteristics of each technology	Negative characteristics of each technology

UNCERTAINTY, DISTRIBUTION AND OTHER ISSUES
Unaddressed Issues: • Uncertainty in cost estimates • Who pays? • Environmental concers • Public policy and public acceptance • Funding

SIMPLIFYING ASSUMPTIONS

Because UREX, COEX and NUEX are non-industrial-scale technologies that have never been industrially implemented, there is less data in the literature on what the costs might be for an industrial implementation of these technologies. Given the lack of accurate cost estimates on

these three technologies, we have chosen to focus instead on quantifying the hypothetical implementation of PUREX and pyroprocessing as a realistic means of investigating the economic feasibility of nuclear reprocessing.

We adopt a mathematically simplified version of the methods outlined in Bunn et al (2003) and Recktenwald et al (2012). In this section, we lay out some of the general assumptions in this process:

1. We assume the existence of a fast nuclear reactor, which removes the problem of spent MOX fuel rods. The use of reprocessed MOX in current slow reactor results in spent fuel that is hotter and has higher radiotoxicity, which presents additional challenges for storage. Nonetheless, we assume fast reactors to be the final goal of the nuclear industry and ready for use by the time our reprocessing technologies are implemented.
2. We ignore economies of scale in the consideration of plant size.
3. The burn-up rates and non-fuel costs of MOX and enriched uranium (LEU) fuels are the same; i.e. both types of fuel are treated equivalently in our cost analysis.
4. We use the fraction of U/Pu recovered by the various technologies directly, treating radioactive decay and loss during reprocessing as negligible.
5. Recovered Pu is utilized immediately, thus pre-empting the issues of radioactive hazards and high storage costs that arise with storage of unused Pu.
6. The cost of building the plant is borrowed at a fixed interest rate with government backing, and repaid across the lifetime of the plant. We further assume that the plant adopts a repayment plan (without specifying it) that is financially sustainable.
7. For each technology, there is a fixed annual expense for operations and maintenance of the reprocessing plant, as well as a fixed per unit expense for fuel refabrication.
8. We consider average costs of storage rather than modeling interim and permanent storage separately, chiefly due to the lack of data.
9. The reprocessing and power facilities are integrated, making transport costs negligible.

Additionally, we assume that there is a nuclear power fleet producing waste, with the following characteristics:

Table 8.2

CHARACTERISTIC	VALUE
Thermal Capacity of Nuclear Power Fleet *(GW)*	130
Capacity Factor (%)	85%
Annual Thermal Output (GWd)	40000
Enriched U *(tHM)*	3380

Enrichment Ratio *(%)*	10
Unenriched U *(tHM)*	33800
Burnup Rate *(GWd/tHM)*	50
Mass of Spent Fuel = Annual Thermal Output / Burnup *(tHM)*	800

Source: Radovic 1997

The reprocessing plant handles all the waste from this fleet and has the following characteristics:

Table 8.3

CHARACTERISTIC	VALUE
Construction Time, T_C *(years)*	10
Operation Lifetime, T_O *(years)*	40
Total Lifespan, $T = T_C + T_O$ *(years)*	50
Effective Reprocessing Capacity of Plant *(tHM)*	800
Thermal Capacity of Reprocessing Plant *(GW)*	1

For purposes of discounting, we assume a 7% discount rate for years 1 through 25, and interpolate linearly from 7% to 1% for years 26 through 50.

Table 8.4

Year	Discount Rate	Year	Discount Rate
1-25	7%	**38**	5.44%
26	6.88%	**39**	5.32%
27	6.76%	**40**	5.20%
28	6.64%	**41**	5.08%
29	6.52%	**42**	4.96%
30	6.40%	**43**	4.84%
31	6.28%	**44**	4.72%
32	6.16%	**45**	4.60%
33	6.04%	**46**	4.48%
34	5.92%	**47**	4.36%
35	5.80%	**48**	4.24%
36	5.68%	**49**	4.12%
37	5.56%	**50**	4.00%

ESTIMATES FROM THE LITERATURE

On the next page, we present a table summarizing unit costs estimated by other papers in the literature. We will use these estimates or averages (if more than one estimate is available) in our subsequent quantitative analysis. For purposes of consistency, all estimates were converted to 2012 dollars using the US Consumer Price Index established by the US Department of Labor.

Table 8.5

**all estimates have been converted to 2012 dollars*

MEAN ESTIMATES

	PUREX	**Pyroprocessing**	**Sources**
Cost of Decommissioning *($)*	1.075e9	9.6e9	b, c, e
Cost of OM *($)*	80e6	80e6	a, c, d, e, g
Cost of Refabrication *($/kgHM)*	1500	1100	a, c, e
Cost of Reprocessing *($/kgHM)*	1000	2700	a, c, e
Amount of Reprocessed U Generated *(%)*	15	30	a, c, e
Cost of Direct Disposal *($/kgHM)*	416.31		See below
Cost of Disposal after Reprocessing *($/kgHM)*	200	100	a, c, e

	PUREX	**COEX**	**Pyroprocessing**	**Sources**
Cost of Construction *($)*	3.584e9	19..57e9	3.2e9	a, c, e, f

a. *Bunn et al, 2003*
b. *OECD, 1994: assumes decommissioning cost to be 30% of overall capital cost*
c. *BCG, 2006*
d. *Recktenwald et al, 2012*
e. *Lee et al, 2010*
f. *GE Hitachi*
g. *Grubert, 2009*

QUANTITATIVE BENEFIT ANALYSIS

In this section, we will focus on:

1. *Savings from reduced uranium needed to maintain the same power output, due to recycled fuel produced from reprocessing,* $\boldsymbol{B_R}$

   Due to prior concerns about the scarcity of uranium, reduced uranium usage was one of the original reasons for pursuing reprocessing technology. Today, this factor might not be one of the main drivers of research on nuclear reprocessing, but is nevertheless useful in reducing costs associated with obtaining nuclear fuel.

   To calculate total monetized benefits, we obtain from literature the percentage increase in volume derived from reprocessed fuel relative to the original volume of uranium. This represents the amount of nuclear fuel saved.

Table 8.6

	PUREX	Pyroprocessing
Reprocessed U Generated (%)	15.00%	30.00%
Amount of Reprocessed U (ton)	120	240

We then derive a constant spot price of around $46 per pound of uranium, for a plant operating for 40 years beginning 2030. A BCG report completed in 2006 assumed a spot price of $31 for a nuclear reprocessing plant that begins operations in 2020, which was a simple average of spot prices in the last 12 months prior to the study. In this study, we have chosen to use futures as a means of estimating future prices, in line with historical prices. To obtain this value, we took the simple average of the prices of uranium futures for the 60-month period beginning December 2012, which we believe would best estimate the future price of uranium. This gave us a value of **$102,291/ton**.

The yearly-monetized benefit of saved nuclear fuel is then given by multiplying the amount of fuel saved, by the derived constant spot price.

Finally, we apply discounting, using the values described in the previous section, to derive the final benefits associated with reduced uranium usage. The detailed calculations for PUREX are provided at the end of this section for an example.

Table 8.7

	PUREX	Pyroprocessing
Discounted Savings of Uranium	$76,868,327.31	$153,736,654.61

2. *Savings from reduced storage needed,* $\boldsymbol{B_S}$

To calculate savings from reduced storage needed for spent nuclear fuel, we make a number of simplifying assumptions. We first assume a constant averaged storage cost per kilogram of spent nuclear fuel, which includes all costs associated with transportation, storage materials and location. Further, we make no differentiation between low and high level waste, assuming that a single storage cost can be applied across various forms of spent nuclear fuel. This storage cost is averaged across comparable values derived from various studies (MIT 2011, BCG 2006 and Grubert 2009).

Table 8.8

DOE, 2001	$548.93
MIT, 2010	$300.00
Gruber, 2009	$400.00
Average ($/kg)	**$416.31**

We then derive from literature the averaged storage cost savings, and multiply it by the amount of spent fuel to calculate the annual savings from reduced waste storage.

Table 8.9

	PUREX	**Pyroprocessing**
Cost of Direct Disposal ($/kgHM)	$416.31	$416.31
Cost After Reprocessing ($/kgHM)	200	100
Saved Costs of Storage ($/kgHM)	$216.31	$316.31
Yearly Cost of Storage ($)	$173,046,937.15	$253,046,937.15

Finally we discount the annual values to derive the total monetized benefits of reduced spent nuclear fuel storage.

Table 8.10

	PUREX	**Pyroprocessing**
Discounted Benefit Storage	$1,083,650,744.72	$1,584,624,994.85

The total benefits of reprocessing are then $\mathbf{B_R + B_S}$:

Table 8.11

	PUREX	**Pyroprocessing**
Discounted Savings of U ($)	$76,868,327.31	$153,736,654.61
Discounted Benefit Storage ($)	$1,083,650,744.72	$1,584,624,994.85
TOTAL DISCOUNTED BENEFITS ($)	**$1,160,519,072.03**	**$1,738,361,649.46**

Table 8.12

EXAMPLE: STORAGE BENEFITS FOR PUREX

Year	Disc Repayment	Discount Factor	Year	Disc Repayment	Discount Factor
1	$0.00	0.93	**26**	$3,725,363.80	0.151745801
2	$0.00	0.8649	**27**	$3,473,529.21	0.141487784
3	$0.00	0.804357	**28**	$3,242,886.87	0.132092996
4	$0.00	0.74805201	**29**	$3,031,450.65	0.123480532
5	$0.00	0.695688369	**30**	$2,837,437.81	0.115577778
6	$0.00	0.646990183	**31**	$2,659,246.71	0.108319494
7	$0.00	0.601700871	**32**	$2,495,437.11	0.101647013
8	$0.00	0.55958181	**33**	$2,344,712.71	0.095507533
9	$0.00	0.520411083	**34**	$2,205,905.72	0.089853487
10	$0.00	0.483982307	**35**	$2,077,963.19	0.084641985
11	$11,050,055.10	0.450103546	**36**	$1,959,934.88	0.07983432
12	$10,276,551.24	0.418596297	**37**	$1,850,962.50	0.075395532
13	$9,557,192.66	0.389294557	**38**	$1,750,270.14	0.071294015
14	$8,888,189.17	0.362043938	**39**	$1,657,155.77	0.067501174
15	$8,266,015.93	0.336700862	**40**	$1,570,983.67	0.063991113
16	$7,687,394.81	0.313131802	**41**	$1,491,177.70	0.060740364
17	$7,149,277.18	0.291212576	**42**	$1,417,215.28	0.057727642
18	$6,648,827.77	0.270827695	**43**	$1,348,622.06	0.054933624
19	$6,183,409.83	0.251869757	**44**	$1,284,967.10	0.052340757
20	$5,750,571.14	0.234238874	**45**	$1,225,858.62	0.049933082
21	$5,348,031.16	0.217842153	**46**	$1,170,940.15	0.04769608
22	$4,973,668.98	0.202593202	**47**	$1,119,887.16	0.045616531
23	$4,625,512.15	0.188411678	**48**	$1,072,403.94	0.04368239
24	$4,301,726.30	0.17522286	**49**	$1,028,220.90	0.041882676
25	$4,000,605.46	0.16295726	**50**	$987,092.07	0.040207369

QUANTITATIVE COST ANALYSIS

In this section, we will focus on:

1. *Costs of building the reprocessing plant,* $\boldsymbol{C_R}$

   Firstly, we calculate the total capital cost of building the reprocessing plant. Cost estimates in the literature are provided in the table above.

Table 8.13

	PUREX	Pyroprocessing
Cost of Construction ($)	3.584e9	3.2e9

Next, we set the capital cost of building the plant to be funded entirely through borrowing, with government backing. We assume an annual interest rate of 4% on the loan, which is appropriate given government backing. The loan is paid back in equal yearly installments, giving a yearly repayment of:

$$\text{Yearly Repayment} = \frac{\square}{1-(1+\square)^{-\square}} \times \text{Total Capital Cost}$$

$\square = \text{interest rate} = 4\%$

$\square = \text{total lifespan of plant} = 50$

Table 8.14

	PUREX	Pyroprocessing
Yearly Repayment ($)	166,835,918.41	148,960,641.44

Finally, we apply discounting to the yearly repayment to arrive at a total discounted cost of building the reprocessing plant, which we term $\mathbf{C_R}$. The detailed calculations for PUREX are provided at the end of this section for an example.

Table 8.15

	PUREX	Pyroprocessing
Discounted Cost of Construction ($)	2,188,527,177.58	1,954,042,122.84

2. *Costs of operating and maintaining the reprocessing plant,* $\boldsymbol{C_{OM}}$

   Three components constitute $\mathbf{C_{OM}}$: (a) the cost of the reprocessing process; (b) the costs of running plant that are not related to the fuel, such as worker salaries and routine plant maintenance; and (c) the cost of decommissioning the reprocessing plant at the end of its

lifespan. In the case of (a), this is essentially the cost of applying the different reprocessing technologies to the SNF.

Table 8.16

	PUREX	Pyroprocessing
Cost of Reprocessing *($/kgHM)*	1000	2700
Total Yearly Cost of Repro ($)	0.8e9	2.16e9

In the case of (b), we assume a fixed annual expense which is dependent only on the total size of the plant. This is reasonable given that we are analyzing costs not related to the fuel.

Table 8.17

	PUREX	Pyroprocessing
Yearly Cost of Ops *($)*	80e6	80e6

In the case of (c), we calculate first the total cost of decommissioning the plant, which we calculate from cost estimates in the literature again. It is standard industry practice for plants to put aside a sum into a decommissioning fund (DF) that will eventually be used for decommissioning the plant. We assume that the DF pays yearly returns of 3%, and that contributions into the DF are made over the entire lifespan. Then the yearly contribution to the DF is calculated by:

$$\text{Yearly DF Contribution} = \square \times \text{Total Decomission Cost}$$

$$\square = \frac{\square_{\square}}{(1+\square_{\square})^{\square}-1}$$

$$\square_{\square} = \text{return on DF} = 3\%$$

Table 8.18

	PUREX	Pyroprocessing
Cost of Decommissioning *($)*	1.075e9	9.6e9
Yearly DF Contribution ($)	9,530,406.52	85,108,746.64

We then apply discounting to the yearly costs to obtain total discounted costs for (a) and (b), which we sum to obtain the discount costs of operating and maintenance. We term this $\mathbf{C_{OM}}$.

Table 8.19

	PUREX	Pyroprocessing
Discounted Cost of Ops	$500,974,250.13	$500,974,250.13
Discounted Cost of Decommission	$125,018,364.70	$1,116,443,070.80
Discounted Cost of	$5,009,742,501.33	$13,526,304,753.59

Reprocessing		
Total Discounted Cost of OM	$5,635,735,116.16	$15,143,722,074.52

3. *Costs of refabricating or treating reprocessed fuel,* C_T

In reality, the refabricating of reprocessed fuel is dominated by a small number of firms such as COGEMA and BNFL (Bunn et al, 2003), meaning that there is very little public information on the costs of refabricating. Nonetheless, studies from the National Academy of Sciences and National Nuclear Security Administration provide some estimates about costs. We will assume that refabricating of reprocessed fuel is done not by an external company (which introduces problems of demand and supply), but rather is done on site. We have adopted per unit costs of refabricating then reflect the uncertainty from not having official costs and prices.

We perform a simple multiplication of unit cost of refabricating by mass of spent fuel to obtain the yearly costs of refabrication.

Table 8.20

	PUREX	Pyroprocessing
Cost of Refab ($/kgHM)	1,500.00	1,100.00
Total Yearly Refab Cost ($)	1,200,000,000.00	880,000,000.00

We then apply discounting to obtain total discounted costs of refabricating, and term this $\mathbf{C_T}$.

Table 8.21

	PUREX	Pyroprocessing
Discounted Cost of Refab ($)	$7,514,613,751.99	$5,510,716,751.46

The total costs of reprocessing are then $\mathbf{C_R + C_{OM} + C_T}$:

Table 8.22

	PUREX	Pyroprocessing
Discounted Cost of Construction ($)	2,188,527,177.58	1,954,042,122.84
Discounted Cost of OM ($)	$5,635,735,116.16	$15,143,722,074.52
Discounted Cost of Refab ($)	$7,514,613,751.99	$5,510,716,751.46
TOTAL DISCOUNTED COST ($)	**$15,338,876,045.73**	**$22,608,480,948.82**

Table 8.23

EXAMPLE: CONSTRUCTION COSTS FOR PUREX

Year	Disc Repayment	Discount Factor	Year	Disc Repayment	Discount Factor
1	$155,157,404.12	0.93	**26**	$25,316,650.00	0.151745801
2	$144,296,385.83	0.8649	**27**	$23,605,244.46	0.141487784
3	$134,195,638.83	0.804357	**28**	$22,037,856.23	0.132092996
4	$124,801,944.11	0.74805201	**29**	$20,600,988.00	0.123480532
5	$116,065,808.02	0.695688369	**30**	$19,282,524.77	0.115577778
6	$107,941,201.46	0.646990183	**31**	$18,071,582.21	0.108319494
7	$100,385,317.36	0.601700871	**32**	$16,958,372.75	0.101647013
8	$93,358,345.14	0.55958181	**33**	$15,934,087.04	0.095507533
9	$86,823,260.98	0.520411083	**34**	$14,990,789.08	0.089853487
10	$80,745,632.71	0.483982307	**35**	$14,121,323.32	0.084641985
11	$75,093,438.42	0.450103546	**36**	$13,319,232.15	0.07983432
12	$69,836,897.73	0.418596297	**37**	$12,578,682.84	0.075395532
13	$64,948,314.89	0.389294557	**38**	$11,894,402.50	0.071294015
14	$60,401,932.85	0.362043938	**39**	$11,261,620.28	0.067501174
15	$56,173,797.55	0.336700862	**40**	$10,676,016.03	0.063991113
16	$52,241,631.72	0.313131802	**41**	$10,133,674.42	0.060740364
17	$48,584,717.50	0.291212576	**42**	$9,631,044.16	0.057727642
18	$45,183,787.28	0.270827695	**43**	$9,164,901.63	0.054933624
19	$42,020,922.17	0.251869757	**44**	$8,732,318.27	0.052340757
20	$39,079,457.62	0.234238874	**45**	$8,330,631.63	0.049933082
21	$36,343,895.58	0.217842153	**46**	$7,957,419.33	0.04769608
22	$33,799,822.89	0.202593202	**47**	$7,610,475.85	0.045616531
23	$31,433,835.29	0.188411678	**48**	$7,287,791.67	0.04368239
24	$29,233,466.82	0.17522286	**49**	$6,987,534.66	0.041882676
25	$27,187,124.14	0.16295726	**50**	$6,708,033.27	0.040207369

CONCLUSIONS FROM QUANTITATIVE ANALYSIS

Table 8.24

	PUREX	Pyroprocessing
TOTAL DISCOUNTED BENEFITS ($)	$1,160,519,072.03	$1,738,361,649.46
TOTAL DISCOUNTED COST ($)	$15,338,876,045.73	$22,608,480,948.82
NET BENEFIT ($)	**$-14,178,356,973.70**	**$-20,870,119,299.36**

From our quantitative analysis, it is clear that both PUREX and pyroprocessing are a net cost compared to direct disposal. This reflects well the general consensus in the literature that reprocessing is not feasible compared to direct disposal currently.

Moreover, PUREX is significantly cheaper than pyroprocessing. As mentioned in previous chapters, the long-term commercial use of PUREX has allowed reductions in cost and increases in efficiency. Consequently the result that PUREX is significantly cheaper was also predicted.

As we will see in the next section, our quantitative analysis does not account for a number of other issues, unique to each technology that will significantly affect both costs and benefits. Thus a conclusion on which technology to choose cannot be made based on quantitative data alone.

QUALITATIVE BENEFIT-COST ANALYSIS

PUREX is currently the only commercially implemented reprocessing technology and has been for some time. PUREX is an aqueous chemical process that separates plutonium and uranium from nuclear fuel. The separated plutonium is converted into plutonium oxide and stored before being sent for MOX fuel fabrication. This separation of plutonium creates a proliferation risk, a risk that is addressed when the plutonium is not separated as an individual stream. UREX, COEX, NUEX and Pyroprocessing alleviate this proliferation concern by not separating pure plutonium and by keeping the plutonium mixed with some combination of transuranics, uranium or uranium-neptunium. In the case of COEX, uranium and plutonium are co-extracted, with UREX and Pyroprocessing the plutonium is recovered with other transuranics and with NUEX the plutonium is in a uranium-plutonium-neptunium mix.

Although NUEX, UREX, COEX and Pyroprocessing alleviate proliferation concerns associated with PUREX it is important to note the technical feasibilities, or lack thereof, of all 4 of these alternative processes. In the case of UREX, the United States Department of Energy has altogether abandoned the process because of chemical safety issues associated with plutonium-neptunium recovery in the aqueous phase. Alternative UREX processes have been theoretically formulated, but they would require significant technological development to become even

somewhat feasible. COEX presents a technical improvement on PUREX by not only alleviating the aforementioned proliferation concern, but also allowing for the integration of the reprocessing and recycling processes in the same facility. This further alleviates the proliferation risks associated with transport of spent nuclear fuel, as well as the larger capital costs associated with developing separate PUREX facilities. As for NUEX, the process equipment has been well proven; it is a chemical modification to the current reprocessing technologies in use in France and requires no further development and thus avoids the PUREX proliferation concerns without posing technical hurdles. In the case of Pyroprocessing there are no technical obstacles to its implementation and there is potential for integration of this reprocessing technology in the same facility as the recycling process.

Carbon emissions have often been a sticking point in the generation of electricity, since most of electricity in the United States is generated through the burning of fossil fuels. With reprocessing nuclear fuel wastes, CO2 emissions will be drastically reduced. The full implementation of Pyroprocessing through proposed Advanced Recycling Centers would reduce carbon emissions by 400 million tons yearly. As for PUREX, given that the amount of uranium saved is usually half of that of Pyroprocessing, this would amount to about 200 million tons of CO2 yearly if full implementation is pursued. Although there is not much data on carbon emissions associated with NUEX, UREX and COEX, we envision that the carbon footprint of the average US citizen would be substantially reduced as in the case that any of the three is implemented to close the nuclear fuel cycle.

Disposal costs would be significantly lower if any reprocessing technology is brought into the nuclear fuel cycle in the US. The wastes remaining after all the mentioned nuclear reprocessing technologies, minus UREX which has documented safety issues, are significantly less dangerous and radioactive than that of ordinary spent fuel and present a significant reduction in storage space and cost. While the safety of the wastes from the various reprocessing technologies does not pose significant safety-related differences since the makeup is generally the same, the amount of waste is a point of divergence. Pyroprocessing creates less waste than does PUREX and thus further reduces the need for storage and geological repositories than does PUREX.

UNCERTAINTY, DISTRIBUTION AND OTHER ISSUES

1. *Uncertainty in cost estimates*

   There are several uncertainties in estimating costs associated with nuclear reprocessing that must be acknowledged for a more comprehensive analysis. First of all, there is still a great amount of uncertainty surrounding the future cost of storage cost, especially those associated with current and future geological repositories. Although there are estimates on the costs

associated with the potential completion and opening of the Yucca Mountain ($45-50B), these estimates may not be accurate because of the delays, which are brought by the ongoing political disputes (BCG, 2006). The changing US political stance also poses an uncertainty on the future of nuclear reprocessing. The US had previously banned nuclear reprocessing and although the ban has been lifted since, there is no established regulatory structure for the disposal of separated high level waste from reprocessed fuel. Moreover, there are no accurate estimates on the costs of storage of MOX fuel (MIT, 2011).

Moreover, there are risks associated with the uncertainty of the development of a repository (if there shall ever be progress). Lengthy licensing processes and stringent requirements set by regulatory authorities constantly hamper the process of launching and developing a geological repository. These delays cause complications and increased costs.

There is an uncertainty in the long-term prices of uranium. In order to have a feasible economic competitiveness comparison between disposal and recycling methods, one must be able to estimate the costs associated with the price of uranium. However, uranium prices have been increasing in the last few years and are expected to continue rising for the next few years, which could amount to higher costs for current and future plant operators. The uncertainty in uranium prices causes its price to be volatile and therefore adds financing risks on nuclear firms. Recycling is one of the ways to mitigate the problem of uranium price volatility (BCG, 2006).

In fact, there aren't any certain estimates of what nuclear fuel recycling would actually cost. Even PUREX recycling, which has been implemented commercially in France and the UK for years, does not have sufficient information that would accurately reflect the cost of using the same technology in the US. Even more difficult would be the cost estimate of technologies (such as COEX and NUEX), which have not reached the commercial stage yet. The different development paths of the different technologies could also alter cost estimates. Furthermore, the costs of fast-reactors are not fully understood because of the lack of large-scale operations in the US (MIT, 2011).

2. *Environmental concerns*

Although difficult to quantify, the potential safety and environment costs and benefits of nuclear reprocessing – and increased reliance on nuclear power in general – are worth noting. Firstly, shifting the United States' power dependence from coal and natural gas to nuclear energy would limit the emission of greenhouse gases. Nuclear power generation does not emit carbon dioxide, sulfur dioxide, or nitrogen oxide ("Nuclear Energy"). Hagen, of the U.S. Department of Energy estimates that a 1,000 MW plant could prevent over 2,000,000 metric tons equivalent of carbon per year. Specifically, if a 1Gw nuclear plant is used to provide

power instead of a coal plant, 2,098,580 metric tons of carbon would be displaced annually, and 1,041,401 metric tons would be displaced per year if a nuclear plant were to replace a natural gas plant (Hagen, 2001). Furthermore, Hagen estimates that in the years from 1960-2000, 3.1 Billion tons of carbon have been offset by 12.7 billion MWh of nuclear power (Hagen, 2001). The potential carbon emissions offset by a continued shift from natural gas and coal are immense.

Although power production in a nuclear reactor is relatively carbon free, the frontend of the fuel cycling, mining and milling the uranium ore does have environmental consequences. According to Sovacool, the total nuclear process (mining, construction, operation, fuel processing, and waste disposal) emits 66 gCO_2e/kWh (Kleiner, 2008). This is still considerably below natural gas and coal emissions, but higher than solar or wind power.

The public also worries about potential adverse health and environmental effects from radiation emitted from nuclear power plants. The typical radiation released from a properly operating plant, however, is minimal. The average yearly radiation dose to employees at uranium mines, who work most closely with radioactive materials, is approximately 2 mSv. The average person not exposed to any extra radiation receives a dose of about 2 mSv/year from background radiation, which is emitted from anything from a cup of coffee to a household smoke detector). Nuclear power plants undergo severe safety controls to ensure that the employees – and area residents – receive negligible doses of non-background radiation. In MOX fabrication the entire process is partitioned from the employees who work via glove boxes to eliminate the possibility of contamination from the plutonium. When employees work at the production line, a 25mm layer of Perspex shields radiation from the plutonium (Jahn, 2012).

Fear of radiation has been stoked, however, by major nuclear accidents in the past, such as Three Mile Island and Fukushima. From Three Mile Island, about two million people received an additional dose of radiation amounting to 1 millirem, or $1/6^{th}$ of a typical chest x-ray (NRC, 2009). The maximum possible dose of radiation is estimated to be 100 millirem. According to the NRC, "most of the radiation was contained and that the actual release had negligible effects on the physical health of individuals or the environment" (NRC, 2009). The more recent Fukushima accident released considerably more radiation, especially to the on-site workers. 167 worker received doses in excess of 100 mSv. On year after the accident, six former reactor workers died; however, the U.N. Scientific Committee on the Effects of Atomic Radiation concluded that none of the deaths were directly caused by radiation (Jahn, 2012). Just as in oil and coal exploration, the occupational hazard of nuclear power generation is significant and must be carefully mitigated, but the risk to the general public is less than commonly perceived.

3. Public policy and public acceptance

Reprocessing nuclear fuel has had little support in U.S. policy in recent decades. President Carter implemented a ban, which was later lifted by Reagan. Reprocessing was pushed under the table until G.W. Bush pushed companies to develop reprocessing technologies in 2001. In 2006 the DOE made an initiative to develop spent fuel recycling using UREX, but any potential progress was halted by President Obama in 2009. The President put a stop to the environmental review that was required for the DOE to continue developing a plan for reprocessing (Andrews, 2008).

In the past, administrations have dismissed nuclear reprocessing on the grounds of proliferation concerns and the economic challenges. Still, the current administration encourages reprocessing outside of the United States. For example, the U.S. is currently supporting reprocessing in India, and has reached an agreement for India to reprocess U.S.-origin spent fuel (Rajghatt, 2010). The administration, however, officially discourages the use of nuclear reprocessing in other countries, such as South Korea.

Nuclear reprocessing has a long way to go politically. Building a nuclear reprocessing plant on U.S. soil appears to be politically challenging in the near-term; however, the government faces considerable pressure to fix its current nuclear program given the potential of nuclear power and problems of finding and building a permanent repository.

9. CONCLUSION

It has been well documented that reprocessing is an expensive technology and less economically feasible than direct disposal in *current* conditions. The key reasons for the high cost of reprocessing are technical hurdles and capital costs, the cost of uranium and the relative cheapness of the disposal of spent nuclear fuel. Capital costs are high for reprocessing plants and efforts are being made to counter this issue. The integration of recycling and reprocessing in one location is a technical strategy being employed and studied to deflect much of the capital costs associated with constructing separate plants for reprocessing. In the case of PUREX, the efficiency of the process must be improved as the levels of Uranium that are saved are only about half of that in Pyroprocessing. With Pyroprocessing, minor actinide recovery rates need to be increased so as to further reduce the longevity of spent nuclear fuel. Furthermore, the salt used in Pyroprocessing is less suitable than the waste materials of PUREX for conversion into glass posing another area where there is room for technical improvement.

The cost of uranium is another reason why reprocessing is so unappealing. It is widely understood that purchasing raw uranium for use in nuclear fuel rods is much cheaper than reprocessing. Additionally, the cost of storage disposal is very cheap in the United States and even without the construction of a geological repository for the storage of spent nuclear fuel, the cost of storing nuclear fuel has remained low for years.

It is important to realize that improvements in reprocessing technologies to yield higher efficiency rates in electricity generation, increases in the price of uranium, a general rise in storage costs, or a combination of these will yield a scenario where reprocessing becomes economically feasible. South Korea currently faces a situation similar to one we envision will be faced by policymakers in the United States in the future. In South Korea, geological repositories are not an option; the country is the size of Virginia and has about six times the population. Storage costs of nuclear waste are more than 2 times higher than storage costs in the US and they are rising due to storage facilities quickly reaching capacity. Additionally, nuclear energy is relatively uncontroversial in South Korea and it is currently the only country with the capability of coupling Pyroprocessing with DUPIC (Direct Use of spent PWR fuel In CANDU) (Yoo, 2012). Given the high costs of spent nuclear fuel disposal and this Pyro-DUPIC advancement, reprocessing is actually the more economically feasible option in South Korea. President Obama has halted all work on the Yucca repository, and without a viable geological repository option the US will likely face a scenario where storage costs rise substantially.

Based on our research and cost-benefit analysis of the various processes and the current landscape of energy and nuclear fuel in the United States it is not currently economically viable to pursue reprocessing. However, PUREX was the most economically feasible of the options we

considered. For now, it would be sensible for the United States to not pursue reprocessing of nuclear fuel until conditions (price of uranium, storage costs, and reprocessing technology improvements) change that would make it economically sensible. Going forth, we should monitor the full-scale implementation of Pyroprocessing in South Korea and Russia and the continuation and further development of PUREX in France to better understand specifically what the advancements and conditions are that would warrant the widespread use of reprocessing technologies to close the nuclear fuel cycle.

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