

NUCLEAR REPROCESSING IN THE US: A LEVELIZED COST ANALYSIS

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ABSTRACT

Although most national policies require the long term storage of spent nuclear fuel, no geologic repository currently exists for this purpose. The United States government assumed the task of finding appropriate storage options for spent nuclear fuel more than twenty years ago. Billions of dollars have been invested into creating the federal repository at Yucca Mountain, yet it currently remains unclear if the facility will ever open. Some nations have begun reprocessing spent fuel inventories as a way to manage waste streams and secure energy supply. Considerable effort has been devoted toward the development of advanced reprocessing technologies that can reduce the volume of radioactive materials needing storage, while also generating electricity. Investment in deployment of such technologies will only be possible if the costs and risks associated with reprocessing can compete with alternative options.

In order to analyze the economics of reprocessing spent nuclear fuel, the Cost of Electricity (COE) of this and other competing technologies was calculated. This evaluation allowed the identification of conditions that make reprocessing technologies competitive under different assumptions regarding uranium price, spent fuel storage cost, and cost of carbon emissions. Based on capital and annual cost estimates from a number of sources, new nuclear plants are economically competitive with new coal plants when carbon emissions assume a cost of \$27 per ton. Reprocessing spent fuel only becomes competitive with direct disposal if uranium prices experience significant increases between \$184 and \$280 per kilogram. If uranium prices remain at current levels, spent fuel storage costs would need to increase from \$400 per kilogram to almost \$1,000 per kilogram for reprocessing one additional time in a thermal reactor to have viability. Storage costs would need to exceed \$2,500 per kilogram for reprocessing in a closed fuel cycle to have economic advantage.

Nuclear energy is one of the few carbon free options capable of generating reliable base load supply; indicating it could have a significant role in meeting future energy demand under policies aimed at reducing greenhouse gas emissions. Significant expansion is unlikely, however, until policies regarding the future of spent nuclear fuel are fully implemented.

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INTRODUCTION

There has been an ongoing debate regarding the appropriate management of spent nuclear fuel in the United States since the commercial deployment of nuclear power plants began in the 60's and 70's. In 1982, the US government promised industry leaders it would take on the responsibility of finding and maintaining long term storage options under the Nuclear Waste Policy Act. Yucca Mountain, located less than 100 miles from Las Vegas, Nevada, was chosen as the site for a federal geologic repository. For more than two decades, Yucca faced continuous delays regarding when it would begin accepting nuclear waste (Andrews 2008). The Department of Energy (DOE) announced earlier this year the Yucca Mountain program would be “scaled back considerably, while the current administration devises a new strategy toward nuclear waste disposal” (WNN 2009).¹

No repository currently exists anywhere in the world for the long term disposal of commercial spent nuclear fuel and most nuclear nations have not yet determined what to do with spent fuel past interim storage (MacFarlane 2006).² Commercial nuclear waste is currently contained among 83 storage facilities located across the country (Andrews 2004). The estimated inventory of spent fuel is approximately 60,000 tons heavy metal (tHM) and the current US nuclear fleet produces an additional 2,000 tHM annually³ (EIA 2008; Andrews 2004). Since

¹ Funding for the Yucca Mountain Program was cut from the federal budget in early 2009. Both the House and Senate approved the official closure of the facility in July 2009, which is awaiting the President's approval. The Yucca Mountain Project began more than two decades ago and has cost more than \$13.5 billion dollars (CBS 2009).

² The DOE has had success in storing spent nuclear waste at its own facility located in Carlsbad, New Mexico. The Waste Isolation Pilot Plant (WIPP) opened in 1999 and is the disposal location for transuranic waste elements from ex-military programs (DOE 2009). WIPP is located 26,000 feet below surface and contained within a Permian salt mine.

³ Nuclear fuel is classified in terms of heavy metal equivalents due to conversion and enrichment processes. The term tHM is used to describe tons of heavy metal.

many of the commercial on-site facilities were built for intermediary storage, many utilities have or will soon run out of space causing the need for additional storage units.

Considerable monies have been invested towards the research, development and deployment of technologies that recycle spent nuclear fuel in order to reduce the volume of radioactive materials needing storage while also generating electricity (DOE 2007; DOE 2002). Investment in implementing such technologies will only be forthcoming if the costs and risks associated with reprocessing can compete with alternative options, which is the subject for this analysis.

OBJECTIVES

This report compares the cost of electricity associated with fuel reprocessing and the status quo of direct disposal, as well as costs associated with new coal plants of similar size. The purpose is to evaluate the cost of direct disposal, uranium and/or carbon required for reprocessing to be considered economically sufficient. Additionally, the maximum installed capacity that can be derived from spent fuel inventory is also estimated in the consideration of cost-benefit.

BACKGROUND

Fission & Enrichment

The central basis for nuclear power is neutron-induced fission, which is the process by which heavy nuclei are split into lighter nuclei. While many heavy nuclei are fissile, most require bombardment by fast neutrons to deliver significant amounts of energy. Isotopes of uranium and plutonium, however, are among a smaller group of heavy nuclei elements that can undergo fission with slower moving neutrons. The amount of energy released during fission is described by the binding energy, or the amount of energy released/required to form/split a nucleus. Binding energy is calculated by using Albert Einstein's famous equation: $E = mc^2$; where c is equal to the speed of light and m is equal to the difference in mass between protons plus neutrons minus the nucleus itself (Kraushaar & Ristinen 1993; Deutch et al. 2003; DeCarolis 2009).

When fission occurs in a controlled environment, like that of a nuclear reactor, a chain reaction can occur (DeCarolis 2009). Uranium (U) is a metal consisting of 92 protons and approximately 140 neutrons. Uranium exists naturally in the form of two isotopes: U^{235} and U^{238} . U^{235} is considered highly fissile in its natural state, while U^{238} cannot undergo fission in modern reactors on its own. U^{238} can, however, acquire a neutron through the enrichment process and transform into plutonium (Pu^{239}). Fission of Pu^{239} produced within the reactor accounts for about 33% of the overall energy generated (Hore-Lacy 2006; GAO 2008).

Mined uranium ore contains 0.7% of U^{235} . Conventional light water reactors (LWR) use enriched uranium containing approximately 4.5% of U^{235} . Based on mass balance of the enrichment process, approximately 10.5 times the amount of natural uranium is required to

produce one unit of initial heavy metal, a term used to describe nuclear fuel, used within a reactor (DeCarolis 2009).

Reactor Basics

Twenty percent of US electricity is generated from nuclear sources (EIA 2009). There are 104 operating nuclear generation plants consisting of mainly pressurized water reactors and boiling water reactors. These plants are located in thirty-one states and provide 100 million kilowatt-hours of electricity (Orzag 2007; DOE 2008).

Although several reactor technologies exist, the overall process remains principally the same. Enriched uranium undergoes fission and releases enough heat to boil water and generate steam. The steam is used to spin a turbine leading to the generation of electricity (Hore-Lacy 2006). Control rods are placed within the fuel rods allowing operators control over the rate of the nuclear reaction. Fuel rods typically remain in the reactor between three-five years, but a portion of fuel assemblies are usually replaced each year. When the fuel is removed from the reactor, it is placed directly under water in a cooling pond in order to remove heat and provide a barrier against radiation (NRC 2008). The last step in what is classified as an “open” fuel cycle involves storing the spent fuel and other nuclear wastes in a geologic repository (Hore-Lacy 2006).

Reprocessing

When nuclear fission was first discovered uranium was believed to be a scarce commodity (Bunn et al. 2003). Since up to 95% of spent fuel is uranium, reprocessing was predominantly introduced as a way to recover the unused uranium and plutonium resources (Hore-Lacy 2006). The remaining spent fuel contains 2% transuranic elements (including

plutonium) and 3% fissionable products⁴ (GAO 2008; DOE 2007; Deutch et al. 2003). As it turned out, uranium is actually a rather abundant metal and occurs naturally in most rocks and in seawater. Most deposits, however, are widely dispersed and occur at low concentration levels (Kee 2007).

The only form of commercial reprocessing is the Plutonium-Uranium Redox Extraction (PUREX). In this method, plutonium and uranium are refabricated into mixed oxide fuel (MOX) (Hore-Lacy 2006). Since MOX is recycled in conventional thermal reactors, the fuel must contain a certain level of pure plutonium requiring its complete separation from other transuranic elements (Hannum et al. 1996). MOX fuel can only be recycled through a reactor one additional time and still requires certain levels of waste storage. Due to extremely low prices of natural uranium, reprocessing remains economically disadvantageous. Reprocessing is, however, popular in certain countries as part of their national energy security policies (Choi 1998).

The US attempted reprocessing nuclear fuel in the 1960's and three plants were built for commercial use. Only one facility in New York was successful in reprocessing spent fuel from defense weapons operations (Andrews 2008). The plant was shut down ten years later due to costly upgrades required by strict safety regulations. In 1976, President Ford suggested reprocessing nuclear fuel for commercial purposes should be suspended until the threat of proliferation had ended, but provided hope that reprocessing could be reestablished if it was consistent with international objectives (Andrews 2008).

⁴ The exact composition of spent fuel is dependent on the fission process undergone within the reactor core so each spent fuel assembly will contain slightly different proportions (Hore-Lacy 2006). Transuranic elements refer to elements with atomic numbers higher than uranium (92) and are highly radioactive. Those found in spent nuclear fuel include neptunium, plutonium, americium, and curium. Fission products are nuclei fragments formed during the breaking of a nucleus. For the fission of uranium in a reactor, the major fission products include iodine and technetium. Small traces of fission products can be irradiated in a fast reactor core. Fission products require long term storage in stable form and are vitrified into glass for this purpose (DOE 2007).

In recent years, multinational collaboration in research and development has provided foundation for modernizing nuclear technology and has led to the promotion of six advanced reactor designs that “present significant improvements in economics, safety and reliability, and sustainability over currently operating reactor technologies” (GFIF 2009). Included in these technologies is the evolution of a closed nuclear fuel system.

The closed fuel system provides advantages over the open and once through fuel cycles as it “emphasizes the management of actinides and conversion of fertile uranium for proliferation resistance” (DOE 2002). Two key factors differentiate a closed fuel system from current reprocessing:

- 1) Advanced reprocessing and fabrication methods that recover 99.99% of transuranic elements.
- 2) Full transmutation of transuranic elements directly in the reactor core.

Two separation techniques have been recommended in order to eliminate plutonium separation and increase proliferation resistance. The first is a pyroprocessing used to create mixed oxide containing transuranic elements in addition to plutonium. The second involves advanced aqueous methods, referred to as the UREX + collection, in the creation of mixed alloy fuel (DOE 2002; Fink & Edelstein et al. 2005; GAO 2008; NRC 2006; Takata et al. 2004). A closed fuel cycle also includes the use of fast reactors (FR). Unlike thermal reactors, FRs can burn both long living actinides and plutonium directly in its reactor core (Hannum et al. 1996; DOE 2002; Hoffman & Stacy 2002).

FRs are not considered a new technology and there is more than 300 reactor years of experience in handling the technology (Hore-lacy 2003). FRs were originally designed to breed

additional plutonium within the reactor, extending the chain reaction and producing higher yields in electricity generation. New designs have flexible conversion ratios allowing the ability to burn or destroy plutonium (and other transuranic elements) directly within the reactor core; essentially removing the volume of radioactive waste requiring long-term storage (Hannum et al. 1996; DOE 2002). The elimination of transuranic levels to trace amounts would increase total capacity of a future geologic repository because most of the thermal load caused during the radioactive decay of spent fuel is produced by plutonium and other transuranic elements (DOE 2007; DOE 2002; Hoffman & Stacy 2002). The DOE estimates an optimistic deployment date for advanced FR technology by 2015, but it is likely commercial deployment of such reactor designs will not be viable on commercial scale until after 2020.⁵

⁵ Further description of advanced fuel cycle technologies are explained in the DOE's *A Technology Roadmap for Generation IV Reactors* (2002).

MATERIALS AND METHODS

Investment of generation options has transformed since the deregulation of electricity markets and technologies with the least intense capital investment option are usually more favored by investors (IEA 2005; Roques et al. 2006; Deutch et al. 2003). In order to analyze the economics of reprocessing spent nuclear fuel, the Cost of Electricity (COE) of this and other competing technologies was calculated under different assumptions pertaining to the price of uranium, cost of spent fuel storage, and cost of carbon emissions. This evaluation allowed the identification of the conditions required for a new reprocessing plant to become a feasible option.

Projected costs of each technology were established by aggregating estimates found in the studies listed in Table 1. As most of these reports were published before steel prices skyrocketed in 2005, all estimates were converted to 2009 dollars using the US Consumer Price Index established by the US Department of Labor and the CRUspi North American index for steel prices (Schlissel & Biewald 2008).⁶ Calculations were based on a new 1,000 MW plant operating at 85% capacity. The discount rate was assumed at 12% in order to have more conservative results and is consistent with discount rates used in similar evaluations (Roques et al. 2006; Deutch et al. 2003; Tolley 2004). Other assumptions related to design are provided in Table 2.

⁶ Information regarding the CRUspi can be found at <http://cruonline.crugroup.com/SteelandFerroalloys/CRUSteelPrices/CRUspi/tabid/143/Default.aspx>

Table 1. Sources used in establishing cost estimates for nuclear and coal technologies.

Organization	MIT	U of Chicago	CBO	NEA & IEA*	Harvard	MIT	Harvard
Year Published	2003	2004	2008	2005	2003	2007	2009
New Nuclear (Advanced LWR)	x	x	x	x			
Nuclear with Reprocessing (MOX)	x	x			x		
Reprocessing with Fast Reactor					x		
Conventional Coal		x	x	x		x	x
Coal with CCS (90% capture)			x			x	x
<p>All estimates have been converted to 2009\$ using the US Consumer Price Index (CPI) established by the US Department of Labor and recalculated using the CRUspi North American index for steel prices.</p> <p>* Harvard estimates are for new IGCC Plant and IGCC with CCS; other estimates represent pulverized coal and combine cycle coal plants. NEA/IEA was for one CCS plant under construction in Germany</p>							

Table 2. Assumed Parameters for Generation Technologies

Parameter	Units	LWR / MOX	Fast Recycle	Coal	CCS (90% capture)
Installed Capacity	MW	1,000	1,000	1,000	1,000
Capacity Factor	%	85%	85%	85%	85%
Thermal Efficiency	%	33%	40%	38%	32%
Discount Rate	%	12%	12%	12%	12%
Plant Life	years	40	40	40	40
Operating time	hours	8760	8760	8760	8760
Burnup	GWd/tHM	50	150-200	---	---
Carbon Intensity (bituminous coal)	(kg C/mmBTU)	---	---	25.8	25.8
Heat Intensity	(BTU/kWh)	10,400	N/A	9,300	10,953

Carbon Price

Lifecycle carbon emissions from nuclear power plants are comparable to those of renewable sources, like wind and solar, and remain one of the few carbon free energy sources capable of competing on scale with coal power sources. As a base-load generating alternative, nuclear technologies were compared to the cost of conventional coal and advanced coal with carbon capture capabilities (Deutch et al. 2003; Bunn et al. 2003; Sailor et al. 2000; Weisser 2007; CBO 2008).

Fuel Reprocessing

Uranium Price

As reprocessed fuel recovers unused uranium, if the value of the uranium resource were to increase, reprocessing would look more attractive. Uranium typically trades between \$30 and \$50 per kg. Uranium price spikes have occurred in the 1950's and 1970's (Appendix A) when the nuclear generation fleets were first under deployment (Kee 2007). In 2007, the uranium spot price jumped dramatically to an all time high of about \$300 per kg because of an unexpected shortage in production⁷ (WNA 2008).

Half of the fuel supply for use in nuclear reactors is provided from ex-military sources as established through a disarmament agreement between the US and Russia. It has been suggested these sources are released in a way that does interfere with free market pricing, but speculation exists as to whether these sources allow for such low uranium prices due the industry's dependence on secondary fuel sources (Kee 2007; Price 2002).

⁷ 1 kilogram = 2.205 pounds

MOX

As only a few firms have reprocessing capabilities, the costs and contract prices associated with the technology on commercial scale is kept classified. Economic analysis published by Harvard University and the Massachusetts Institute of Technology indicate MOX recycling faces additional costs of \$1,000 per kg HM for reprocessing and \$1,500 per kg HM for fuel fabrication (Deutch et al. 2003; Bunn et al. 2003).

Fast Reactor

The actual projected cost of a FR is not well known. Harvard's study estimates an additional \$200-\$400 more per kilowatt (kW) in initial capital investment over an advanced thermal reactor design of the same capacity. For the purpose of this analysis, an additional charge of \$500 per kW was added to overnight construction costs of a new thermal reactor of the same size as an estimated value for a FR. For simplification, yearly operating and maintenance fees were assumed the same as new thermal reactor for both reprocessing facilities (Bunn et al. 2003).

Considerable investment has been focused towards reducing the cost of fuel reprocessing techniques for use in a FR. However, a FR has an advantage in that they have a burnup 3-4 times higher than its thermal reactor counterpart (DOE 2002). At the same costs assumed for the MOX process, the overall fuel cost for the FR on a \$/MWh scale is on par with fuel costs in a LWR because the FR can generate more electricity from the same amount of fuel.

Fuel Storage

The nuclear industry is charged a fee of \$1.00 per megawatt-hour (MWh), or \$400 per kg HM, for future disposal of nuclear waste in a geologic repository (Deutch et al. 2003). This value was assumed as the cost of directly disposing of nuclear waste, although recent studies suggest

utilities reserve up to \$1000 per kg HM for direct storage. The small fee, as established under the Nuclear Waste Act of 1982, keeps the immediate process of direct disposal more economical than recycling fuel, albeit the process remains incomplete (Orzag 2007; Bunn et al. 2003).

Scenario Analysis: Levelized Cost

A levelized cost analysis is often used to compare competing investment options of electricity generation technologies. In this method, costs are analyzed by discounting cash flows over the life of a plant in order to gauge the cost of producing electricity (LCOE). Levelized cost comparisons are appealing as they allow for a simple cost evaluation without performing an extensive financial model and continue to be a popular method used by utilities (DeCarolis 2009; Roques et al. 2006). The formula used in this report is listed in Equation [A].

[A]

$$\text{LCOE} = \frac{C_o \left[\frac{r}{1-(1+r)^{-t}} \right]}{Q} + \text{Fuel} + \text{O\&M} ; \text{ where}$$

C_o : the capital investment in dollars,

r : the interest rate

t : the life of the plant in years,

Q : annual output,

Fuel: the annual costs of the fuel cycle, and

O&M: represents other yearly operating and maintenance costs.

Once a baseline LCOE was established, a straightforward model was created using Excel in order to evaluate breakeven values of direct storage costs, natural uranium prices, and future costs of carbon emissions required in order for reprocessing to become more economically viable. Each scenario evaluated one parameter option while the other two parameters remained at their assumed base levels. For example, in evaluating carbon the LCOE was calculated as if the price of carbon is zero and then calculated at the cost of complying with carbon emission regulations by assuming a "carbon cost" in \$/MWh as shown in Table 3. A similar format was used to establish uranium price and storage cost, but as both of these parameters are considered part of fuel costs, their values were analyzed within the scope of the nuclear fuel cycle (Table 4). Assumed values for fuel cycle costs were based on estimates found from studies listed in Table 1 and are provided in Appendix B.

Table 3. Model Structure for Comparing Carbon price

Technology Option	COE	Cost of Carbon	TCOE
Nuclear LWR	\$ per MWh	\$ per MWh as a function of carbon intensity and price per quantity	COE + Carbon cost
Nuclear with MOX reprocessing			
Closed fuel cycle with Fast Reactor			
Conventional Coal			
Coal with Carbon Capture and Sequestration			

Table 4. Model Structure for Evaluating Cost of Storage and Uranium Price

Technology Option	COE	Cost of :	COE + Storage Costs or COE + Uranium Price
Nuclear LWR		Waste Storage	
Once Recycle with MOX		Uranium	
Closed Cycle with Fast Reactor			

Fuel Cycle Comparison

A mass balance analysis of the fuel cycles allows for estimation in the reduction of waste volume and corresponding waste costs associated with a closed-fuel system. MOX fuel cycles are not evaluated as its impact on any future repository is only a fraction of the estimated impact associated with the closed fuel cycle. Based on theory of mass balance, the potential capacity was calculated using basic principles of mass flow and simple engineering concepts based on reactor design. Methodology was derived from the Massachusetts Institute of Technology's *The Future Role of Nuclear Power* and by using fuel and reactor characteristics described in Hannum et al.'s *The Benefits of an Advanced Fast Reactor Fuel Cycle for Plutonium Management* (Deutch et al. 2003). The amount of energy a nuclear reactor can produce per ton of heavy metal corresponds to the reactor's burnup. The annual discharge of spent fuel can be applied in Equation B in order to estimate projected installed capacity for FRs in the closed cycle. Parameters assumed for reactor design are provided in Table 2.

[B]

$$\text{Mass of spent fuel} = \frac{\text{Annual thermal output}}{\text{Reactor burnup}}$$

Current inventory of spent fuel is approximately 60,000 tHM and the current US nuclear fleet produces an additional 2,200 tHM annually (EIA 2008; Andrews 2004). Fresh fuel for use in a fast reactor contains a ratio between transuranic elements and uranium of roughly 33% (Hannum et al. 1996). Assuming 2% of spent fuel is plutonium and minor actinides, this indicates approximately 1,200 tons of transuranic elements available for recycle found in interim storage with an additional input of 42 tons annually (DOE 2007; GAO 2008). These estimates infer the potential recycle of 4,800 tons HM from interim storage is available in addition to 160 tHM annually. These estimates refer to fuel reprocessed for use in a fast reactor only. Additional uranium could be extracted and re-incorporated into thermal reactors through the enrichment process but is not thoroughly analyzed in the scope of this analysis.

RESULTS

Levelized Cost

In this section we identify the conditions that could allow reprocessing plants a competitive edge. The LCOE for business-as-usual costs are provided in Table 5 and derived from reactor design assumptions listed in Table 2. As expected, new coal is the most attractive option followed by new nuclear and both reprocessing options. Values of uranium, storage and carbon emission regulations used in the base evaluation include:

- Uranium Price: \$48 per kilogram
- Storage Cost: \$400 per kilogram
- Carbon Price: \$0 per ton.

Table 5. Base case estimates in \$2009

	Units	Nuclear	Nuclear + MOX recycle	Nuclear + FR recycle	Conventional Coal	Coal + CCS
Overnight Capital Investment	\$/kW	3,260	3,328	3,828	2,281	3,625
O&M	\$/MWh	9.02	9.02	9.02	7.11	10.51
Fuel Costs	\$/MWh	5.12	6.26	4.00	14.86	18.45
LCOE	\$/MWh	60.28	64.10	69.18	55.43	82.14

Carbon Price

The first calculation estimated the carbon price that would be required for any nuclear technology to be competitive with coal, assuming the base case scenario levels for the other relevant parameters regarding uranium and storage costs (Table 6). Each value listed is the lowest cost per ton of carbon emissions that would provide enough additional costs associated in coal generation in order for each nuclear option to breakeven with the COE of coal. For a carbon tax of \$27.25, a new nuclear plant will be competitive with a coal plant of the same size. A fast reactor does not become competitive against coal until carbon reaches almost \$60 per ton.

These values are consistent with estimates found in literature that estimate a range of carbon prices between \$10 and \$100 per ton carbon needed to incentivize nuclear growth (CBO 2008; Birol 2006; Deutch et al. 2003; Sailor et al. 2000). Additionally, the EU Trading Scheme experienced an average trading price per ton carbon of \$23 in 2005 and \$33 in 2006, indicating a similar price associated with carbon emissions is likely expected if an analogous system was implemented in the US.

Table 6. Cost of carbon emissions required for each technology to “breakeven” with coal generation in \$/ ton Carbon and \$/MWh.

Minimum Cost of Carbon Required	\$ / ton Carbon	\$ / MWh
Nuclear	27.25	6.53
Nuclear + MOX recycle	36.14	8.67
Nuclear + FR recycle	57.31	13.75
Coal + CCS	195.93	47.01

Uranium Price

The price of uranium is currently \$48 per kg which comprises approximately \$1.27 per MWh of annual fuel costs. Before either reprocessing technology is competitive with directly disposing of nuclear waste, uranium prices would need to reach \$124 per kg and near \$280 per kg for MOX and a FR, respectively (Table 7). As uranium prices have experienced some volatility over the past fifty years (Appendix A), it could be likely prices may increase to levels for both reprocessing cycles to have a competitive advantage. The likelihood prices would remain at such high levels is questionable since the trend indicates prices drop just as quickly as they increased.

Table 7. Natural Uranium price required for each reprocessing technology to become competitive with direct disposal in \$ per kg. The equated value is also provided in \$/MWh.

Minimum Price of Uranium Required	\$ / kg Uranium	Equated Value in \$/MWh
Nuclear + MOX recycle	124	3.29
Nuclear + FR Recycle	280	7.42

Storage Costs

The cost of storing spent nuclear fuel, as realized by an investor, would need to increase substantially for reprocessing to have an economic advantage over direct storage in the open fuel cycle (Table 8). Utilities do not bear the full cost of long-term storage since the government accepted the responsibility of finding suitable storage options. As no repository has begun accepting spent nuclear fuel from commercial sources, the actual costs associated with direct disposal are “most uncertain” (Bunn et al. 2003). Additionally, “on-site cooling ponds were created to support reactor use and not as an option for storing considerable quantities of spent fuel over significant periods of time” (Rojas de Diego 1990).

Table 8. Minimum cost of direct disposal of spent fuel required for each reprocessing technology to become competitive with direct disposal in \$ per kg.

Minimum Cost of Direct Disposal	\$ / kg Uranium	Equated Value in \$/MWh
Nuclear + MOX recycle	969	2.44
Nuclear + FR Recycle	2,562	6.31

Fuel Cycle Comparison

For this section of analysis, the FR was assumed to have 1,000MW installed capacity, operate at 85% capacity, with a thermal efficiency of 40%, and a burnup of 175 GWd/ tHM.⁸ The annual flow of recyclable spent fuel, estimated at 160 tons fresh HM, alone could power a fleet of FRs with 34 gigawatts installed capacity. A schematic of the closed fuel cycle is provided in Figure 1. Additionally, FR installed capacity would exceed 100 gigawatts if the inventory of spent fuel is incorporated annually over the course of fifteen years. This would

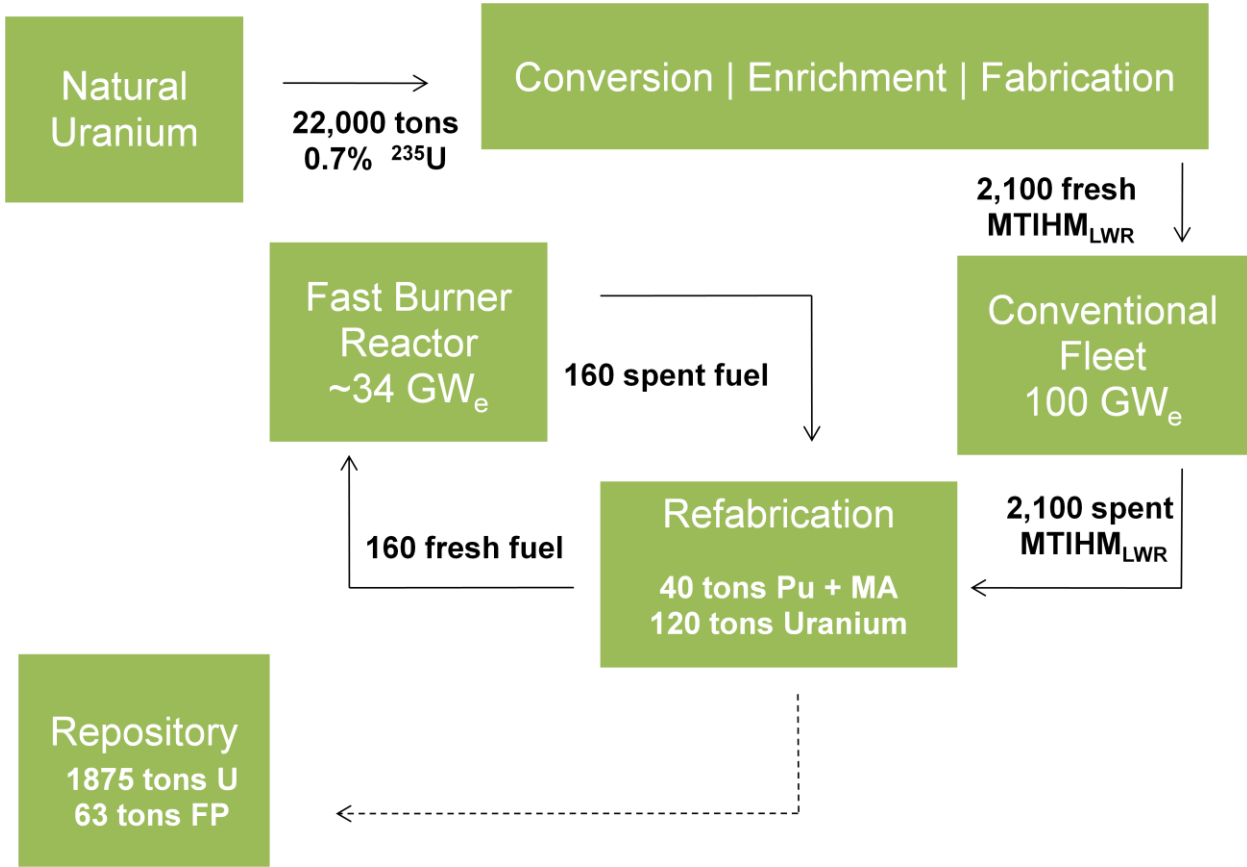
⁸ Consistent with design parameters of a Sodium-Cooled Fast Reactor.

essentially double the current level nuclear capacity in the US for that time period. The time period of 15 years was chosen arbitrarily as a way of incorporating the fuel source into a balanced annual cycle. If this time period shortened, more installed capacity would be possible for that period alone.

These calculations are based on major assumptions regarding the composition of both spent fuel from thermal reactors and fresh fuel for use in a FR. If fuel for the FR has a component ratio other than 33%, this would also have considerable effects on installed capacity. Fuel assemblies and fuel assembly composition was not analyzed in this report nor was the affect of associated cooling time. It still remains a useful tool when analyzing the future growth of nuclear energy and management of spent nuclear as the feasibility of fuel reprocessing is dependent on spent fuel from thermal reactors.

Expansion of thermal reactors is likely to precede implementation of advanced technologies associated with reprocessing capabilities indicative of a closed fuel cycle. As a nuclear reactor has not been commissioned in the US in more than thirty years, there is doubt in the speed nuclear deployment could gain significantly larger levels of market share in the near future. The Energy Information Administration projects financing incentives established by the Energy Policy Act of 2005 will create enough incentive for the first handful of thermal reactors approved of construction and similar incentives could improve the economics of reprocessing when commercial deployment of such technologies becomes available (EIA 2009).

Figure 1. Schematic of closed fuel cycle based on mass balance potential of current annual spent fuel flows.

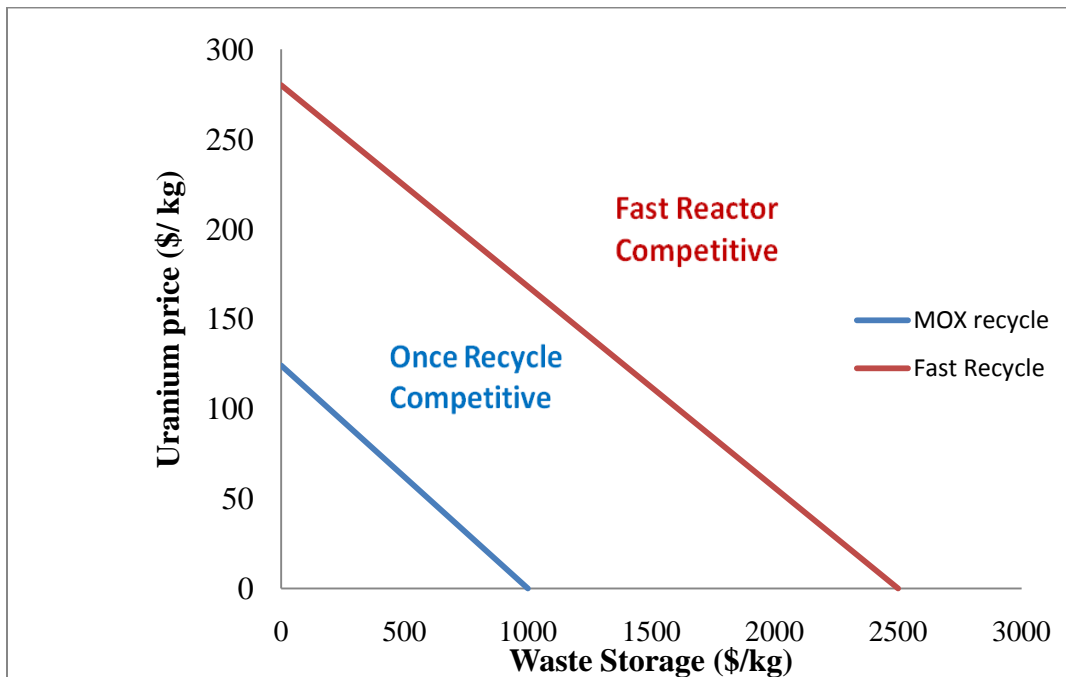


CONCLUSION

For half a century, nuclear energy has played an integral role in providing consistent base energy without emitting any greenhouse gas emissions (Weisser 2008). However, nuclear growth will remain controversial until the fate of spent fuel has been decided and implemented (Pauluis 2001). The proper management of spent nuclear fuel continues to be debated not only in the US, but worldwide. Fuel reprocessing is an alternative that could significantly reduce nuclear waste and cost associated with its long term storage. Due to its high capital costs compared to conventional nuclear it is unlikely it will become competitive unless significant increases in storage cost and/or uranium prices become a reality.

A base case LCOE calculation, with average capital and O&M estimates from recent literature, shows that a price of \$27 per ton carbon would create enough economic incentive for new nuclear reactors in comparison to coal. Once nuclear reactors are competitive, increases in storage costs and uranium prices would be needed to create incentives for closed-cycle technologies.

Figure 2. Reprocessing Competitiveness by Uranium and Disposal Costs.



Based on the mass flow of spent fuel, the current inventory of spent fuel could generate more than a third of nuclear energy's current installed capacity by incorporation in a fast reactor. The future deployment of reprocessing and a closed fuel cycle will only be feasible if the price of uranium increases as it did in 2007 and/or the full costs of directly disposing nuclear waste are considered. Figure 2 shows the combination of uranium prices and waste storage costs that are necessary to make MOX Recycle and Fast Recycle competitive. Ultimately, the decision of how to appropriately handle spent nuclear fuel in the future will take account of essential factors concerning proliferation resistance and safety, which may weigh more significantly than simple economic cost-benefits. The safe and proper management of spent fuel should remain a top priority no matter the cost.

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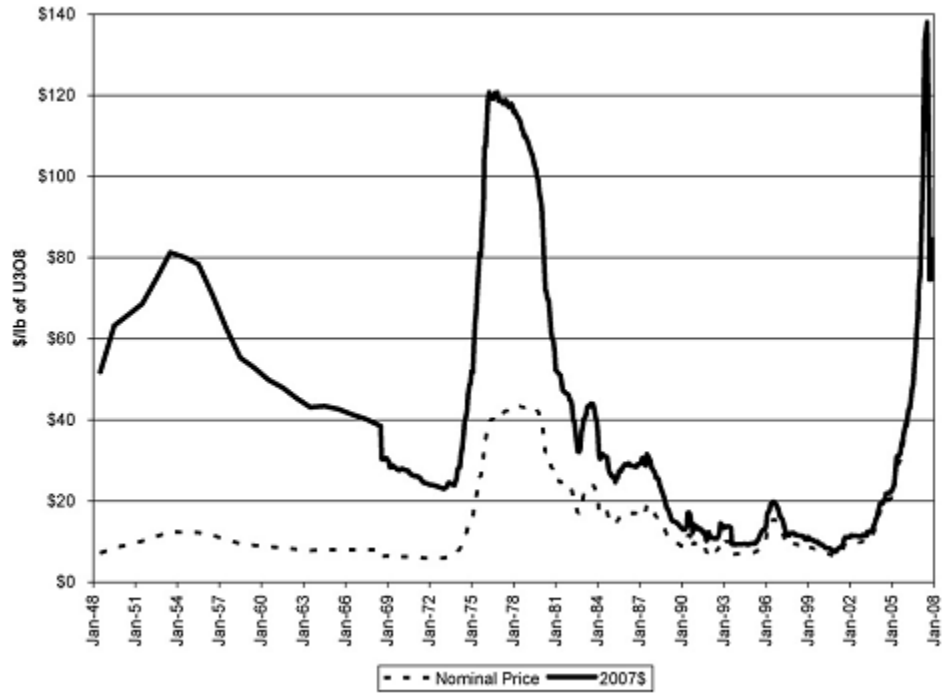
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APPENDIX A: Uranium Spot Prices

Figure A1. Uranium Spot Prices between 1948 and 2007 (Source: Kee 2007)



APPENDIX B: Nuclear Cost Estimates and Model Structure

Table B1. Nuclear Cost Estimates for Advanced Thermal Reactor in 2009 Dollars. Costs were reevaluated accounting for inflation by using the Consumer Price Index and steel prices using the CRUs_{pi} steel index.

Organization Source	Year of Study	Overnight Investment \$2009	O & M \$2009/MWh	Fuel Cost Estimates in \$2009/MWh
MIT	2003	4,673	9.58	1.41
U of Chicago	2004	2,773	8.02	5.09
CBO	2008	2,652	8.56	8.56
NEA/IEA	2005	2,941	9.91	5.45
Average		3,260	9.01	5.12

Table B2. Open fuel cycle costs and model structure

Nuclear Fuel Cycle Components	Mass of Input (kg)	Cost (\$)	Direct Cost (\$/kg)	Total Fuel Cycle \$5.12 / MWh
Natural Uranium	10.5	48		
Enrichment	6	150		
Fabrication	1	250		
Interim storage	1	400		

Table B3. MOX fuel cycle costs and model structure

MOX Fuel Cycle Components	Mass of Input (kg)	Cost (\$)	Direct Cost (\$/kg)	Total Fuel Cycle \$6.86 / MWh
Natural Uranium	3	-48		
Reprocessing	3	1000		
Fabrication	1	1500		
Interim storage	1	-400		

Table B4. Fast Reactor with reprocessing fuel costs and model structure.

MOX Fuel Cycle Components	Mass of Input (kg)	Cost (\$)	Direct Cost (\$/kg)	Total Fuel Cycle \$4.06 / MWh
Natural Uranium	5	-48		
Reprocessing	5	1000		
Fabrication	1	1500		
Interim storage	1	-400		