**The Thesis Committee for Darshan Jitendra Sachde**
**Certifies that this is the approved version of the following thesis:**

# Uranium Extraction from Seawater: An Assessment of Cost, Uncertainty and Policy Implications

**APPROVED BY**
**SUPERVISING COMMITTEE:**

**Supervisor:**
Howard Liljestrand

**Co-Supervisor:**
Erich Schneider

Varun Rai

# Uranium Extraction from Seawater: An Assessment of Cost, Uncertainty and Policy Implications

**by**

**Darshan Jitendra Sachde, B.S. Ch.E.**

**Thesis**

Presented to the Faculty of the Graduate School of
The University of Texas at Austin
in Partial Fulfillment
of the Requirements
for the Degrees of

**Master of Science in Engineering**
**and**
**Master of Public Affairs**

**The University of Texas at Austin**
**August 2011**

# Dedication

To my parents for all of the sacrifices they made to give me my opportunities, to Sara for the constant support despite my neglect of everything outside of school, and to all of my friends and family that give me support with everything I pursue.

# Acknowledgements

I would like to thank Dr. Erich Schneider for the opportunity to work on a fulfilling and challenging research project. Dr Schneider exemplifies leadership in bridging disciplines to address challenging technical issues and was an ideal mentor for my cross-disciplinary graduate education. I would also like to thank him for the countless hours he spent providing guidance, support and knowledge, and his general dedication to his students. This thesis would not be possible without Dr. Schneider's commitment and vision. I would also like to acknowledge Dr. Varun Rai for his help on this thesis and other research efforts during my time as a graduate student. He has always been enthusiastic, supportive, and open for discussion on a myriad of research topics. It was my pleasure to have an opportunity to work with Dr. Rai. I would like to thank Dr. Howard Liljestrand for his guidance throughout my graduate education. Dr. Liljestrand was always available for discussion on everything from planning my degree path to my work after graduation. His patience and support allowed me to take full advantage of the wide-ranging opportunities available to me in interdisciplinary research.

# Abstract

## Uranium Extraction from Seawater: An Assessment of Cost, Uncertainty and Policy Implications

Darshan Jitendra Sachde, MPAff; MSE
The University of Texas at Austin, 2011

Supervisors: Howard Liljestrand and Erich Schneider

Technology to recover uranium from seawater may act as a potential backstop on the production cost of uranium in a growing international nuclear industry. Convincing proof of the existence of an effective expected upper limit on the resource price would have a strong effect on decisions relating to deployment of uranium resource consuming reactor technologies. This evaluation proceeds from a review of backstop technologies to detailed analyses of the production cost of uranium extraction via an amidoxime braid adsorbent system developed by the Japan Atomic Energy Agency (JAEA). An independent cost assessment of the braid adsorbent system is developed to reflect a project implemented in the United States. The cost assessment is evaluated as a life cycle discounted cash flow model to account for the time value of money and time-dependent performance parameters. In addition, the cost assessment includes uncertainty propagation to provide a probabilistic range of uranium production costs for the braid adsorbent system. Results reveal that uncertainty in adsorbent performance (specifically, adsorption capacity, kg U/tonne adsorbent) is the dominant contributor to overall uncertainty in uranium production costs. Further sensitivity analyses reveal adsorbent capacity, degradation and production costs as key system cost drivers. Optimization of adsorbent performance via alternate production or elution pathways provides an opportunity to significantly reduce uranium production costs. Finally, quantification of uncertainty in production costs is a primary policy objective of the analysis. Continuing investment in this technology as a viable backstop requires the ability to assess cost and benefits while incorporating risk.

# Table of Contents

# List of Tables

# List of Figures

# Chapter 1: Introduction

The growth of emerging economies such as China and India as well as concerns regarding long-term energy supply in the context of climate change has led to renewed interest in the expansion of nuclear power. As of 2008, nuclear power made up 13.5% of total international electricity generation (International Energy Agency 2010). The Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD) noted growth in the sector; as of January 1, 2009, 438 commercial reactors were operational internationally with an additional 46 reactors under construction (12 in China and 6 in India). Furthermore, IAEA projections indicated 37% expansion in nuclear capacity by 2035 in its "low" growth scenario and 110% expansion in its "high" growth scenario (Nuclear Energy Agency 2010).

The potential for climate change policies and legislation are an important part of the expansion of nuclear power. For example, many greenhouse gas mitigation scenarios include portfolios of energy technologies oriented toward reducing emissions. Among these portfolio concepts, "stabilization wedges" developed by Pacala and Socolow in 2004 suggested a doubling of nuclear power generation capacity by 2054 as part of a strategy to limit atmospheric concentrations of $CO_2$ to below double pre-industrial concentrations (Pacala and Socolow 2004).

The growth of nuclear power in the United States is less certain, however; the NEA projections range from a 36% decline in generating capacity to a 39% increase relative to the 2009 installed capacity (Nuclear Energy Agency 2010). However, extension of current operating licenses is underway in the United States; as of July 2009, the Nuclear Regulatory Commission (NRC) had granted 20 year extensions (beyond the initial 40 year operating license) to 50 of 104 operating reactors in the United States. In addition, the United States Department of Energy (DOE) and the NRC, alongside industry participants, have started to investigate operation and licensing of plants beyond 60 years. (U.S. EIA 2010). When the U.S. extensions are considered alongside the international growth in generating capacity, the United States has a vested interest in the connection between long-term uranium resource availability and the viability of the nuclear power industry.

An important part of any nuclear expansion scenario includes long-term nuclear fuel resource availability. Fuel resource strategies include expansion of conventionally mined uranium resources, improved fuel utilization via new reactor technologies, and development and expansion of alternate sources for nuclear fuel. Long-term public research and development (R&D) is focused on the latter two strategies.

International reactor technology development has included a focus on uranium resource utilization efficiency. For example, the International Atomic Energy Agency (IAEA) states fast neutron reactors "may be economical and advantageous for countries which lack abundant uranium resources (International Atomic Energy Agency n.d.)." India's Nuclear Power Program (NPP) includes fast reactors to utilize plutonium followed by advanced reactor designs explicitly developed to utilize abundant domestic thorium reserves ( Department of Atomic Energy, Government of India 2005).

Alternatively, unconventional resources such as uranium from phosphates and uranium extraction from seawater can augment or replace conventional fuel supplies. The United States DOE has specifically cited uranium from seawater as an appropriate research area for federal funding (U.S. Dpeartment of Energy, Nuclear Energy 2010). Alternative sources may provide countries with access to important domestic reserves of uranium, addressing concerns such as energy security and independence. More fundamentally, mineral resources from seawater have long been regarded as a backstop technology that could provide a nearly infinite supply if the market price of minerals were to rise to a level to make seawater extraction feasible. The existence of a viable backstop technology eliminates the need for reactor technology to address fuel resource concerns.

Organizations such as the U.S. DOE face funding and resource allocation decisions between the multiple paths to nuclear fuel resource development. These decisions require an understanding of the costs of the various technology pathways. The current work attempts to address these data needs by developing an independent component-based cost estimate of the state of the art technology for uranium extraction from seawater. The estimate includes a probabilistic range of uranium production costs and the contributing components to the uncertainty. Previous cost estimation efforts for uranium extraction from seawater have not included the level of detail in the current cost estimates and accompanying methodology. The current work also provides the first assessment of uncertainty in production costs, including the key components of the uncertainty. The estimates developed in this analysis allow policy makers to quantify the risk of further research investment in seawater extraction technology, identify areas for further research focus (based on cost and uncertainty reduction), and compare the current state of uranium extraction technology to alternative resource development paths such as advanced reactor design. This is a critical step to initiate a cost-benefit analysis for future funding decisions.

The analysis will start by reviewing the theory of backstop technologies and by evaluating uranium from seawater as an exemplar. Next, the current status of technology in Japan, a leader in development of the technology, will be reviewed. The review will focus on a recent cost assessment by the Japan Atomic Energy Agency (JAEA), including sensitivity analyses on the baseline assumptions made in the Japanese report to identify research areas to reduce extraction costs. Thereafter, an independent cost assessment will be developed for a facility in located in the United States using the same production capacity, design basis and technology as the JAEA analysis. The independent assessment will explicitly define cost estimation sources and methodology and include a code of accounts to allow evaluation of costs by process area. Finally, the data from the independent cost assessment will be compared to Japanese results, used in an analysis of uncertainty in the cost of uranium extraction from seawater, and used for further sensitivity analyses to identify cost drivers. The analysis will conclude with detailed recommendations on process alternatives, identification of future research focus areas, and discussion of potential policy implications of the economics of uranium extraction from seawater.

# Chapter 2: Literature Review: Backstop Technology

Backstop technology was defined by Nordhaus et al. as “a set of processes that (1) is capable of meeting the demand requirements and (2) has a virtually infinite resource base” (Nordhaus, Houthakker, & Solow, 1973). In this chapter, a review of the theory and some of the fundamental research regarding backstop technologies in natural resources will be used to provide a basis for the relationship between uranium from seawater and the conventional uranium resource base. In addition, the benefit to society from the development of backstop technologies will be highlighted.

Secondly, a review of seawater extraction technology and cost estimates to date will be used to indicate the current status of the potential backstop technology. As part of this analysis, the state of the art system under evaluation by the DOE will be discussed in detail.

Finally, projections of uranium supply, demand and prices will be used to evaluate the potential viability of seawater extraction as a source of uranium currently and in the future. The cost estimates for the state of the art extraction technology will be used to assess viability.

## 2.1 BACKGROUND

### What is the Potential Benefit of Uranium from Seawater?

The subsequent sections in this chapter will discuss in detail the idea of a backstop technology, including some of the fundamental economic theory and practical implications of the technology. More generally, however, a basic cost-benefit scenario can be used to describe the potential value of developing technology to extract uranium from seawater. Figure 2.1 provides a general depiction of the potential uncertainty of long run supply and demand of uranium. The demand is represented in two cases: a high nuclear growth case vs. a low nuclear growth case. Similarly, supply is depicted by two distinct long-term supply curves – these supply curves represent uranium from conventional sources. In addition, two vertical lines represent the potential supply of uranium from seawater; essentially, seawater will provide all required supply at a single price once the long term marginal cost of the conventional resources is equal to the production cost of uranium from seawater. As with the demand and conventional supply, uncertainty exists around the price of seawater extraction.

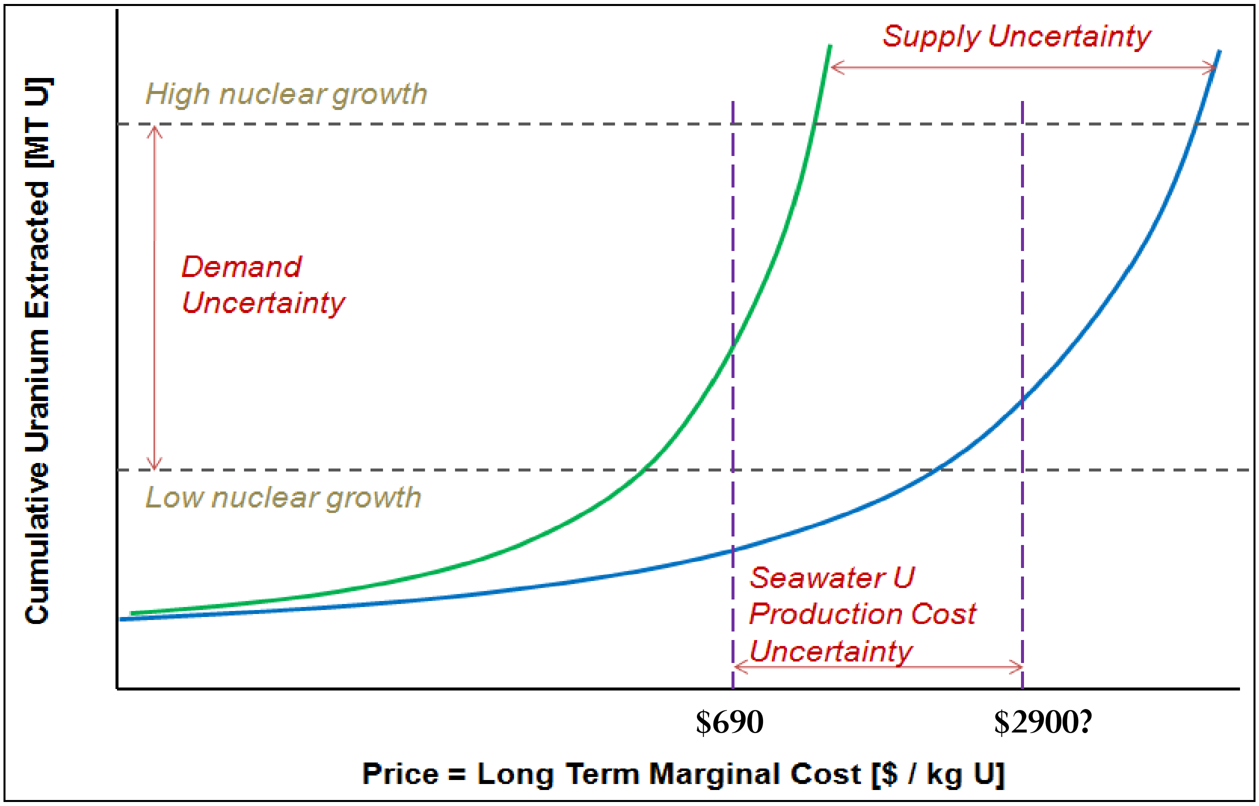


Figure 2.1: Potential Supply of Uranium from Seawater with Uncertainty in Supply and Demand (Schneider, Systems / Economics: Status and Path Forward 2010)

Figure 2.2 shows the same scenario as Figure 1 above; however, the shaded areas in Figure 2.2 correspond to the cost savings to society of using a supply of uranium from seawater at a constant production cost versus the same supply from conventional resources.

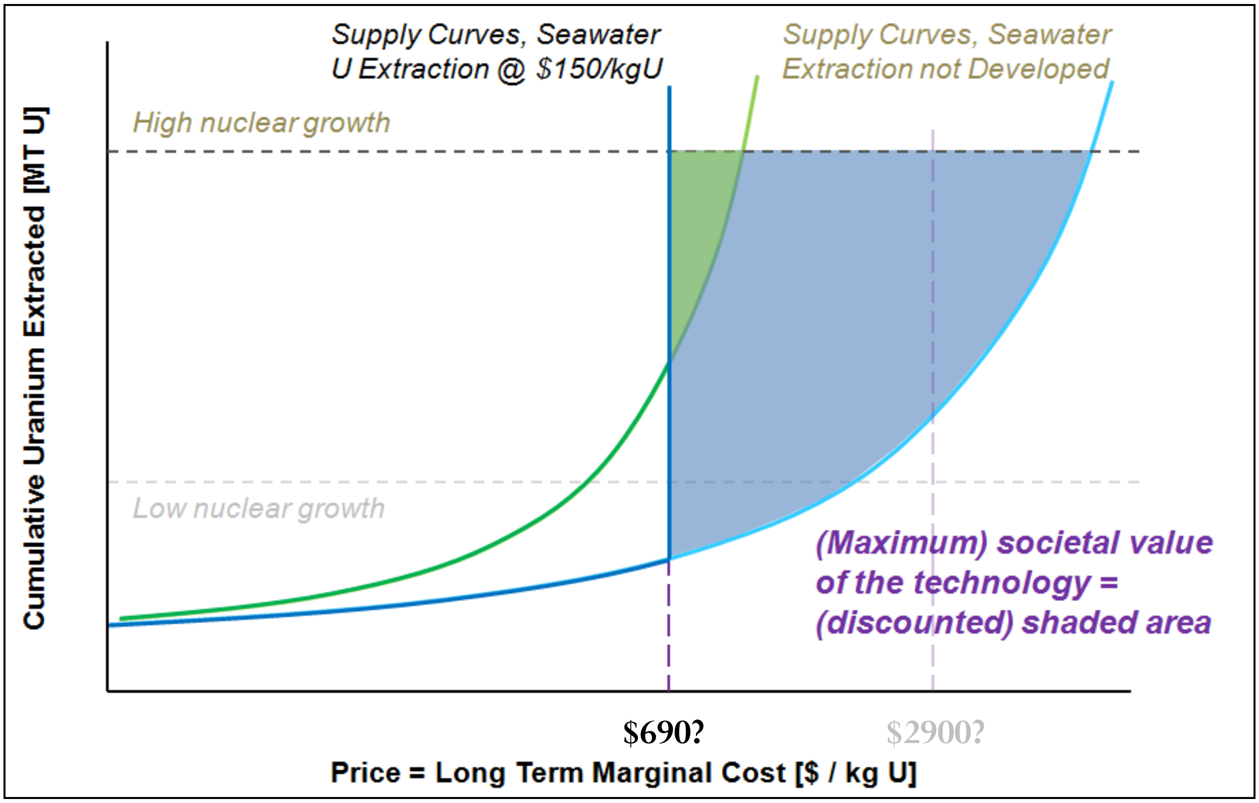


Figure 2.2: Quantifying the Potential Benefit of Uranium Extraction from Seawater (Schneider, Systems / Economics: Status and Path Forward 2010)

As seen in the figure, the largest benefit to society occurs when uranium from seawater is produced at $690/kg U, a high nuclear growth demand scenario is in place, and conventional resource supply is represented by the high-cost, outermost curve (blue supply curve). Here, relatively cheap uranium from seawater replaces a large amount of high-cost conventional resource. At the other extreme, uranium from seawater at $2900/kg U, a low nuclear growth scenario, and low-cost conventional resources (green supply curve) yields no benefit to society since the cost of uranium from seawater is always higher than the conventional resource price.

The illustrative exercise highlights the motivation for research and development (R&D) of seawater extraction technology. The potential long-term cost-savings from uranium from seawater must be discounted to present day and compared against the cost of R&D; this cost-benefit analysis must consider the potential uncertainty around the supply and demand as depicted above. A comprehensive decision analysis is beyond the scope of this work. However, it is clear that if the long-term cost savings outweighs the present day cost of R&D, society will benefit from the investment. The potential role of uranium extraction from seawater as a backstop for long-term uranium prices is critically dependent on the production cost of the extraction process and the uncertainties surrounding it. These areas are the focal point of this thesis.

## Uranium in Seawater: The Resource

All naturally occurring elements are present in seawater at varying concentration levels (The Open University 1989). Uranium has an average ocean concentration of approximately 3.3 parts per billion; hence there is roughly 4 billion metric tons of uranium in the ocean. For comparison, Figure 2.3 below depicts the ore grade and recoverable resource size of conventional and unconventional uranium resources alongside seawater; the data is based on estimates in 1975.

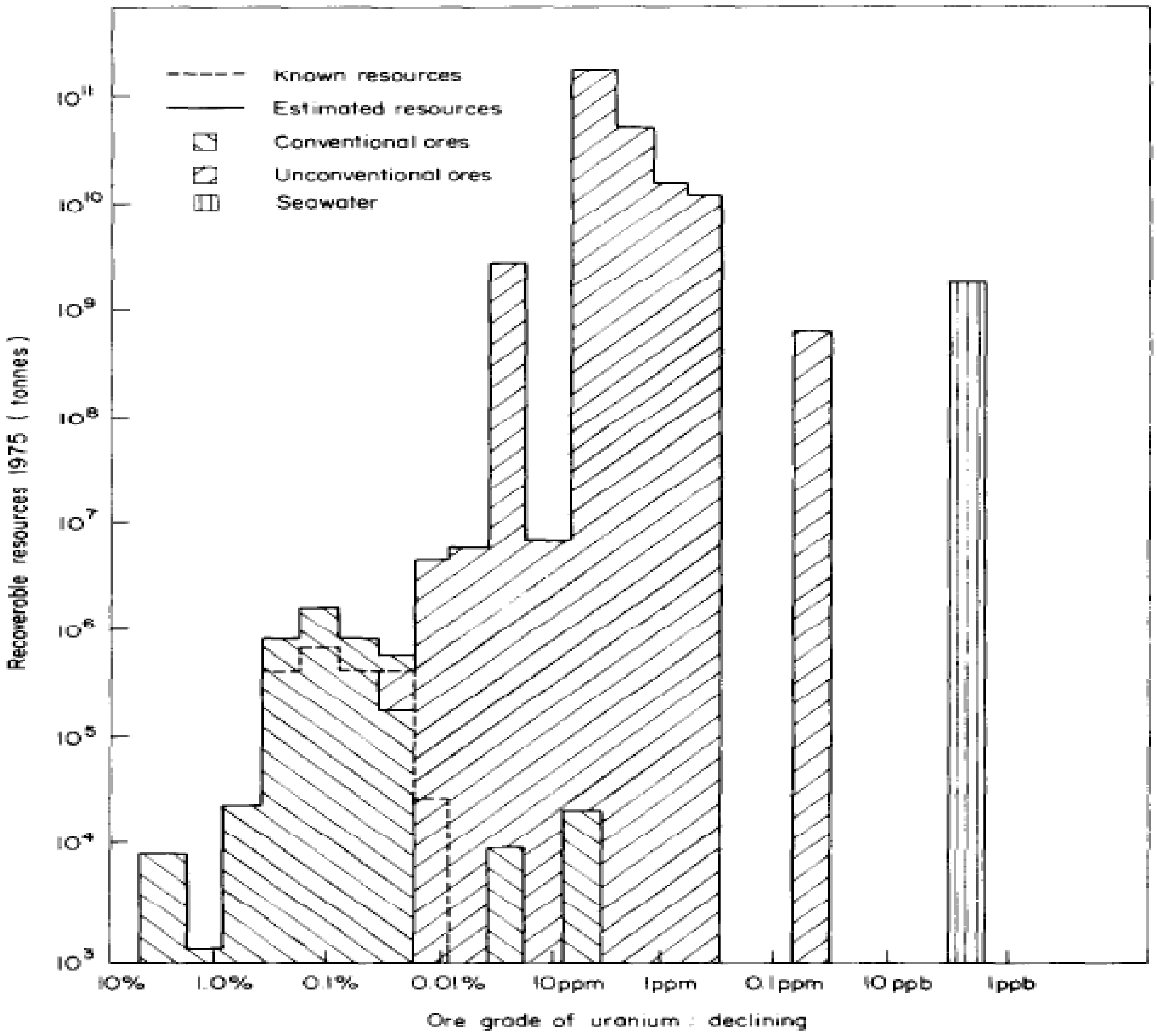


Figure 2.3: Recoverable Uranium Resources at Varying Ore Grades (Mortimer 1980)

The total recoverable resource[1] size has changed over time, and current estimates will be discussed in more detail in subsequent sections; however, the chart clearly depicts that uranium from seawater is a very large resource compared to those currently considered economically recoverable. On the other hand, its concentration in seawater is several magnitudes lower than that of any other potentially viable source of uranium. Therefore, the high expected cost of recovering the uranium may limit the extent to which conventional resources can be augmented or supplanted. The specific costs of uranium extraction from seawater will be evaluated later in this thesis; however, the availability of the large resource base makes uranium from seawater a candidate as potential backstop technology for conventional resources.

## 2.2 BACKSTOP TECHNOLOGY

### Basic Theory

As indicated in the previous discussion, uranium from seawater provides a large resource base (approximately 4 billion metric tons in total). Using an annual consumption of 140,000 t U/year (NEA "high" growth case for 2035 - 120% increase over 2009) (Nuclear Energy Agency 2010), seawater resources would last in excess of 20,000 years. For practical purposes, the uranium from seawater would serve as an infinite resource. A

---

[1] Recoverable resources are defined as a combination reasonably assured resources (RAR) and inferred resources. These categories will be used throughout the report and are defined by the NEA as follows:
Reasonably Assured Resources - refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology, can be specified
Inferred Resources - refers to uranium that is inferred to occur based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposit's characteristics, are considered to be inadequate to classify the resource as RAR

more precise definition of a backstop technology was developed shortly after Nordhaus et al. coined the term; Dasgupta and Heal defined a backstop as a new technology producing a close substitute to an exhaustible resource by using relatively abundant production inputs and rendering the reserves of the exhaustible resource obsolete when the average cost of production of the backstop technology falls below the spot price of the exhaustible resource (Dasgupta and Heal 1979). This definition more clearly fits the case of uranium extraction from seawater and identifies a central research question for this work – what is the cost of uranium extraction from seawater and when will this technology become economically viable?

The initial models for backstop technology were developed in the context of exhaustible natural resource problems. The resources used in energy technology were considered to be cheap but finite; a backstop technology would ultimately remove concerns over scarcity and mineral extraction prices would be controlled by capital and labor markets (Nordhaus, Houthakker and Solow 1973). In other words, the backstop technology was essentially a boundary condition to analyze an exhaustible resource problem; some discussion of specific technology, such as breeder reactors or solar energy, appeared in the research but was not the focus of the analysis. Rather, this initial work sought to develop optimal depletion planning scenarios for the conventional resource when considering a backstop technology; while the conventional resource base is not the focus of the work in this report, this fundamental research still highlights the importance of the backstop technology and its characteristics.

A simple model of the backstop problem is formulated here based on the work of Nordhaus et al. The model depicts two processes; the first process uses a conventional energy resource, such as mined uranium. The second process will use a backstop technology such as uranium from seawater. First, the price of a resource is defined as follows:

$$\boldsymbol{p(t) = MEC(t) + z(t)} \tag{2.1}$$

where

MEC = Marginal extraction cost of the resource,

z = Royalty or scarcity rent,

t = time (any units).

The concept of a royalty or scarcity rent was originally developed by Gray and Hotelling (Gray, 1914 and Hotelling, 1931) and reflects the value of the ore that remains in the ground versus the ore that is extracted (in the case of perfect competition). The rent is expected to increase over time as a function of the rate of interest reflecting the increasing scarcity of the resource. This original theory has since been criticized as a limited case which does not account for exploration or improvements in technology and thus does not adequately reflect long-term price behavior (Adelman, et al. 1983). However, the results derived from the model do provide insight into the effect of a backstop technology. The time when a backstop technology (such as uranium from seawater) replaces the conventional technology is reflected in the following relationship:

$$\boldsymbol{T = R/D} \tag{2.2}$$

where

T = Time of switch to backstop technology, years (uranium from seawater)

R = Recoverable Resource Base (Conventional Uranium)

D = Yearly Demand for Uranium (Assumed Inelastic)

Equation 2.2 simply depicts that uranium from seawater will displace conventional uranium when the conventional uranium base is depleted. The price at time T, when the switch to the backstop technology occurs, is dictated by the cost of the backstop technology itself.

$$\boldsymbol{p(T) = (r + s) * K} \tag{2.3}$$

where

r = Interest Rate,

s = Depreciation Rate,

K = Capital cost of the Backstop Technology.

This price only reflects the price at the transition to uranium from seawater; the full price path, as derived by Nordhaus et al. is given by the following (extraction costs are neglected for simplicity):

$$\boldsymbol{p(t) = (r + s) * K * \exp\,[-r(T - t)]} \tag{2.4}$$

The importance of equation 2.4 is reflected in the cost of deploying the backstop technology, (r+s)*K. Therefore, the full price path of the exhaustible resource is the transition price discounted back to the initial time, t. Since the extraction costs are assumed negligible, the change in price over time is simply the royalty or scarcity rent described previously.

The result of this basic model has a few important conclusions regarding backstop technology:

1) If the price of the backstop technology is low, the royalty on the conventional resource will be relatively lower (the opposite is true for high backstop costs).
2) If the switch date to the backstop technology is far off, the royalty on the conventional resource is also low (the opposite is true for a near-term transition).

The significance is that the nature of the backstop technology will impact optimal use of the conventional resource base; any uncertainty in this backstop technology may also create volatility in the price of the resource. Therefore, from a planner or policy-maker perspective, an incentive exists to understand and develop a backstop technology.

This initial view of backstop technology has been updated over time. The work of Heal (1976) started with the assertion that many "exhaustible" resources, such as metals, are in fact effectively inexhaustible – the resource is simply available at varying ore grades and costs (Heal 1976). This assertion is consistent with later conclusions by authors such as Adelman who found the resource exhaustibility problem to be one of economic rather than physical exhaustion (Adelman, 1990). Heal further recognized that these resources are effectively inexhaustible due to the potential of extraction from unconventional resources; seawater is specifically cited as an option for metals such as uranium. The treatment of the backstop problem as the transition of a resource from an exhaustible source to an infinite source at a fixed cost yields the following important modifications to the previous analysis:

1) Extraction costs of the resource will rise over time as a function of the total amount of the resource extracted (as opposed to a constant extraction cost)
2) The difference in price and extraction cost is no longer a scarcity rent – the resource is infinite in this case – rather, the difference in price and cost is a social cost that accounts for the increase in future cost due to current extraction.
3) This social cost will fall over time as it approaches the backstop technology (where the social cost is 0).

The practical purpose of this updated model is to explain the differences between price and extraction costs. The cost and timing of the backstop technology are still critical to the price path of the conventional resource as before; however, in the previous case the timing of the backstop technology was simply related to the exhaustion of the conventional resource. In this updated view, the timing of the backstop technology is controlled by the economic viability of the backstop technology. That is, when the production cost of uranium from seawater is equal to the extraction cost of the conventional resource, uranium extraction from seawater becomes the sole, infinite resource base. This model more accurately represents the idea of economic exhaustion of a resource. Therefore, understanding the cost of uranium extraction from seawater can also provide policy-makers with an understanding of when a potential transition of resource technologies might occur.

The model proposed by Heal, however, still misses an important consideration for the transition from conventional resource to a backstop technology; in reality, the transition is not likely to be discrete from conventional uranium to uranium from seawater. Rather, as the extraction cost of conventional uranium approaches the production cost of uranium from seawater, a transition period will occur. Liski and Murto associate this period with phases (Liski and Murto 2006).

In an initial phase, the conventional market is stable, though the quality of the conventional resource base is deteriorating (i.e. ore grades declining); backstop technologies may serve as a one to one substitute if economically viable. Many conventional firms remain in the market with lower cost resources.

In a second phase, continuing degradation leads to volatility. Conventional firms may choose to go idle rather than exit the market – this is characteristic of capital-intensive resource markets. Backstop technology still substitutes, but an overlap of technology occurs between conventional and new resources. Price fluctuations may occur based on the behavior of the idle firms.

Finally, market conditions for the conventional resource persist at high costs over time, and conventional resources are replaced by new extraction technology.

The transitional behavior described above is particularly relevant when considering dynamic conventional and backstop resource markets together. For example, continuing research in a backstop technology can reduce costs over time. The volatility in the conventional market can lead to gradual adoption of the backstop technology while reduced costs driven by R&D can accelerate the displacement. Thus, the benefits of the backstop technology can accrue over time along with the costs of R&D. Further, the incorporation of inherently less volatile resources can reduce costs to society from supply side shocks or other external factors that affect energy commodity prices.

Finally, the backstop technology model has also been evaluated when considering environmental impacts of conventional mining. More specifically, a societal value to preserve land is considered alongside the traditional resource extraction problem

(Krautkraemer 1986). In short, the marginal value of production of land used for a resource must outweigh the marginal environmental or “amenity” value of the land to justify production; the incorporation of a backstop technology, however, provides an alternative that may allow for continued production growth and conservation. In the case of uranium extraction from seawater, the environmental impacts of seawater extraction should be considered alongside those of traditional mining; this is particularly important as technology improvements may reduce the price of mining more environmentally damaging conventional ores. The development of a backstop technology becomes an environmental policy tool to correct a potential market failure in uranium mining.

In summary, the basic theory of backstop technology in natural resources provides several important conclusions for the development of a resource such as uranium from seawater. First, the cost (and related uncertainty) of uranium extraction from seawater can impact the price path of the conventional resource; therefore, understanding the cost of uranium from seawater can provide information to the conventional uranium market that may improve the efficiency of the market. Second, understanding the cost of the uranium extraction from seawater can allow for long-term resource planning by providing a clear picture of when seawater extraction can provide resources to the marketplace. Next, continued development of seawater extraction as a backstop can allow gradual displacement of conventional resources in a volatile uranium market; this allows accrual of near-term benefits for uranium extraction from seawater and reduced market volatility. Finally, the development of uranium extraction from seawater can provide an alternative in cases where conventional resources are constrained by environmental considerations. Preservation is no longer a function of the economics of the conventional resource alone; environmental costs may make seawater extraction viable sooner, and provide an alternate route to preservation of the environment.

## 2.3 VIABILITY OF URANIUM EXTRACTION FROM SEAWATER AS A BACKSTOP

The preceding section highlights the importance of the cost of a backstop technology such as uranium from seawater and provides incentive to better understand its cost. In fact, research and development in uranium extraction from seawater has a long history spanning multiple countries and a variety of methods; the variability in approaches has led to a wide range of cost estimates over time (see (Rao 2009) or (Kelmers 1980) for detailed discussion of the history of research). The work in Japan, in particular the economics of the state of the art system, will be evaluated in detail in Chapter 3. However, to provide a preliminary evaluation of uranium from seawater as a backstop technology, a point cost estimate from analysis of the Japanese system will be used; estimates for the Japanese system are approximately \$1000 per kg U (derived from Tamada, Seko, Kasai, & Shimizu, 2006).

Figure 2.4 shows the spot prices of uranium from the end of 2002 to the end of 2009.

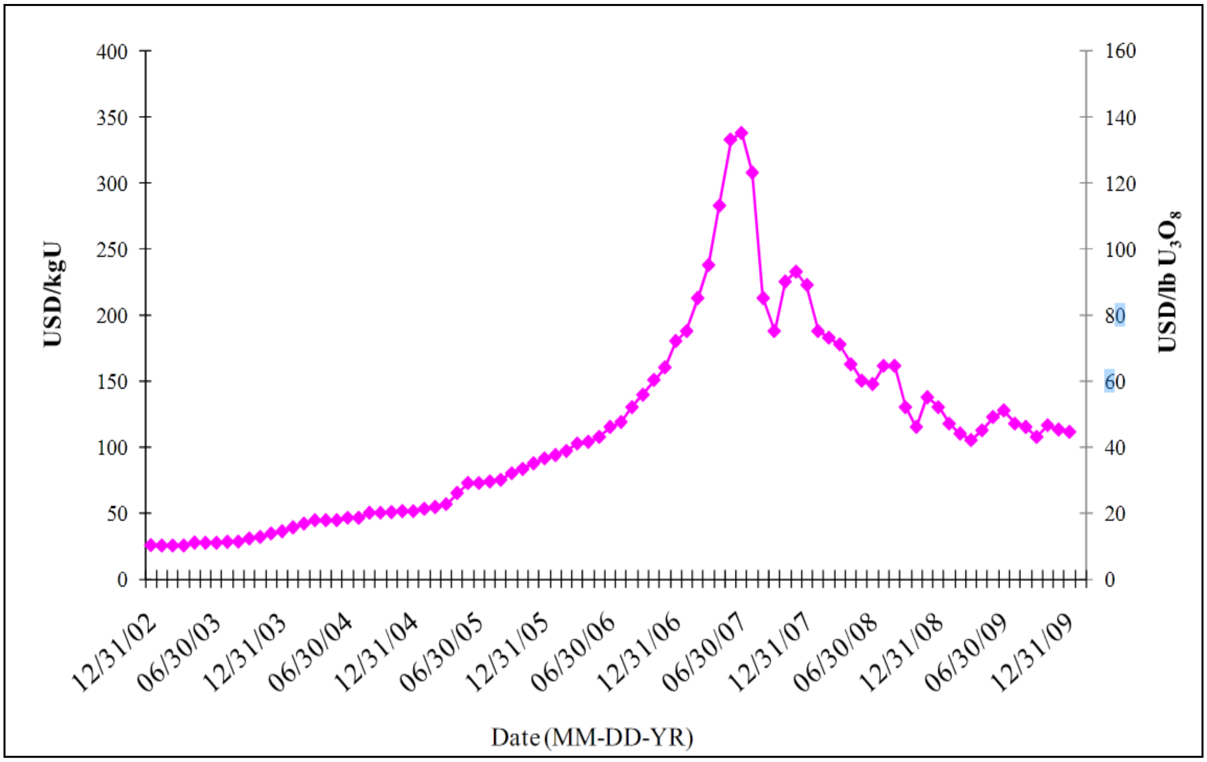


Figure 2.4: Uranium Spot Prices End 2002 – End 2009 (Nuclear Energy Agency 2010)

The figure shows record high uranium spot prices that reached as high as $354 per kg U in 2007; however, the seawater extraction estimates are still well-above this value. As previous sections have discussed, the value of a backstop technology is not strictly limited to immediate economic viability. Therefore, further analysis is needed to determine if seawater extraction might become viable under expected nuclear expansion scenarios.

## Cumulative Availability Curve

One approach to evaluate the long-term viability of uranium extraction from seawater is via the use of a cumulative availability curve. A cumulative availability curve depicts “the amount of a mineral commodity that can be recovered profitably at various prices from different types of mineral deposits under current conditions (Yaksic Beckdorf and Tilton 2009).” In order to construct a cumulative availability curve for uranium, data regarding uranium resources was derived from the NEA Red Book (Nuclear Energy Agency 2010). The data includes the reasonably assured resources and inferred resources than make up “recoverable resources” (see footnote 1 for detailed definitions). In addition to these resources, so-called undiscovered resources[2] were incorporated into the analysis. The NEA data includes expected recovery costs for all categories of resources – this allows for straightforward construction of a cumulative availability curve as described in work by Yaksic Beckdorf and Tilton (2009).

In addition to the resource availability data, the NEA Red Book contains nuclear growth forecasts as discussed in the introduction and expected uranium requirements to 2035. Using the data provided by the NEA for a high growth nuclear case (110% growth from current capacity), simple linear interpolation and extrapolation were used to fill in annual uranium requirements from 2008 to 2100. These annual requirements could then be summed to find aggregate demand over any time period of interest. Note that this analysis is limited by the fact that demand can be met by secondary sources of uranium as well as stocks and inventories. The potential for these sources of supply were not considered in this analysis.

---

[2] Undiscovered resources are defined by the NEA as resources that are expected to occur based on geological knowledge of previously discovered deposits and regional geological mapping.

Figure 2.5 presents the cumulative availability curve for uranium when considering all recoverable and undiscovered resources. The curve also includes uranium from seawater at $1000 per kg U.

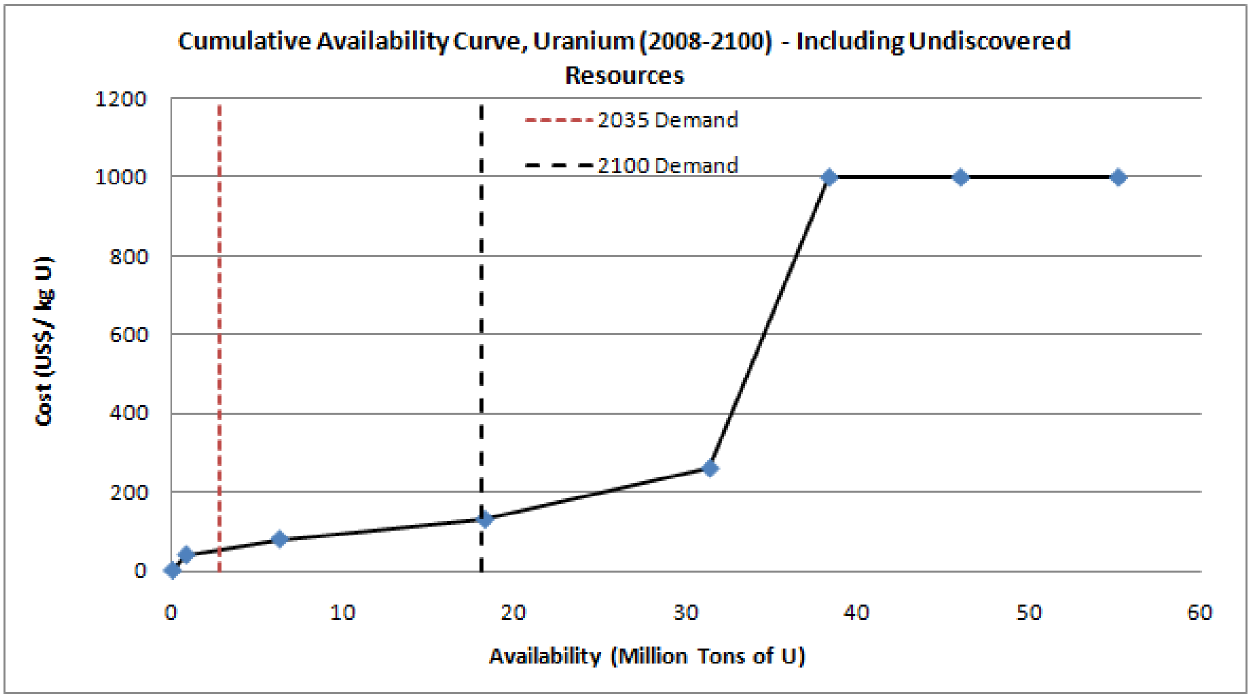


Figure 2.5: Cumulative Availability Curve and Aggregate Demand, Uranium – Includes Recoverable and Undiscovered Resources

The figure also includes two aggregate demand lines – one for 2035 (the projection based on NEA data with interpolation) and one for 2100 (based on NEA data extrapolated from 2035 to 2100). The important result from this chart is that neither aggregate demand reaches the plateau of the cumulative availability curve. This plateau represents uranium extraction from seawater at $1000 per kg U. Therefore, in the window of this analysis, in does not appear uranium extraction from seawater is a viable backstop technology at a price of $1000 per kg U. In addition, the analysis indicates that to become viable at the 2100 demand scenario, production costs of uranium from seawater would have to drop below $130/ kg U.

If the undiscovered resources are excluded from the analysis to offer a conservative depiction of resource availability, Figure 2.6 below is the result.

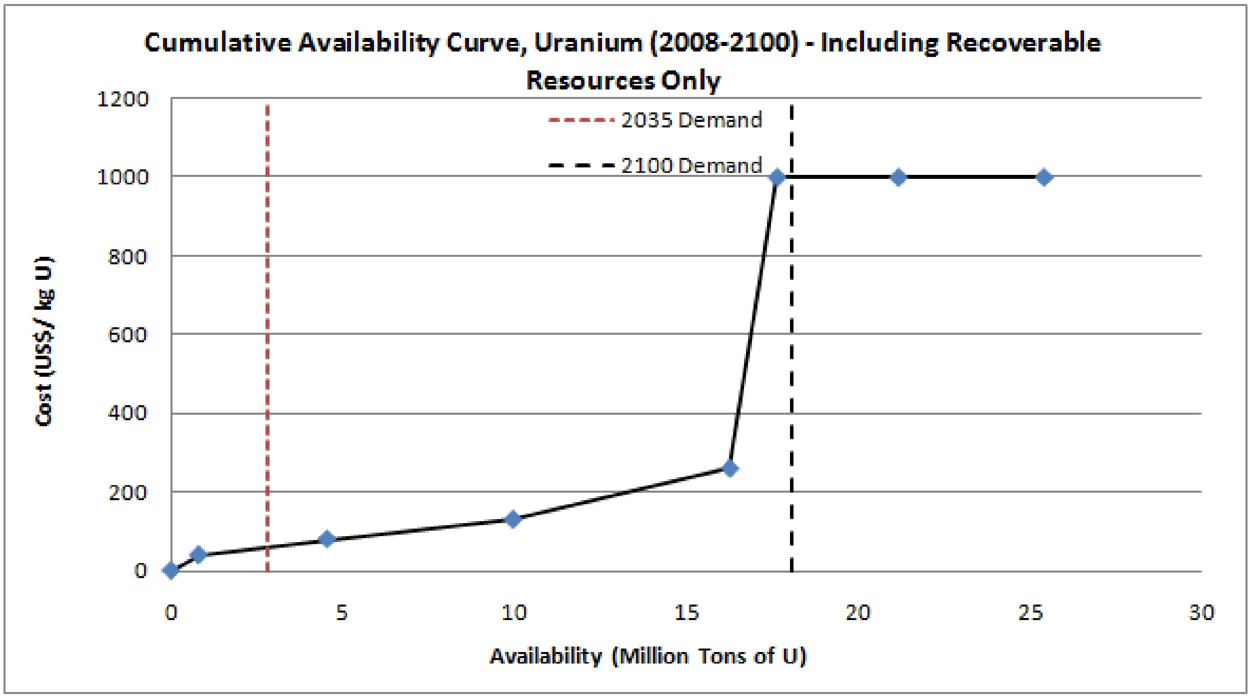


Figure 2.6: Cumulative Availability Curve and Aggregate Demand, Uranium – Includes Recoverable Resources Only (RAR +Inferred)

This figure indicates that, based on the high growth estimate for 2100, uranium from seawater will become a viable technology and provide a backstop on resource prices at $1000 per kg U. The case for 2035 still requires production costs of uranium to fall below $100/ kg U.

It is important to note that this discussion was illustrative of the potential viability of uranium extraction from seawater. The uncertainty in data used to produce the aggregate demand lines and the cumulative availability curve were not analyzed. A full sensitivity and viability analysis would include discussion of exploration and technology advances in conventional uranium mining that might shift the cumulative availability curve down and to the right. In addition, a full discussion of the many factors that would impact nuclear demand, which might include many sectors of the economy, would be necessary to complete the demand analysis provided here. This portion of the analysis could serve as future work.

Finally, the analysis to this point assumed that uranium from seawater would remain at its current estimate of $1000 per kg U. However, the purpose of investigating this technology and funding R&D is to reduce the cost (and associated uncertainty) of the technology. The remainder of this thesis will focus on the detailed aspects of the cost of uranium extraction from seawater including key cost drivers that may be the focus of R&D.

# Chapter 3: Review of Work in Japan and Development of Life Cycle Discounted Cash Flow (LCDCF) Methodology

To understand the economics of uranium extraction from seawater, state of the art technology will be evaluated and serve as the basis for recommendations for research and development. The Japan Atomic Energy Agency (JAEA) and Japan Atomic Energy Research Institute (JAERI) have led research in the production and performance evaluation of braided amidoxime adsorbents for uranium extraction from seawater (Sugo, et al. 2001). An overview of the technology used to manufacture, deploy and recover uranium from the amidoxime adsorbents will be covered in this chapter. In addition, a life cycle discounted cash flow (LCDCF) methodology will be developed and implemented in sensitivity analyses of JAEA cost estimation results.

## 3.1 TECHNOLOGY OVERVIEW

The advantages of the system used by the Japanese include passive collection of uranium via ocean current passing through the braided adsorbent material and the drastic weight reduction of a system that allows for free-standing adsorbent versus a large support structure as in previous systems (Tamada, et al. 2006). The improvements made by Japanese research to date reflect the potential for uranium extraction from seawater. For example, DOE funded research in the 1980's concluded that pumping seawater at more than 10 feet of head would require more energy than supplied by the recovery of uranium; this made most pumping schemes unviable (Best and Driscoll 1980). The Japanese adoption of a passive adsorption system eliminates the need for pumping. In addition, the amidoxime adsorbent developed by the Japanese improved adsorption capacity (kg U per tonne of adsorbent material over a 30 day period) by more than an order of magnitude over titanium oxide, the state of the art material in the 1980's (Rao 2009).

Figure 3.1 provides a generic overview of the seawater recovery process, highlighting three major areas: adsorbent production, mooring or deployment of the adsorbent, and desorption-purification of the recovered uranium.

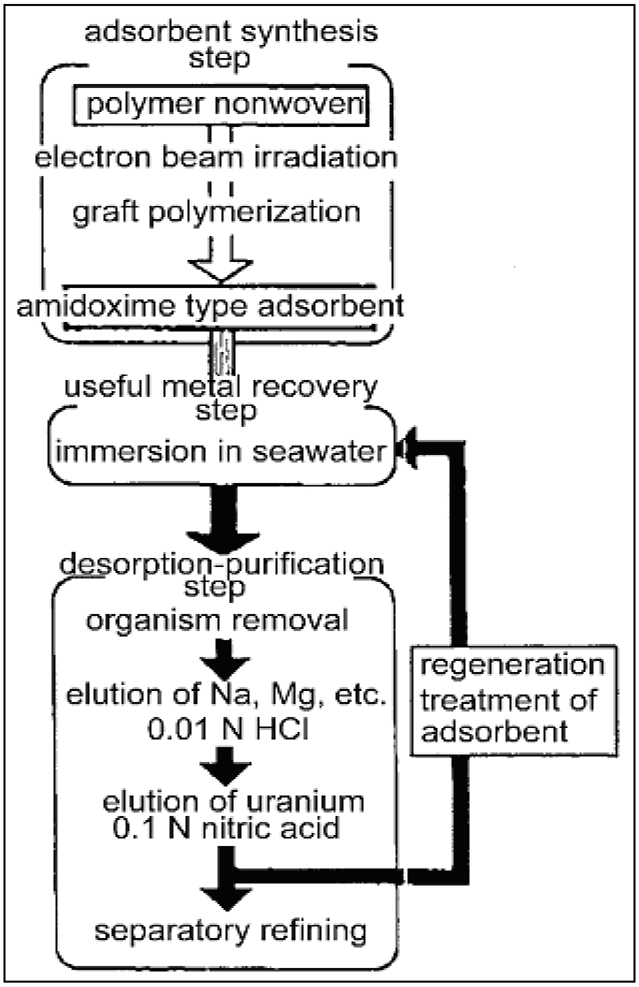


Figure 3.1: Uranium Extraction from Seawater – Process Overview (Sugo, et al. 2001)

The adsorbent production process and desorption-purification process (the first and third steps in Figure 3.1) are primarily based on established, well-known commercial processes. In addition, the amidoxime type adsorbent appears to be the established state of the art adsorbent material in current Japanese research. Therefore, mooring system design has been emphasized in previous cost estimation work. Several cost estimates for different adsorbent mooring systems have been developed – previous work by Sugo et al. in 2001 (work for JAERI) focused on three mooring systems – buoy method, floating body method, and a chain-binding system. In the preliminary stages of the analysis for this thesis, the chain-binding system cost estimates from JAERI were reproduced. The JAERI analysis and the reproduction verified that the mooring system was a major component of the total system production cost; JAERI estimates found that mooring system costs accounted for more than 70% of the total cost (Sugo, et al., 2001). Figure 3.2 depicts an adsorbent bed used in the chain-binding system.

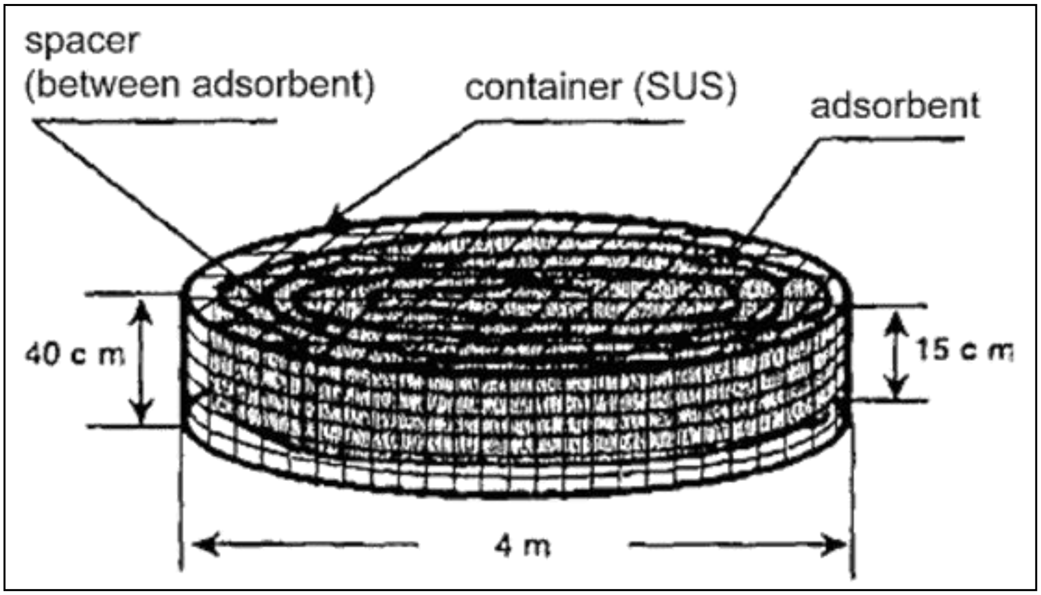


Figure 3.2: Adsorbent bed used in the chain-binding system developed by JAERI

The focus on reducing mooring system costs (and specifically mooring system weight) led to the development of a new mooring design, the braid-type adsorbent system (Tamada, et al. 2006). The cost estimates and analysis in this thesis focus on the braid-type adsorbent system; Figure 3.3 shows the braid adsorbent and mooring system.

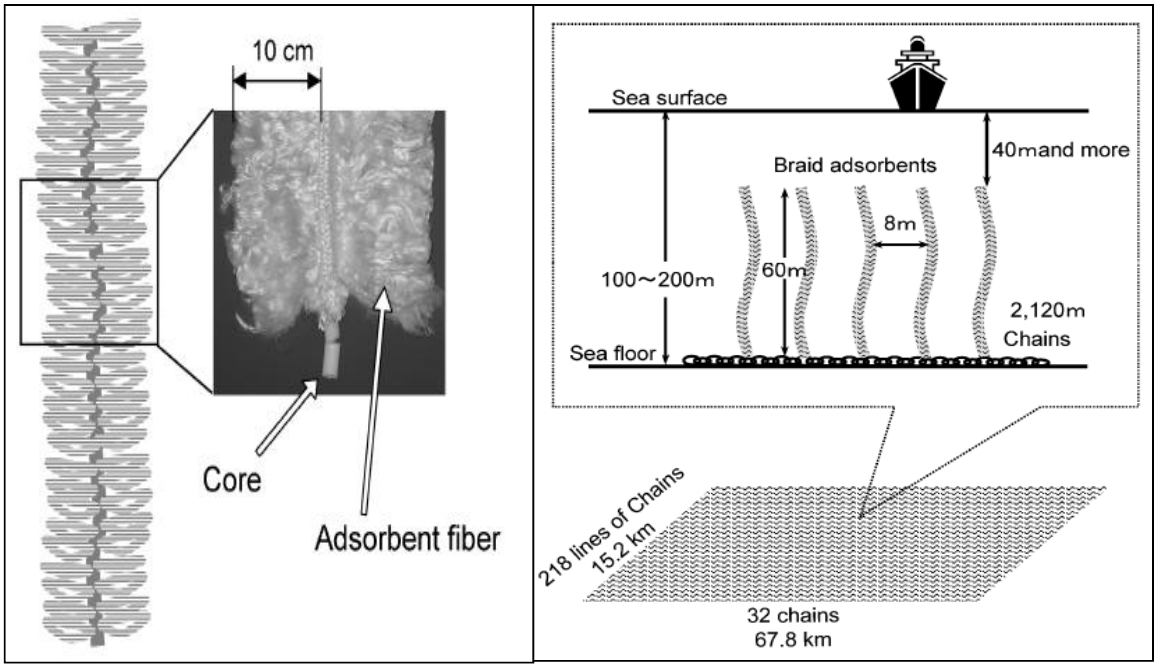


Figure 3.3: Braid Adsorbent and Mooring System (Tamada, et al. 2006)

The primary benefits of the braid system include the elimination of the metal beds used in the chain-binding system include reducing overall weight as well as improved contact with seawater due to the open structure of the adsorbent units (Tamada, et al. 2006).

The analysis in the subsequent sections serves two primary purposes. First, the estimates made by Tamada, et al. (2006) for JAEA are reviewed and reproduced using the basic data supplied in that report in order to understand the cost-estimation methods used by JAEA. Additionally, using the baseline annual cost estimates from the JAEA report, a cash flow analysis is developed over the lifetime of one ton of adsorbent; this method tracks production costs over the lifetime of the adsorbent and allows detailed sensitivity analysis of several system parameters that may vary with time or with reuses of the adsorbent.

### 3.2 REVIEW OF JAEA COST ESTIMATES

Basic system parameters for the braid adsorbent cost estimates performed by Tamada et al. are provided in Table 3.1.

Table 3.1: JAEA System-wide Parameters for Braid Adsorbent Cost Estimation

| Item | Value | Units | Comments |
|---|---|---|---|
| Uranium Production | 1,200 | metric tons per year | Metallic U basis |
| Adsorbent Capacity | **2** | **kg-U/t-adsorbent** | Mooring for 60 days in a region of 25°C ocean current |
| Length of Campaign (Recovery time period) | 60 | days per use | Time period moored in seawater |
| Number of Campaigns (Recovery frequency) | **6** | **times per year** | Number of reuses during 1 year |
| Adsorbent reuse count | **6** | **recycles** | Lifetime of Adsorbent |
| Adsorbent Required | 100,000 | metric tons per year | Calculated |
| Adsorbent Replaced | 100,000 | metric tons per year | Calculated |

The last two parameters in Table 3.1 (adsorbent required and adsorbent replaced annually) were calculated from other system parameters in the table. The adsorbent required is calculated as follows:

$$\boldsymbol{A_{REQ} = \frac{U_P * 1000}{C_{Ads}}} \tag{3.1}$$

where

$A_{REQ}$ = Adsorbent required annually, metric tons

$U_P$ = Annual uranium production requirement, metric tons (1200 metric tons)

$C_{Ads}$ = Adsorbent production capacity, kg U per metric ton adsorbent

The adsorbent replaced annually was implicitly derived from the following relationship:

$$\boldsymbol{A_{REP}} = \left(\frac{\boldsymbol{RF}}{\boldsymbol{R_{Ads}}}\right) * \boldsymbol{A}_{\boldsymbol{REQ}} \tag{3.2}$$

where

$A_{REP}$ = Adsorbent replaced annually, metric tons

RF = Adsorbent recovery frequency or number of mooring campaigns per year

$R_{Ads}$ = Number of recycles or reuses per adsorbent

The parameters in Table 3.1 form the basis for the cost calculations in all three major process areas and will serve as the “base case” for all subsequent analysis in this thesis. JAEA cost estimates for each of the three areas in Figure 3.1 are reviewed in the subsequent sections. Common assumptions for all costs summarized in the following tables include amortization of capital equipment expenses at 3% over 15 years, amortization of building capital costs at 3% over 30 years, and annual maintenance costs taken as 3% of total equipment cost (Tamada, et al. 2006).

### 3.2.1 Adsorbent Production

An overview of the adsorbent production process is depicted in Figure 3.4 below.

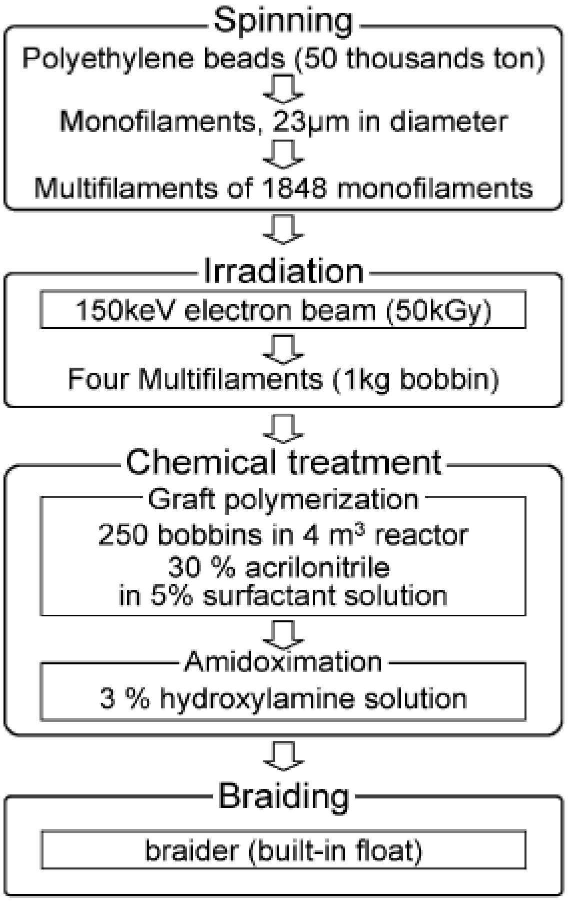


Figure 3.4: Adsorbent Production Process (Tamada, et al. 2006)

The adsorbent production cost from the process in Figure 3.4 was divided into several categories of capital and operating costs; Table 3.2 below shows cost categories as defined by JAEA, the original JAEA estimate for annual costs for each category and the relative contribution of each component to total annual cost. All values given in the JAEA estimate were based on an adsorbent production capacity of 100,000 tons per year of production (derived from the annual recycle rate in equation 3.2).

Table 3.2: Adsorbent Production Costs – JAEA Estimation (Tamada, et al. 2006)

| **Items** | **JAEA Estimate - Annual Cost** | | **Percent of Total Area Costs** |
|---|---|---|---|
| | **billion yen (2005)** | **millions US$ (2010)*** | |
| **Capital Amortization Cost: Principal** | 2 | 20 | 3% |
| **Capital Amortization Cost: Interest** | 0.57 | 6.10 | 1% |
| **Land Rent** | 0.01 | 0.10 | 0.01% |
| **Cost of labor** | 2.8 | 28 | 4% |
| **Utility Cost** | 6.4 | 65 | 9% |
| **Chemicals and Materials** | 59.9 | 610 | 82% |
| **Maintenance for Plant** | 0.77 | 7.8 | 1% |
| **Maintenance for Building** | 0.22 | 2.2 | 0.3% |
| **TOTAL** | 72.7 | 739 | 100% |

***Conversion to US Values from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. Capital costs were adjusted with the Chemical Engineering Price Index (Appendix B). All other values inflated using the general CPI (Appendix B). Converted values for reference only.**

The JAEA analysis also provided detailed equipment capital costs by equipment type required for adsorbent production and utility and raw materials cost for adsorbent production.

Table 3.3: Summary of Adsorbent Manufacturing Capital Equipment (Tamada, et al. 2006)

| **Items** | **Quantity** | **Unit Cost** | **Total Cost** | |
|---|---|---|---|---|
| | | | **billion yen (2005)** | **millions US$ (2010)*** |
| **Spinning Lines (25,000 tonnes/yr)** | 2 | 1.6 billion yen | 3.2 | 34 |
| **Electron Accelerators (150kV)** | 12 | 140 million yen | 1.7 | 18 |
| **Reactors (4 m$^3$)** | 186 | 22 million yen | 4.1 | 44 |
| **String/Braiding Devices** | 1275 | 880,000 yen | 1.1 | 12 |

***Conversion to US Values from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. Equipment costs were adjusted with the Marshall and Swift Index (Appendix B). Converted values for reference only.**

Table 3.4: Summary of Adsorbent Manufacturing Raw Materials (Tamada, et al. 2006)

| **Items** | **Quantity** | **Unit Cost** | **Total Cost** | |
|---|---|---|---|---|
| | | | **billion yen (2005)** | **millions US$ (2010)*** |
| **Polyethylene** | 50,000 tonnes | 100 yen/kg | 5.0 | 51 |
| **5% Surfactant** | 3,415 $m^3$/year | 430000 yen/$m^3$ | 1.5 | 15 |
| **30% Acrylonitrile** | 43,953 $m^3$/year | 430000 yen/$m^3$ | 18.9 | 192 |
| **Dimethylformamide** | 68,300 $m^3$/year | 230000 yen/$m^3$ | 15.7 | 159 |
| **3% Hydroxylamine** | 22,164 $m^3$/year | 720000 yen/$m^3$ | 16.0 | 162 |
| **Water/Methanol** | 66,592 $m^3$/year | 40000 yen/$m^3$ | 2.7 | 27 |
| ***Conversion to US Values from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. Chemicals costs were adjusted using the general CPI (Appendix B). Converted values for reference only.** | | | | |

The JAEA analysis found that almost 70% of total uranium production costs for the system came from adsorbent production (Tamada, et al. 2006) so understanding the details of this process will be important for further analysis. Cost estimation details will be covered in Chapter 4 as part of an independent cost estimate for this thesis.

### 3.2.2 Mooring and Recovery

The second major component of uranium extraction cost was the adsorbent mooring and recovery costs. Figure 3.3, shown previously, contained a basic schematic of the mooring system which primarily consists of the chains required to anchor the adsorbent structure itself – this simplified mooring design allows for the reduction in mooring costs relative to previous designs. The adsorbent is then recovered and re-deployed continuously by boats. Table 3.5 summarizes the JAEA mooring cost categories and Table 3.6 provides major equipment costs.

Table 3.5: Adsorbent Mooring Costs – JAEA Estimation (Tamada, et al. 2006)

| **Items** | **JAEA Estimate - Annual Cost** | | **Percent of Total Area Costs** |
|---|---|---|---|
| | **billion yen (2005)** | **millions US$ (2010)*** | |
| **Capital Amortization Cost: Principal** | 11.7 | 119 | 38% |
| **Capital Amortization Cost: Interest** | 3 | 30 | 10% |
| **Cost of labor** | 8.1 | 82 | 26% |
| **Chemicals and Materials** | 2.7 | 27 | 9% |
| **Maintenance for System** | 5.3 | 54 | 17% |
| TOTAL | 30.8 | 312 | 100% |

***Conversion to US Values from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. All costs were adjusted using the general CPI (Appendix B). Converted values for reference only.**

Table 3.6: Summary of Mooring Capital Equipment (Tamada, et al. 2006)

| **Items** | **Quantity** | **Unit Cost** | **Total Cost** | |
|---|---|---|---|---|
| | | | **billion yen (2005)** | **millions US$ (2010)*** |
| **Chains (44mm stud link anchor chain)** | 6976 | 180,000 yen/ton | 112.9 | 1,145 |
| **Boats (1000 deadweight tonne capacity)** | 116 | 140 million yen/boat | 16.2 | 165 |
| ***Conversion to US Values from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. All costs were adjusted using the general CPI (Appendix B). Converted values for reference only.** | | | | |

The improved mooring design still represents the largest portion of capital costs in the sweater extraction system and may hold opportunity for additional optimization and design improvement. The cost of labor was not evaluated in detail but accounts for over 25% of the total mooring costs and will be an important part of subsequent analysis of the mooring system (Tamada, et al. 2006). Chemicals and materials costs were determined to be fuel costs for boats after discussions with one of the author's of the paper, Dr. Takao Shimizu. No details were provided for fuel costs but will be considered in the analysis in chapter 4. While these fuel costs make up the smallest portion of costs in Table 3.5, they may vary greatly with system design, location, boat design and capacity and fuel prices. The fuel consumption will also be important for understanding the overall energy consumption of the uranium recovery process.

### 3.2.3 Elution-Purification

The final major step in the uranium recovery process is elution and purification; this process encompasses multiple steps including repeated acid elution and purification of recovered products. The separated heavy metals, including uranium, are further processed and refined to produce the pure metallic forms of the elements; in this analysis, uranium recovery is the only focus. Figure 3.5 gives an overview of the desorption-purification process.

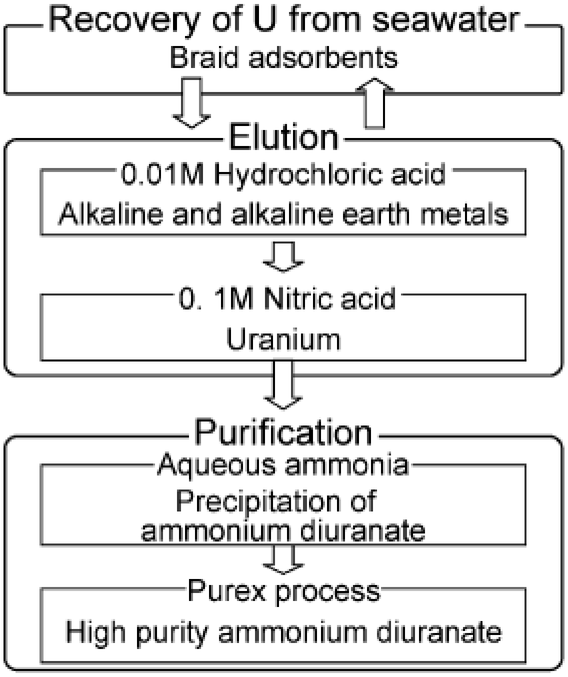


Figure 3.5: Uranium Desorption-Purification Process (Tamada, et al. 2006)

Table 3.7 provides the cost breakdown for the JAEA analysis of the elution-purification process on the basis of 1200 tonnes of uranium recovered and processed annually.

Table 3.7: Uranium Elution-Purification Costs – JAEA Estimation (Tamada, et al. 2006)

| **Items** | **JAEA Estimate - Annual Cost** | | **Percent of Total Area Costs** |
|---|---|---|---|
| | **billion yen (2005)** | **millions US$ (2010)*** | |
| **Capital Amortization Cost: Principal** | 0.79 | 8.4 | 39% |
| **Capital Amortization Cost: Interest** | 0.24 | 2.6 | 2% |
| **Land Rent** | 0.002 | 0.02 | 0% |
| **Cost of labors** | 0.49 | 5.0 | 0% |
| **Utility Cost** | 0.04 | 0.41 | 0% |
| **Chemicals and Materials** | 0.02 | 0.20 | 49% |
| **Maintenance for Plant** | 0.29 | 2.9 | 1% |
| **Maintenance for Building** | 0.14 | 1.4 | 1% |
| TOTAL | 2.01 | 21 | 100% |

***Conversion to US Values from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. Capital costs were adjusted with the Chemical Engineering Price Index (Appendix B). All other values inflated using the general CPI (Appendix B). Converted values for reference only.**

Price and consumption data provided for chemicals in the elution purification area is summarized in Table 3.8. Details on chemicals in the purification process are not included but the process mimics a commercial PUREX process using an organic solvent such as tributyl phosphate (TBP). Detailed process flows in chapter 4 will include the solvent extraction process as part of the cost analysis.

Table 3.8: Summary of Elution-Purification Raw Materials (Tamada, et al. 2006)

| **Items** | **Quantity** | **Unit Cost** | **Total Cost** | |
|---|---|---|---|---|
| | | | **million yen (2005)** | **thousands US$ (2010)*** |
| **0.01 M HCl** | 382.5 tons/yr | 19 yen/ kg | 7.27 | 74 |
| **0.1 M Nitric Acid** | 54 tons/yr | 55 yen/kg | 2.97 | 30 |
| **Ammonia** | 450 kg/yr | 85 yen/kg | 0.04 | 0.4 |
| ***Conversion to US Values from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. Chemicals costs were adjusted using the general CPI (Appendix B). Converted values for reference only.** | | | | |

The elution and purification process represents the smallest portion of the total annual production costs in the JAEA braid adsorbent cost analysis (~2%) (Tamada, et al. 2006) and scale primarily with the uranium production level as opposed to other process areas which depend on the braid adsorbent field size and production. However, the back end process provides opportunities to reduce production costs via production of co-products or, more directly, by efficient recovery of uranium without reducing the capacity of the adsorbent material to recover uranium in subsequent cycles. These impacts are considered in sensitivity analyses.

### 3.2.3 Summary of JAEA Cost Assessment

The JAEA estimate of annual costs resulted in a uranium production cost of approximately 87,700 yen (in 2005) per kg U extracted. Depending on the specific method of inflation and changes in exchange rate, the JAEA estimate reflects a production cost of between $900 to $1000 per kg U (2010 US$). The $1000 per kg U was used in the previous chapter to assess the viability of seawater extraction as a backstop technology.

## 3.3 ADDITIONAL ANALYSES

The cost estimates from JAEA were reproduced using the data and assumptions provided in their work; estimates were reproduced to within 1% in all process areas. The cost reproduction methodology is not discussed in detail here; for each process area, the cost and consumption data for individual equipment and raw materials given in the JAEA analysis were used directly to reproduce annualized costs by standard techniques such as amortization of capital costs. The primary purpose of the reproduction was to develop a cost model to connect JAEA component costs (e.g. at the individual equipment or chemical level) to the primary production parameters summarized in Table 3.1 and ultimately the uranium production cost. For example, the cost of chains is connected to the number of chains required to moor 100,000 tons of adsorbent and should scale as the field size changes.  By developing the underlying cost equations that determine the unit cost of uranium extracted (dollars or yen per kg U), the cost data provided by JAEA could be used to develop cash flow and sensitivity analyses.

### 3.3.1 Life Cycle Cash Flow Model

The estimates provided by JAEA are given on a single year basis – therefore, the production cost estimate of 87,700 yen per kilogram of uranium provided by JAEA does not include time value of money or account for the timing of cash flows or uranium production. In order to allow for analysis over time, a cash flow table was developed by treating the single-year cost estimates provided by the JAEA analysis as cash flows over time. Uranium production was also tracked over time to account for the "benefits" or production of the system with time. The important features of the cash flow analysis methodology are detailed here.

#### *Pre-Production Start-Up Period*

Prior to deploying adsorbent and recovering uranium, the initial adsorbent must be produced. The timing of this initial production is important in a cash flow analysis since all of the operating, maintenance and material costs for adsorbent production are incurred during this initial period when following a ton of adsorbent through its lifetime. In this cash flow analysis, the initial adsorbent production was assumed to take place 6 months prior to the initial deployment. Longer production lead times will lead to larger present values for adsorbent production costs. This value should be fixed based on real data about lead-times for adsorbent production start-up.

### *Normalizing to One Ton of Adsorbent*

To accurately derive production costs of the braid-system, the cash flow analysis was done on the basis of following one tonne of adsorbent through its lifetime. The costs (and benefits– uranium production) developed in the JAEA estimate were reduced to a single tonne of adsorbent basis and distributed as events over the lifetime of the adsorbent. This method avoids transient effects of a system-wide analysis of all of the adsorbent in the system, such as one-time expenses associated with new adsorbent start-up. A full field of adsorbent leads to unsteady cash flows that are difficult to model without real production field data.

To associate annual costs, such as those provided in the JAEA analysis with a tonne of adsorbent over its lifetime two steps are taken:

1) The annual costs in each area are divided by the total annual uranium production. This results in a unit annual cost for each area.
2) The uranium unit cost can be associated with a tonne of adsorbent and its life cycle via the adsorption capacity. Adsorption capacity is given in kg U per tonne of adsorbent and is associated with a period of one recycle or campaign (i.e. 60 days in the base case). By multiplying the unit production cost of each cost category by the capacity of a tonne of adsorbent, the annual costs have been converted to a cost per recycle of a ton of adsorbent.

The annual costs can be represented as a negative cash flow with each period being a recycle of adsorbent. The benefit of the adsorbent system is simply the production of uranium. In traditional cash flow analysis, the specific cash value of the uranium produced would be important. However, in this analysis, the goal is to derive a production cost (yen or dollar per kilogram of uranium), so the important value is the absolute amount of uranium produced over time, not a specific cash flow. Therefore, the uranium produced for each recycle of a tonne of adsorbent is directly derived from the adsorbent performance as specified in the system-wide parameters in Table 3.1; in the base case provided by JAEA, one tonne of adsorbent produces 2 kg of uranium for each recycle of the adsorbent.

***Discounting Costs and Benefits***

With costs and benefits in terms of recycles of adsorbent, they can be distributed over the lifetime of the adsorbent (over 6 recycles in the base case). The costs and uranium production are then discounted using a present value factor as follows:

$$\boldsymbol{NPPC} = {\textstyle\sum_{0}^{n}} (\boldsymbol{CF_n} * \boldsymbol{PVF}) \Big/ {\textstyle\sum_{0}^{n}} (\boldsymbol{U_n} * \boldsymbol{PVF}) \tag{3.3}$$

where

NPPC = Net Present Value of unit production cost ($/kg U)

$CF_n$ = Cash Flow in year n

$U_n$ = Uranium production in year n

PVF = Present Value Factor = $(\mathbf{1}+\boldsymbol{i})^{-\boldsymbol{n}}$

i = discount rate

n = time of cash flow in years.

Amortized equipment and building cash flows were not discounted using this method. The amortized cash flows already include the time value of money in the amortization process (interest rate of capital). Discounting the amortized cash flows would exaggerate the time value of money effect and deflate the capital costs. All other costs and the absolute uranium production were discounted using the process described above.

### *Base Case Verification*

When the discount rate for the cash flow analysis is set to 0%, the time value of money is no longer a factor in the analysis. Therefore, the production cost derived from the cash flow analysis should be equivalent to the production cost derived for the single year system-wide estimate as reported by JAEA. Table 3.9 shows the cash flow analysis for six recycles at 0%.

Table 3.9: Cash Flow Analysis for 6 Recycles at 0% Discount Rate – Verification of Methodology

| **Years** | **Cycles Completed** | **Cumulative Cost** | **Discounted Product** | **Production Costs** |
|---|---|---|---|---|
| # | # | Yen | kgU | yen/kgU |
| -0.50 | 0 | 699,000 | 0 | 0 |
| 0.00 | 0 | 780,000 | 0 | 0 |
| 0.17 | 1 | 833,000 | 2 | 417,000 |
| 0.33 | 2 | 888,000 | 4 | 222,000 |
| 0.50 | 3 | 943,000 | 6 | 157,000 |
| 0.67 | 4 | 997,000 | 8 | 125,000 |
| 0.83 | 5 | 1,052,000 | 10 | 105,000 |
| **1** | **6** | **1,053,000** | **12** | **87,700** |

The table shows six recycles of the adsorbent, the cumulative cost (includes all costs for adsorbent production, deployment, and desorption/purification), the cumulative uranium production for 1 tonne of adsorbent, and the production cost. As seen in the last row of the table, the production cost estimate for 6 recycles of 1 ton of adsorbent using a discount rate of 0% was 87,700 yen/kg of uranium providing verification of internal consistency between the original calculations based on JAEA estimate and the cash flow analysis method. Note that numbers in the table have been rounded so calculation of production cost from numbers in the table may not match perfectly.

### *The Impact of Cash Flow Analysis*

While Table 3.9 illustrates the general timing of cash flows, it does not fully illustrate the effect of time and recycles on the system. Figure 3.6 uses the same data that was used to develop Table 3.9 to illustrate the timing of the many component cash flows and uranium production during the lifetime of an adsorbent.

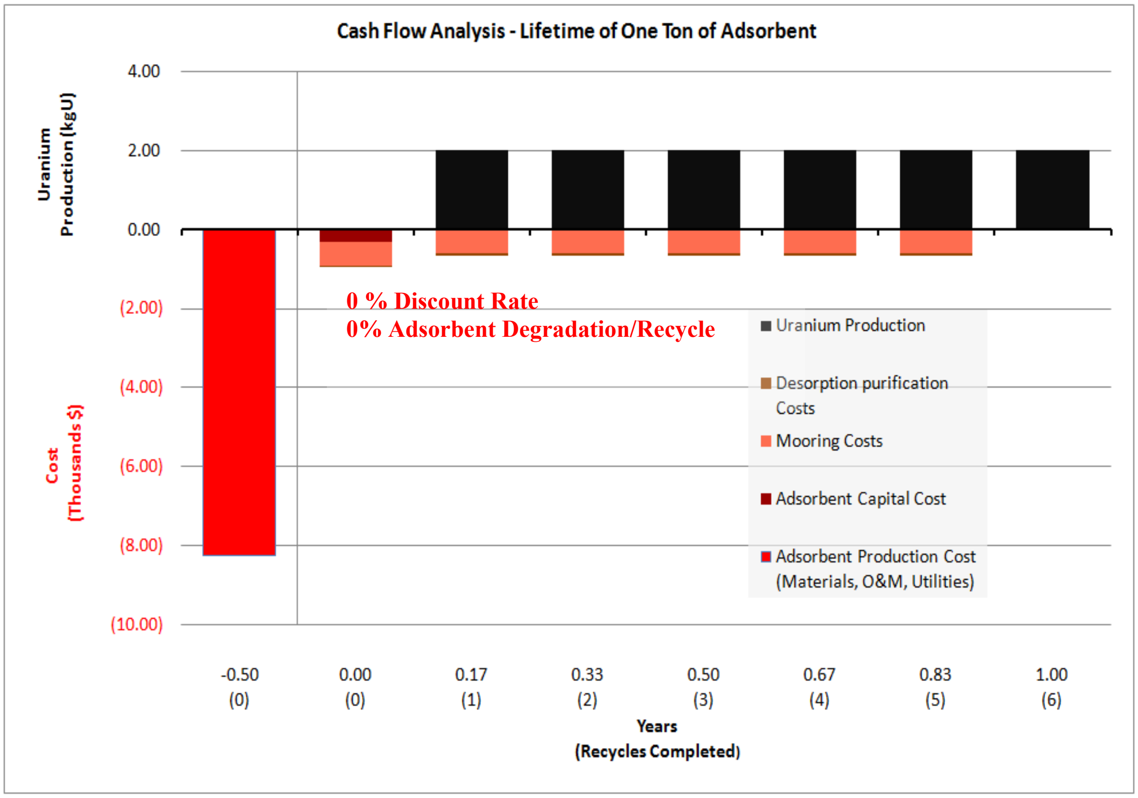


Figure 3.6: Cash Flow Diagram, 0% Discount Rate and Adsorbent Degradation Rate

The diagram illustrates the variation in timing of different events through the lifetime of the adsorbent; for example, the major cost for the system, adsorbent production, occurs 6 months before the adsorbent is deployed at time 0. The diagram also illustrates in the lag in timing between adsorbent mooring and production of uranium which occurs after the campaign as the adsorbent is ready to be moored again – this is most clearly illustrated at time 0 when mooring costs are incurred without associated uranium production until after recycle one is complete. The diagram was produced with a 0% discount rate and 0% degradation of the adsorbent performance with each recycle.

Figure 3.7 incorporates a 10% discount rate and 10% degradation in adsorbent capacity per recycle to illustrate the importance of considering production costs over time.

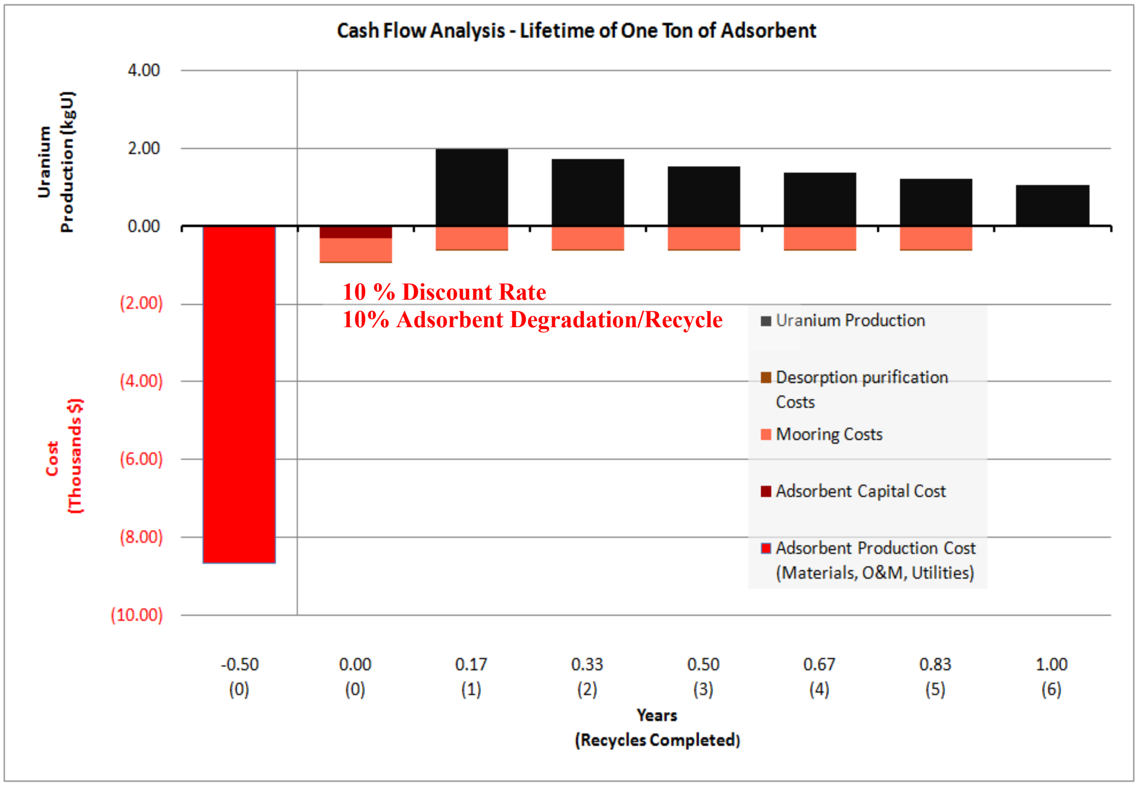


Figure 3.7: Cash Flow Diagram, 10% Discount Rate and Adsorbent Degradation Rate

The most obvious impact is on the uranium production, which declines over time due to both the time value of money and the degrading adsorbent performance as it is recycled. More subtly, the adsorbent production costs that occur before time 0 are inflated by the time value of money; this could be exacerbated by long lead times in adsorbent production.

These charts provide a basic illustration of the timing of cash flows and potential impact of the timing on production costs; the following section performs sensitivity analysis on a few of the variables that can impact the cash flows as discussed in the next section. The discounted cash flow methodology will be carried throughout the thesis.

### 3.4.1 Sensitivity Analysis

With the cash flow methodology in place, a sensitivity analysis was performed on several system parameters to identify the impact on production costs of the adsorbent system. The cash flow framework allows for the sensitivity analysis to account for the impact of system parameters on the timing of critical events such as uranium recovery as well as the size of the events. In addition to an analysis of the basic system parameters, such as those listed in Table 3.1, several new parameters were introduced into the cost model.

#### *Reduced Adsorbent Performance*

In addition to the time value of money, other factors can impact the production of uranium over time. One important factor added to the cash flow analysis was the adsorbent performance over time. The JAEA estimate does not include any degradation or loss in performance of the adsorbent after each recycle; however, in the system description by JAEA, experimental data was cited indicating as much as a 20% reduction in adsorbent performance after 5 reuses (Sugo, et al. 2001). In order to account for potential degradation, a variable was created indicating the remaining capacity of the adsorbent:

$$\boldsymbol{C_R} = \mathrm{C}_0 * (\mathbf{1} - \boldsymbol{L_R})^{\boldsymbol{R}} \tag{3.4}$$

where

$C_R$ = Remaining adsorbent capacity after recycle R

$C_0$ = Initial adsorbent capacity (2 kg U/ tonne of adsorbent in base case)

$L_R$ = Fractional Reduction in Adsorbent Performance for each recycle

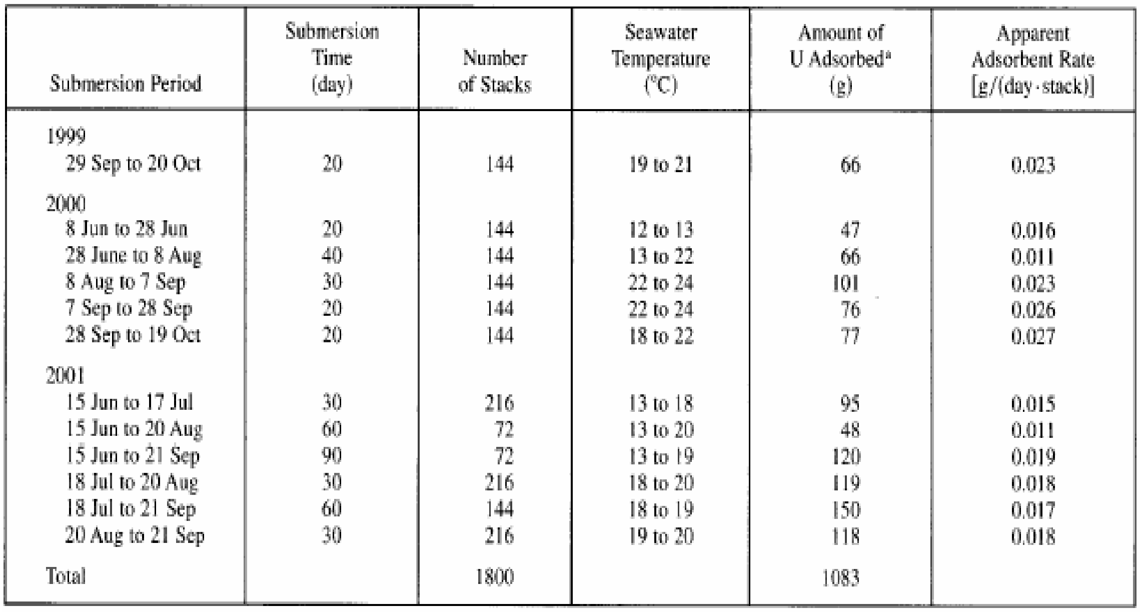
R = Number of recycles completed

This calculation accounts for continuous reduction in adsorbent performance and uranium production over the lifetime of the adsorbent

### *Impact of Time and Temperature*

The final parameters introduced into the model for sensitivity analysis were time of each campaign and the temperature of the ocean during the campaign. Table 3.10 shows field data reflecting the relationship of submersion time and temperature to the amount of uranium adsorbed.

Table 3.10: Field Data on Uranium Adsorption (Rao 2009)



| Submersion Period | Submersion Time (day) | Number of Stacks | Seawater Temperature (°C) | Amount of U Adsorbed[a] (g) | Apparent Adsorbent Rate [g/(day·stack)] |
|---|---|---|---|---|---|
| 1999 | | | | | |
| 29 Sep to 20 Oct | 20 | 144 | 19 to 21 | 66 | 0.023 |
| 2000 | | | | | |
| 8 Jun to 28 Jun | 20 | 144 | 12 to 13 | 47 | 0.016 |
| 28 June to 8 Aug | 40 | 144 | 13 to 22 | 66 | 0.011 |
| 8 Aug to 7 Sep | 30 | 144 | 22 to 24 | 101 | 0.023 |
| 7 Sep to 28 Sep | 20 | 144 | 22 to 24 | 76 | 0.026 |
| 28 Sep to 19 Oct | 20 | 144 | 18 to 22 | 77 | 0.027 |
| 2001 | | | | | |
| 15 Jun to 17 Jul | 30 | 216 | 13 to 18 | 95 | 0.015 |
| 15 Jun to 20 Aug | 60 | 72 | 13 to 20 | 48 | 0.011 |
| 15 Jun to 21 Sep | 90 | 72 | 13 to 19 | 120 | 0.019 |
| 18 Jul to 20 Aug | 30 | 216 | 18 to 20 | 119 | 0.018 |
| 18 Jul to 21 Sep | 60 | 144 | 18 to 19 | 150 | 0.017 |
| 20 Aug to 21 Sep | 30 | 216 | 19 to 20 | 118 | 0.018 |
| Total | | 1800 | | 1083 | |

This limited field data was used to develop a regression model of the relationship between uranium adsorbed and the time and temperature of the mooring. The results of the regression are shown in Figure 3.8 and equation 3.5.

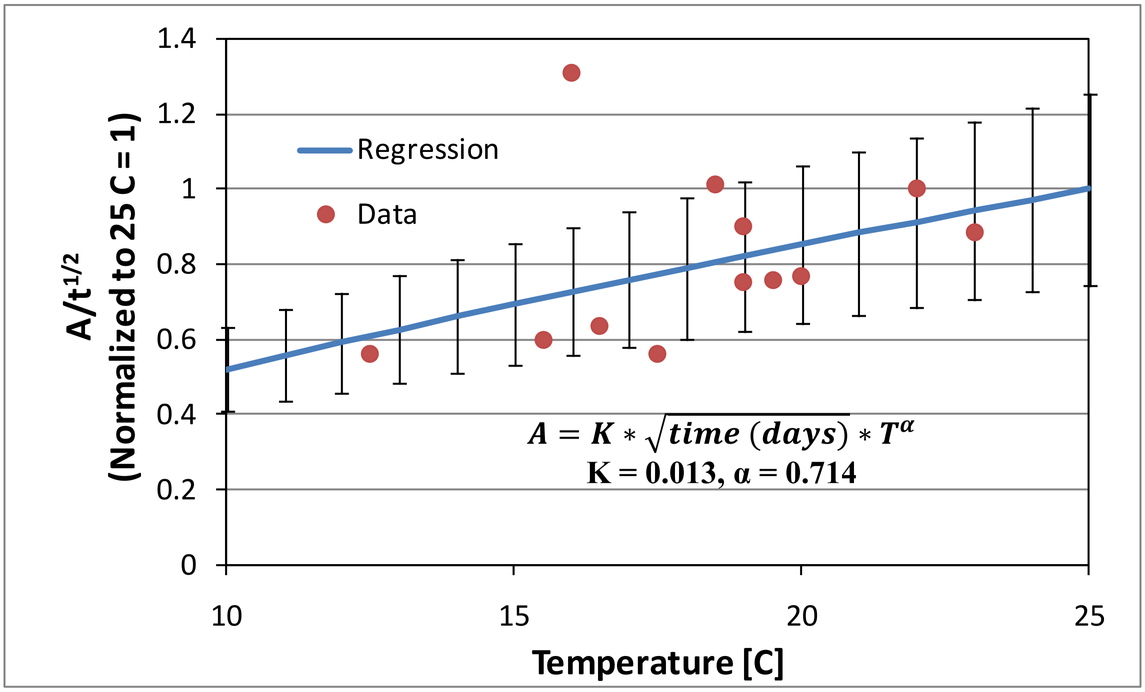


Figure 3.8: Time and Temperature Dependence of Adsorption (Schneider and Sachde, Cost and Uncertainty Analysis of an Adsorbent Braid System for Uranium Recovery from Seawater 2011)

$$A = \mathrm{K}\sqrt{\mathrm{t}}\,\mathrm{T}^{\alpha} \tag{3.5}$$

where

A = amount of uranium adsorbed (kg U/t ads)

t = immersion time (days)

T = water temperature (C)

K, α = regression coefficients (inherited units)

The figure is normalized to a value of 1 at 25°C, the reference temperature of the design and cost model. The regression parameters from the model are provided in Table 3.11. The standard error of the fit parameters will be considered during subsequent uncertainty analysis in chapter 4 (See section 4.7.2 for s discussion of error propagation from regression models).

Table 3.11: Regression parameters for time and temperature dependence of adsorption (Schneider and Sachde, Cost and Uncertainty Analysis of an Adsorbent Braid System for Uranium Recovery from Seawater 2011)

| **Parameter** | **Value** | **Standard Error** | **T statistic** |
|---|---|---|---|
| ln(K) | -4.348 | 1.306 | -3.328 |
| α | 0.714 | 0.451 | 1.583 |

The regression results also depict the basic empirical equation relating uranium adsorbed to time and temperature. The square root of time relationship with adsorption is consistent with diffusion limited physical processes; the temperature regression is strictly an empirical relationship based on best fit of the data.

***Results***

The results of sensitivity analyses on the key parameters discussed thus far are summarized in Table 3.12.

Table 3.12: Summary of Sensitivity Analyses: Change from Base Production Cost

| | **Base Case Conditions** | Test Point 1 | *% Change* | Test Point 2 | *%Change* |
|---|---|---|---|---|---|
| Discount Rate (%) | **0%** | 5% | *4%* | 10% | *8%* |
| Interest Rate of Capital | **3%** | 5% | *3%* | 10% | *10%* |
| Recycles | **6** | 10 | *-28%* | 20 | *-48%* |
| Seawater Temperature | **25 C** | 20 C | *17%* | 30 C | *-12%* |
| Adsorbent Performance Loss (%/Recycle) | **0%** | 5% | *13%* | 10% | *28%* |
| Adsorption Capacity (g-U/kg-ads) | **2** | 4 | *-50%* | 6 | *-67%* |

**Change in Production Costs is relative to base case defined in the "Base Case Condition" column (87,700 yen/kg U); these conditions are consistent with the analysis in Tamada et al. 2006

The first column in the table shows the base case conditions that were used by JAEA to arrive at the 87,700 yen/kgU cost estimate. The subsequent columns show the modified parameters and corresponding percentage change of the uranium production cost. The results show that the major cost drivers for braid adsorbent system center on the adsorbent performance; this includes the kinetics and thermodynamics of the adsorption process (represented by temperature and capacity), the reuse of the adsorbent after a large initial investment, the degradation of the adsorbent over time. The financial parameters are not insignificant; the 10% interest rate for the high test point reflects a realistic private capital investment and would increase production costs by 8%. In addition, parameters were analyzed for 6 recycles over one year. If the adsorbent lifetime is stretched over time, the impact of discount rate will be more important.

To present an optimistic cost estimate for the current seawater extraction technology, the recycles were increased from 6 to 20, the performance loss maintained at 0%, and the adsorption capacity increased to 6 g U / kg adsorbent. The result of this change was a uranium production cost of about $180 / kg U or more than 80% reduction in production costs versus the base case.

Using this new cost estimate and the curves in Figures 2.5 and 2.6, a quick assessment of the viability of uranium extraction as a backstop technology can be made. Table 3.13 summarizes this assessment.

Table 3.13: Optimistic Seawater Extraction Estimate – Viability under Aggregate Demand Scenarios

| | **2035 Demand Scenario** | **2100 Demand Scenario** |
|---|---|---|
| **With Undiscovered Resources** | No | Yes |
| **Without Undiscovered Resources** | No | Yes |

In this case, the extraction technology appears to serve as a long-term backstop technology (by year 2100) in both resource estimate cases, but is still too costly to be a near term backstop for demand as predicted by the NEA through 2035.

Additional sensitivity studies using the same methodology and many of the same parameters discussed in this chapter will be conducted following the development of an independent cost assessment in Chapter 4.

# Chapter 4: Cost Assessment Methodology

The previous chapter utilized high level system parameters as given by JAERI for the braid adsorbent technology; the resulting sensitivity analyses provided insight regarding key system cost drivers. The basic process flow and production capacity will continue to be taken directly from the JAERI estimates to ensure a common basis. However, previous work did not extend to development of original estimates of underlying capital and operating costs and key performance and sizing variables within the process areas.

In this section, detailed, independent cost estimates will be developed for the braid adsorbent system. The goals of the independent assessment include:

- further validation of the Japanese cost estimates,
- development of cost estimates (and associated uncertainties) relevant and specific to the United States,
- transparency in methods and assumptions,
- evaluation of process input sensitivities and uncertainties to guide R&D decisions.

## 4.1 DEFINING THE SCOPE AND DATA REQUIREMENTS: CODE OF ACCOUNTS

The first step in developing an independent cost estimate is to define the scope of the assessment, beginning with the specific costs pertinent to the unit production cost of uranium. The Economic Modeling Working Group (EMWG) of the Generation IV International Forum (GIF) produced detailed cost estimation guidelines for nuclear fuel cycle facilities that will provide the framework for the subsequent analysis; specifically, the guidelines provide a code of accounts (COA) that define relevant cost categories and provide organizational structure for cost estimation (EMWG-GIF 2007). Table 4.1

depicts a generic COA adapted from the EMWG framework that will be used for capital cost estimation for this analysis. Table 4.2 reflects the COA for annualized operating and maintenance costs (O&M) and financial costs.

Table 4.1: Modified COA for Capital Cost Estimation (EMWG-GIF 2007)

| EMWG Acct # | Account Title | Description |
|---|---|---|
| **1** | **Capitalized Pre-construction Costs (Subtotal)** | |
| **10 series** | | |
| **11** | **Land and land rights** | **Purchase of new land including land rights** |
| **12** | **Site permits** | **Site related permits required for construction of the permanent plant** |
| **13** | **Plant licensing** | **Plant licenses for construction and operation** |
| **14** | **Plant permits** | **Permits for operating and construction** |
| **15** | **Plant studies** | **Studies for site or plant in support of construction or operation** |
| **16** | **Plant reports** | **Production of major reports such as environmental impact statement or safety analysis** |
| **17** | **Other Pre-Construction Costs** | **Incurred by owner prior to construction such as public awareness, remediation, etc.** |
| **18** | **Reserved for other activity as needed** | |
| **19** | **Contingency on Pre-Construction Costs** | **Additional cost to achieve desired confidence to prevent pre-construction cost over-run** |
| **2** | **Capitalized Direct Costs (Subtotal)** | |
| **20 series** | | |
| **21** | **Structures and Improvements** | **Civil work and structures, primarily buildings** |
| **22** | **N/A** | |
| **23** | **Process Equipment** | **All process equipment and systems associated with plant output** |

Table 4.1 (continued)

| | | |
|---|---|---|
| 24 | **Electrical equipment** | **All equipment required for electric service to plant and process equipment** |
| 25 | **Heat Rejection System** | **Includes equipment such as water pumps, recirculation pumps, valves, cooling towers, etc.** |
| 26 | **Miscellaneous plant equipment** | **Any equipment not covered above** |
| 27 | **Special materials** | **Materials needed prior to start-up** |
| 28 | **N/A** | |
| 29 | **Contingency on Direct Costs** | **Additional cost to achieve desired confidence to prevent direct cost over-run** |
| **Sum 1-2** | **TOTAL DIRECT COST** | |
| | | |
| **3** | **Capitalized Indirect Services (Subtotal)** | |
| **30 series** | | |
| 31 | **Field indirect costs** | **Includes construction equipment, temp. buildings, tools, supplies, other support services** |
| 32 | **Construction supervision** | **Direct supervision of construction activities** |
| 33 | **Commissioning and Start-Up Costs** | **Includes start-up procedure development, trial test run services, and commissioning of materials, etc.** |
| 34 | **Demonstration Test Run** | **All services required for demonstration run including labor, consumables, spares, and supplies** |
| **Sum 1 - 34** | **TOTAL FIELD COST** | |
| 35 | **Design Services Offsite** | **Engineering, design, and layout work conducted at offsite office (vendor or architects/engineers)** |
| 36 | **PM/CM Services Offsite** | **Project management and support occurring offsite** |
| 37 | **Design Services Onsite** | **Same as 35 except on-site at plant** |
| 38 | **PM/CM Services Onsite** | **Same as 36 except on-site at plant** |

Table 4.1 (continued)

| | | |
|---|---|---|
| 39 | Contingency on Indirect Services | Additional cost to achieve desired confidence to prevent indirect services cost over-run |
| Sum 1-3 | BASE CONSTRUCTION COST | |
| 4 | Capitalized Owner's costs (Subtotal) | |
| 40 series | | |
| 41 | Staff recruitment and training | Recruit and train operators before plant start-up |
| 42 | Staff housing facilities | Relocation costs, camps, or permanent housing for O&M staff |
| 43 | Staff salary-related costs | Taxes, insurance, benefits, fringes, etc; other salary-related costs |
| 44 | Reserved | |
| 45 | Reserved | |
| 46 | Other Owners' capital investment costs | |
| 47 | Reserved | |
| 48 | Reserved | |
| 49 | Contingency on Owner's Costs | Additional cost to achieve desired confidence to prevent owner's cost over-run |
| 5 | Capitalized Supplementary Costs (subtotal) | |
| 50 series | | |
| 51 | Shipping & transportation costs | Shipping and transportation for major equipment or bulk shipments with freight forwarding |
| 52 | Spare parts and supplies | Spare parts furnished by system suppliers for first year of operation |
| 53 | Taxes | Taxes associated with the permanent plant, such as property tax - capitalized with the plant |
| 54 | Insurance | Insurance associated with the permanent plant, such as property tax - capitalized with the plant |
| 55 | N/A | |
| 56 | Reserved | |

Table 4.1 (continued)

| | | |
|---|---|---|
| **57** | **Reserved** | |
| **58** | **Decommissioning Costs** | **Decommission, decontaminate, and dismantle plant at end of commercial operation** |
| **59** | **Contingency on supplementary costs** | **Additional cost to achieve desired confidence to prevent supplementary cost over-run** |
| **Sum 1-5** | **OVERNIGHT CONSTRUCTION COST** | |
| **6** | **Capitalized Financial Costs (subtotal)** | |
| **60 series** | | |
| **61** | **Escalation** | **Typically excluded for fixed year, constant dollar analysis** |
| **62** | **Fees/Royalties** | **Fees or royalties to be capitalized with the plant** |
| **63** | **Interest during construction** | **Applies to all costs incurred before commercial operation and assumed to be financed by loan.** |
| **64** | | |
| **65** | | |
| **66** | | |
| **67** | | |
| **68** | | |
| **69** | **Contingency on financial costs** | **Additional cost to achieve desired confidence to prevent financial cost over-run (including scheduling issues)** |
| **Sum 1-6** | **TOTAL CAPITAL INVESTMENT COST** | |

Table 4.2: Modified COA for Annualized O&M and Financial Cost Estimation (EMWG-GIF 2007)

| EMWG Acct # | Account Title | Description |
|---|---|---|
| **7** | **Annualized O&M Cost (subtotal)** | |
| **70 series** | | |
| **71** | **Operations Staff** | **Salary Costs of operations staff** |
| **72** | **Management Staff** | **Salary Costs of operations management staff and clerical staff** |
| **73** | **Salary-Related Costs** | **Taxes, insurance, benefits, fringes, etc; (included in 71 and 72 above)** |
| **74** | **Raw Materials** | **Process chemicals as identified in process flow diagrams.** |
| **75** | **Spare Parts** | **Any operational spare parts - excludes capital plant upgrades or major equipment that is capitalized or amortized** |
| **76** | **Utilities, Supplies and Consumables** | **Water, gas ,electricity, tools, non-process chemicals, maintenance equipment and labor, office supplies, etc. purchased annually** |
| **77** | **Capital Plant Upgrades** | **Upgrades to maintain or improve plant capacity, meet regulations or extend plant life** |
| **78** | **Taxes and Insurance** | **Property taxes and insurance costs, excluding salary-related** |
| **79** | **Contingency on O&M Cost** | **Additional cost to achieve desired confidence to prevent annualized O&M cost over-run** |
| **9** | **Annualized Financial Costs (subtotal)** | |
| **90 series** | | |
| **91** | **Escalation** | **Typically excluded** |
| **92** | **Fees** | **Annual fees such as licensed process, operating license fees, etc.** |
| **93** | **Cost of Money** | **Value of money used for operations - financed or retained earnings** |
| **94** | | |
| **95** | | |
| **96** | | |
| **97** | | |

Table 4.2 (continued)

| | | |
|---|---|---|
| **98** | | |
| **99** | **Contingency on Financial Costs** | |

The categories in the table have been modified from the EMWG COA to tailor the accounting system to the braid adsorbent project (e.g. exclusion of nuclear reactor and electricity production accounts). Note that some categories appear in the capital cost accounts (1-6) and the O&M and financial accounts (7,9); for example, taxes or insurance are duplicated because the costs may either be treated as an upfront cost capitalized with the plant cost or as an annual expenditure during the operating lifetime of the project.

The code of accounts provides detailed guidelines for costs that should be considered when developing the figure of merit for this project. In many cases, the two-digit categories in the table may be estimated in aggregate within the one-digit heading category when detailed data is not available. One goal of this assessment is to ensure the one-digit categories of the COA (at minimum) have been estimated and the methodology for the estimation is transparent and reproducible. Where further detail is available, the two-digit accounts will be populated and the sources and methods will be described.

### 4.2 SELECTION OF APPROPRIATE COST ESTIMATION TECHNIQUES

To populate the code of accounts, a method of cost estimation for the project must be developed based on the level of information available regarding the process, equipment, and associated costs. The EMWG guidelines broadly define two categories of estimation: bottom-up and top-down.

### 4.2.1 Bottom-Up Assessment

Bottom-up estimates are developed for projects that are approaching the construction phase. The estimates are developed from detailed project plans, equipment designs, plant layouts, stream flows, piping and instrumentation diagrams (PI&D), structural materials inventories, and electrical equipment requirements. The level of detail should sufficient to populate the COA to the three- and four-digit levels (see EMWG guidelines for details on accounts beyond the two-digit level discussed in this work) (EMWG-GIF 2007). In some cases, if detailed estimates and design for a nearly identical plant or system have been developed, the bottom-up method can be implemented for a new project early in its development (well before the construction phase) by leveraging the older project data. This is particularly applicable for a modular design or plant.

### 4.2.2 Top-Down Assessment

Top-down estimates are appropriate for projects where detailed design of the equipment and process have not been completed; these projects are typically in an early stage of development (EMWG-GIF 2007). The cost estimates will be based on a reference design of similar, though not necessarily identical, previously constructed facilities and/or equipment; standardized cost-scaling techniques are implemented based on the capacity of the reference design versus the capacity of the project under assessment.[3]

In addition, many of the costs in the COA not related to equipment (such as land or indirect costs) can be estimated by standard methods using the cost of the purchased equipment for the process. The top-down approach is more flexible (i.e. costs can be scaled for the entire process or single items of equipment, operating costs, etc. based on

---

[3] See the following references for detailed discussion and data for cost-scaling methods: Peters, Timmerhaus and West 2003; Remer, et al. 2008. Techniques will be discussed later in this chapter as well.

level of data available) and appropriate for technology in early stages of development. However, scaling relationships introduce a higher degree of uncertainty to the estimates and contingency costs must rise accordingly to cover the uncertainty.

### 4.2.3 Estimation Technique Used in this Assessment

The estimates developed in this assessment will use a combination of top-down and bottom-up methods based on the level of detail provided by the previous work conducted by JAERI. The cost estimate in this analysis will conform to the Japanese plant design and process exactly; therefore, despite the fact that the braid adsorbent process is still in early development, bottom-up assessment is possible where JAERI has provided detailed design information (e.g. specific chemical stream flows, specific equipment sizing, specific building or land requirements, etc.). This detailed information will be verified independently as part of the cost estimation process in this chapter. However, the JAERI assessment was an overview of key cost components and therefore did not include documentation in the form of detailed equipment design, process flow diagrams, P&IDs, project plans, or plant layouts; top-down assessment will be used to supplement the available information.

## 4.3 GENERAL COST ESTIMATION PROCEDURE

Several cost estimation techniques will be used in tandem with specific data provided in the Japanese assessment to populate the COA described in Table 4.1. The techniques will be covered generically in this section and will be adapted to specific process areas as needed. Table 4.3 below provides an overview of the techniques that will be used to populate each of the single-digit accounts in the COA. Note that the specific techniques for Interest during Construction (Acct 63) calculations are discussed in detail in Appendix C.

Table 4.3: Overview of Cost Estimation Techniques used to Populate Code of Accounts

| Account | Category | Estimation Technique | Location |
|---|---|---|---|
| 1 | Capitalized Pre-Construction Cost | Fixed Capital Investment Technique | This Chapter |
| 2 | Capitalized Direct Cost | | |
| 3 | Capitalized Indirect Services Cost | | |
| 4 | Capitalized Owner's Cost | Labor Estimation Technique | This Chapter |
| 5 | Capitalized Supplementary Cost | Fixed Capital Investment Technique<br>Decommissioning Not Covered | This Chapter |
| 6 | Capitalized Financial Cost | 62: Fixed Capital Investment | This Chapter |
| | | 63: IDC Estimation | Appendix C |
| 7 | Annualized O&M Cost | Labor Estimation Technique<br>Utility and Chemicals Estimation<br>Fixed Capital Investment Technique | This Chapter |
| 9 | Annualized Financial Cost | N/A | N/A |

Fixed capital investment, labor estimation, and utility and chemical cost estimation will be discussed in the subsequent sections.

### 4.3.1 Capital Cost Estimation: Fixed Capital Investment (COA 1 to 5)

In order to standardize cost and uncertainty assessment methods, the chemical process industry has defined five classifications of capital cost assessment including the data requirements, preparation effort/cost, and expected accuracy of the estimates. These techniques will be applicable to accounts 1 through 6 in the COA shown previously in Table 4.1. Table 4.4 below summarizes the techniques and data requirements.

Table 4.4: Capital Cost Estimation Techniques (Peters, Timmerhaus and West 2003) and (Turton, et al. 2009)

| | **Data Required** | **Accuracy of Estimate (+/-)** | **Applicable to this Work?** |
|---|---|---|---|
| **Order of Magnitude** | Cost information for a complete process taken from previously built plants. Adjusted via scaling laws and inflation indices. Basic block flow diagram (BFD) is sufficient. | >30% | Yes |
| **Study** | Utilizes a list of major equipment in the process with approximate sizes and costs.. Equipment costs are factored to estimate total capital cost. Requires detailed process flow diagram (PFD). | 30% | Yes |
| **Preliminary Design** | Requires more rigorous sizing of equipment and approximate layout; Estimates of piping, instrumentation, and electrical requirements. Utilities estimated. PFD plus equipment sketches, plot plan, and elevation diagrams. Used for budgeting. | 20% | No |
| **Definitive** | Requires preliminary specifications for ALL equipment, utilities, instrumentation, electrical, and off-sites. Final PFD, equipment sketches, plot plan, elevation diagrams, utility balances and a preliminary P&ID. | 10% | No |
| **Detailed** | Complete engineering of the process, all off-sites, and utilities. Vendor quotes for most expensive items. Next step is construction phase. All diagrams in final version for construction. | 5% | No |

As seen in the table, the capital cost estimation in this work will largely be a combination of order of magnitude and study level estimation and should be interpreted with the associated range of uncertainty in the estimates. In addition, uncertainty around input parameters will be propagated through the cost estimation to provide a confidence interval around the figure of merit; uncertainty propagation is discussed in detail at the end of this chapter.

This analysis will rely on cost-scaling estimates based on the equipment lists and required capacity from the JAERI estimates; where possible, vendor quotes are obtained to provide specific equipment cost points. Sizing and costing assume the JAERI base case, 100,000 tonnes of annual adsorbent production and 1200 tonnes of uranium produced. Well-established relationships are applied to scale equipment costs if data is available only for non-base case capacities.[4]. Process and equipment cost scaling will also be employed when the overall uranium production capacity is to be varied. In both cases, the following general cost scaling law is used:

$$\boldsymbol{C_2 = C_1 * \left(\frac{I_2}{I_1}\right) * \left(\frac{S_2}{S_1}\right)^{x}} \tag{4.1}$$

where

$C_2$ = Cost of current design or estimate, U.S. dollars

$C_1$ = Cost of the reference design, U.S. dollars

$I_2$ = Engineering Cost Index at current time (Cost Indices discussed below)

$I_1$ = Engineering Cost Index at reference design time (discussed below)

$S_2$ = Capacity/size of current design (characteristic dimension of equipment)

---

[4] As discussed in previous chapters, 100,000 tonnes of adsorbent must be produced to recover 1200 tonnes of uranium when the adsorbent has a capacity of 2 grams of U per kg of adsorbent, a lifetime of six reuses, and six recovery campaigns are performed in one year (all adsorbent replaced in one year).

$S_1$ = Capacity/size of reference design (characteristic dimension of equipment)

x = Scaling exponent

For each piece of equipment, a cost scaling exponent x will be identified, from literature specific to the item when possible. In cases where detailed references are not available or sizing is not possible at the equipment level, the scaling relationship in equation 4.1 will be applied to the entire process area. In the absence of scaling exponents and relationships in the literature, the “two-thirds” scaling rule will be applied (an exponent of 0.67 will be used in equation 4.1); the 0.67 value represents an average across all types of chemical plants (Remer and Chai 1993a). Use of the rule to depict economies of scale effects is considered more accurate when applied to an entire process area due to average effects of scaling of all equipment taken together (Turton, et al. 2009).

Two engineering cost indices will be used in this analysis: the Marshall and Swift Equipment Cost Index (M&S) for individual equipment cost scaling and the Chemical Engineering Plant Cost Index (CEPCI) for plant or process-wide scaling. Table B.4.1 in Appendix B is a reference for these indices.

The purchased equipment cost derived from equation 4.1 is a component of the fixed capital investment (FCI) categories in the COA (Accts 1 to 5). The method used here for FCI estimation is is based on delivered equipment cost and described in Peters, Timmerhaus and West (2003). Purchased equipment prices estimated by the scaling methods described above are typically free on board (f.o.b) meaning the purchaser is responsible for freight; to estimate the delivered cost of equipment, 10% of the equipment cost will be added as delivery costs, as recommended in (Peters, Timmerhaus and West 2003). Based on this delivered equipment cost, the FCI can be estimated as follows:

$$\boldsymbol{C_n} = \boldsymbol{E} * \sum(\mathbf{1} + \boldsymbol{f_1} + \boldsymbol{f_2} + \cdots + \boldsymbol{f_n}) \tag{4.2}$$

where

$C_n$ = Fixed Capital Investment

E = Delivered Equipment Cost (1.1 * Purchased Equipment Cost)

$f_1$, $f_2$, ... , fn = multiplying factors for various direct and indirect capital costs

The factors for equation 4.2 are given in Table 4.5 below are again based on industry-wide average values for chemical plants (Peters, Timmerhaus and West 2003):

Table 4.5: Factors for estimating fixed capital investment from delivered equipment cost (Peters, Timmerhaus and West 2003); Grass roots adjustment from (Turton, et al. 2009)

| | **% of Delivered Equipment cost (E)** | **Notes** |
|---|---|---|
| **Direct Costs (DC)** | | |
| Purchased Equipment delivered (E) | 100% | |
| Purchased Equipment installation | 39% | |
| Instrumentation and Controls (Installed) | 26% | |
| Piping (Installed) | 31% | |
| Electrical systems (Installed) | 10% | |
| Buildings (including Services) | 29% | JAERI provided detailed information on buildings that will be used in place of this estimation. |
| Yard Improvements | 12% | This value does not include the cost of the land |
| Service Facilities (Installed) | 55% | |
| **Total Direct Plant Cost** | 302% | |
| **Indirect Costs (IC)** | | |
| Engineering and Supervision | 32% | |
| Construction Expenses | 34% | |
| Legal Expenses | 4% | |
| Contractor's Fee | 19% | |
| Contingency | 37% | Contingency will be 10% of each 1-digit COA in this analysis |
| **Total Indirect Plant Cost** | 126% | |
| **Grass Roots Adjustment (GR)** | | |
| Auxiliary Facilities | 50% | Accounts for additional costs to bring facilities services to a new location |
| **Fixed Capital Investment (DC+IC+GR)** | **478%** | |

### 4.3.2 Annualized O&M Cost Estimation

***Operations and Management Staff (COA 71, 72, AND 73)***

Labor cost calculations require techniques to estimate the man-hours required to operate the process as well as the appropriate wage for the industry, skill level, and location of the process. Ideally, a detailed design could be used with historical knowledge or a reference design to precisely predict staffing requirements; however, at this early stage, labor estimations will be driven by the major equipment in each process area. The technique used in this estimation was developed from a correlation of historical labor requirements for United States chemical companies and applied generically to chemical process plants (Wessell 1952). The correlation, which remains in wide use today, yielded the following empirical relationship:

$$\boldsymbol{O_{WH}} = \boldsymbol{t} * \left[\frac{\boldsymbol{N_P}}{\boldsymbol{C_D}^{0.76}}\right] \tag{4.3 a}$$

where

$O_{WH}$ = Operating work hours per ton of product

t = 23 for batch operations with a maximum of labor

t = 17 for operations with average labor requirements

t = 10 for well-instrumented continuous process operations

$N_{np}$ = Number of major process steps

$C_D$ = Plant capacity, tons/day

The number of operators is then estimated from the man-hours requirement:

$$N_{OL} = \frac{O_{WH}}{H_W} * C_Y \qquad (4.3\ b)$$

where

$N_{OL}$= Number of operators required

$H_W$ = Hours worked by single operator (1960 hours per year) [5]

$C_Y$ = Plant capacity, tons/year

The method requires judgment about the complexity of the process and what constitutes a major process step. In this analysis, batch and adsorbent handling processes (such as the elution process) will use the labor-intensive t-value of 23. All other processes will use the t value of 17, which corresponds to average labor intensity. Major process steps are defined as those that include unit operation such as separations equipment or a reactor; storage tanks, pumps, and material handling equipment are not considered a major process steps. The method provides an estimate without detailed equipment specifications; however, labor estimates should be revised based on the final system design following the detailed design phase and/or pilot scale deployment.

The average wage rate for operators is obtained from the United States Bureau of Labor Statistics (BLS). The rates used in this analysis are summarized in Table 4.6.

---

[5] Assumes a single operator works an average of 49 weeks a year (3 weeks time off) and five 8-hour shifts a week for a total of 245 shifts a year per operator. If the plant operates nominally for 24 hours a day, three shifts are required per day. For 365 days a year, this means 1095 operating shifts must be covered. Given that one operator can cover 245 shifts, approximately 4.5 operators (1095 shifts / 245 shifts per operator) are hired to provide one operator worth of manpower for a year. (Turton, et al. 2009).

Table 4.6: National average wage rates for selected occupations, 2010 U.S $ (United States Department of Labor 2011)

| Occupation Code | Occupation Title | Mean Hourly | Mean Annual |
|---|---|---|---|
| 51-8091 | Chemical Plant and System Operators | $26.30 | $54,700 |
| | *with Benefits* | $39.85 | $82,879 |
| 53-5011 | Sailors and Marine Oilers | $18.28 | $38,030 |
| | *with Benefits* | $28.12 | $58,508 |
| 53-5021 | Captains, Mates, and Pilots of Water Vessels | $33.89 | $70,500 |
| | *with Benefits* | $52.14 | $108,462 |

The wage rates used in labor cost estimation will include benefits to reflect the true cost to employers. The last two rows in Table 4.6 apply specifically to the mooring and deployment operations; other staff will be treated as chemical plant operators. The final labor cost estimate from this method is estimated as follows:

$$\boldsymbol{C_{OL} = N_{OL} * W} \tag{4.4}$$

where

$C_{OL}$ = Annual Cost of Operating Labor, 2010 U.S. $

W = Annual Wage rate for operator (including benefits), 2010 U.S. $

The methods presented thus far account only for operating labor for day to day operations of the respective process facilities; additional labor costs are incurred due to supervisory and clerical labor directly associated with operations (this includes administrative, engineering and support personnel). The additional labor costs are commonly estimated as a fraction of the operating labor costs, ranging from 10 to 25%

(Turton, et al. 2009). For this analysis, supervisory and clerical labor will be estimated as 18% of the operating labor costs. The cost of management staff for a process can be finally summarized as:

$$\boldsymbol{C_{ML}} = \boldsymbol{f_{labor}} * \boldsymbol{C_{OL}} \tag{4.5}$$

where

$f_{labor}$ = Fraction of operating labor costs, 0.18 (range 0.1 to 0.25)

$C_{ML}$ = Cost of Management Labor, 2010 U.S. $

$C_{OL}$ = Cost of Operating Labor, 2010 U.S. $

The cost for maintenance labor will be included in another operating cost category since the estimation method for maintenance and repair costs aggregates labor costs with the materials required for maintenance and repair. This is addressed in the following section.

***Raw Materials (COA 74)***

Raw materials or process chemicals costs are derived from the mass balance of chemicals used in each process and the price of each chemical. The chemical usage and costs will be summarized for each process area in the analysis in the subsequent sections.

***Utilities, Supplies and Consumables (COA 76)***

Utility costs are obtained in much the same manner as the raw material costs; the energy balance from the process flow for each area will provide most utility requirements (including the type of utility required); the mass balance will provide any process water requirements for each section. The standard price used for each type of utility in this analysis is given in Table 4.7. All values are inflation adjusted using the Consumer Price Index, which can be found in Tables B.4.2 and B.4.3 in Appendix B.

Table 4.7: Utility Prices in 2010 U.S. dollars; assume utilities are provided from outside source (not produced on-site).

| Utility | Cost (2010 US$) | Source | Cost | Base Year |
|---|---|---|---|---|
| Electricity (\$/kWh)[a] | 0.069 | U.S. EIA 2010 | | |
| Cooling Water (\$/1000 $m^3$) | 16.01 | Turton, et al. 2009 | 14.8 | 2006 |
| *High Purity Water (\$/1000 kg):* | | | | |
| Process Water | 0.072 | Turton, et al. 2009 | 0.067 | 2006 |
| Boiler Water (@ 115 °C) | 2.65 | Turton, et al. 2009 | 2.45 | 2006 |
| Potable Water | 0.28 | Turton, et al. 2009 | 0.26 | 2006 |
| Deionized Water | 1.08 | Turton, et al. 2009 | 1 | 2006 |
| *Steam (\$/1000 kg):* | | | | |
| Low Pressure - 5 barg, 160°C | 31.68 | Turton, et al. 2009 | 29.29 | 2006 |
| Medium Pressure - 10 barg, 184°C | 32.01 | Turton, et al. 2009 | 29.59 | 2006 |
| High Pressure - 41 barg, 254°C | 32.42 | Turton, et al. 2009 | 29.97 | 2006 |
| *Wastewater Treatment (\$/1000 $m^3$):* | | | | |
| Primary (filtration) | 44.35 | Turton, et al. 2009 | 41 | 2006 |
| Secondary (filtration + activated sludge) | 57.33 | Turton, et al. 2009 | 53 | 2006 |
| Tertiary (filtration, activated sludge, chemical treatment) | 60.57 | Turton, et al. 2009 | 56 | 2006 |
| *#2 Fuel Oil: (\$/gallon)* | | | | |
| New York Harbor #2 Heating Oil, Spot Price[b] | 2.12 | U.S. EIA 2011 | | |

**Notes:**

**a. Annual average industrial electricity price from 1998-2010 in 2010 dollars**

**b. Annual average spot price from 2005-2010 in 2010 dollars. #2 Heating Oil is a common commercial maritime fuel.**

The remaining costs in the utilities, consumables and supplies category can be estimated from the fixed capital investment as calculated by equation 4.2. The two primary components remaining in this cost category, maintenance costs and supplies, are estimated as follows (Turton, et al. 2009):

$$\boldsymbol{C_{OS} = f_{supplies} * C_n} \tag{4.6}$$

where

$f_{supplies}$ = Fraction of fixed capital investment, 0.011 (range 0.002 to 0.02)

$C_{OS}$ = Cost of Operating Supplies, 2010 U.S. $

$C_n$ = Fixed Capital Investment, 2010 U.S. $

*And*

$$\boldsymbol{C_M = f_{maint} * C_n} \tag{4.7}$$

where

$f_{maint}$ = Fraction of fixed capital investment, 0.06 (range 0.02 to 0.1)

$C_M$ = Cost of Maintenance, 2010 U.S. $

$C_n$ = Fixed Capital Investment, 2010 U.S. $.

The fractions (and associated ranges) used in equations 4.6 and 4.7 were obtained from Turton, et al. (2009). Finally, the total costs associated with account 76 are summarized as:

$$\boldsymbol{C_{76} = C_U + C_{OS} + C_M} \tag{4.8}$$

where

$C_{76}$ = Total cost of utilities, supplies and consumables, 2010 U.S. $

$C_U$ = Cost of utilities, 2010 U.S. $.

### *Taxes and Insurance (COA 78)*

Taxes and insurance are also estimated as a portion of the fixed capital investment (Turton, et al. 2009):

$$\boldsymbol{C_{TI} = f_{taxes} * C_n} \tag{4.9}$$

where

$f_{taxes}$= Fraction of fixed capital investment, 0.032 (range 0.014 to 0.05)

$C_{TI}$ = Cost of taxes and insurance, 2010 U.S. $

$C_n$ = Fixed Capital Investment, 2010 U.S. $.

***Summary of Operating Costs***

Table 4.8: Summary of Annualized Operating Cost Estimation Techniques

| EMWG Acct # | Account Title | Cost Calculation |
|---|---|---|
| **7** | **Annualized O&M Cost (subtotal)** | |
| **70 series** | | |
| **71** | **Operations Staff** | **Number of Operators (Total) * Wage rate for operator *(See equations 4.3 and 4.4)*** |
| **72** | **Management Staff** | **0.18 * Cost of Operating Staff *(See equation 4.5)*** |
| **73** | **Salary-Related Costs** | **Included in 71 and 72 above** |
| **74** | **Raw Materials** | **Quantity consumed * Price of chemical *(See Cost Estimation by Process Area)*** |
| **75** | **Spare Parts** | **N/A** |
| **76** | **Utilities, Supplies and Consumables** | **Utilities consumed * Price of Utility + 0.011*FCI + 0.06*FCI *(See equations 4.6 - 4.8 and Table 4.7)*** |
| **77** | **Capital Plant Upgrades** | **N/A** |
| **78** | **Taxes and Insurance** | **0.032 * FCI *(See equation 4.9)*** |
| **79** | **Contingency on O&M Cost** | **0.1 * sum of accounts 71 through 78** |
| **9** | **Annualized Financial Costs (subtotal)** | |
| **90 series** | | |
| **91** | **Escalation** | **Typically excluded** |
| **92** | **Fees** | **Annual fees such as licensed process, operating license fees, etc.** |
| **93** | **Cost of Money** | **Value of money used for operations - financed or retained earnings** |
| **94** | | |
| **95** | | |
| **96** | | |
| **97** | | |
| **98** | | |
| **99** | **Contingency on Financial Costs** | |

## 4.4 COST ESTIMATION BY PROCESS AREA

The generic cost estimation methods described thus far will be applied to all areas of the uranium production process. The overall process will be divided into three distinct process areas as in previous chapters:

- adsorbent production,
- mooring and deployment,
- elution and purification.

Each process area will have its own COA (accounts 1-9). Within each process area, the following steps will serve as a guideline to develop all cost estimates for the area:

1) develop Block Flow Diagram (BFD)[6] or Process Flow Diagram (PFD),
2) generate equipment and stream lists for each process area,
3) estimate sizes and cost for major equipment from known throughput information,
4) use purchased equipment cost to estimate TCIC for each area,
5) estimate labor requirements based on PFD and equipment list,
6) develop chemical and utilities cost from stream summaries and price references,
7) populate COA for each area.

---

[6] Block flow diagrams provide an overview of major process equipment and flows while process flow diagrams contain additional equipment, detailed stream information, utility streams, and basic control loops. To avoid confusion, only the term process flow diagram will be used in this work and will refer to either a BFD or PFD.

This procedure is implemented in each process area with specific modification for the level of information available and the nature of the individual processes and equipment making up the process area. For example, the mooring and deployment area will not contain a traditional PFD since the area does not contain a chemical or manufacturing process; however, many of the same techniques for will be used for scaling capital costs and estimating operating costs. Deviations from the standard process or methodology will be addressed in the subsequent sections.

### 4.4.1 Adsorbent Production

Adsorbent production involves three distinct processes: fiber spinning, irradiation, and grafting. The processes are included in one process flow diagram as described below, but sizing and costing will be discussed by individual process. The adsorbent consists of 50,000 tonnes of high density polyethylene (HDPE) grafted with amidoxime functional groups at a 100% degree of grafting.

$$\boldsymbol{Degree\ of\ Grafting}\ (\%) = \frac{\boldsymbol{W_G - W_O}}{\boldsymbol{W_O}} * \mathbf{100} \tag{4.10}$$

where

$W_G$ = Weight of grafted polyethylene (100,000 tons)

$W_O$ = Weight of ungrafted polyethylene (50,000 tons)

Grafting will be discussed in detail in the subsequent analysis; the 100% grafting assumption provides the capacity basis for the adsorbent production process.

#### *Process Flow and Equipment*

Figures A.4.1 and A.4.2 in Appendix A depict the process flow diagram (PFD) for adsorbent production; Tables A.4.1 and A.4.2 are the accompanying PFD tables which provides details about the equipment and streams associated with the PFD. HDPE chips or pellets are fed to single-screw extruder (denoted by A in the in the PFD and equipment table) which uniformly melts the polymer. The polyethylene melt is pumped (B) through a filter (C) and finally to a spinneret (D) for fiber formation. The fibers leaving the spinneret are cooled using filtered air (E), stretched via a godet roll (F), and wound on a take up device (G) in preparation for further processing. Figure 4.1 below is an overview of the melt spinning process.

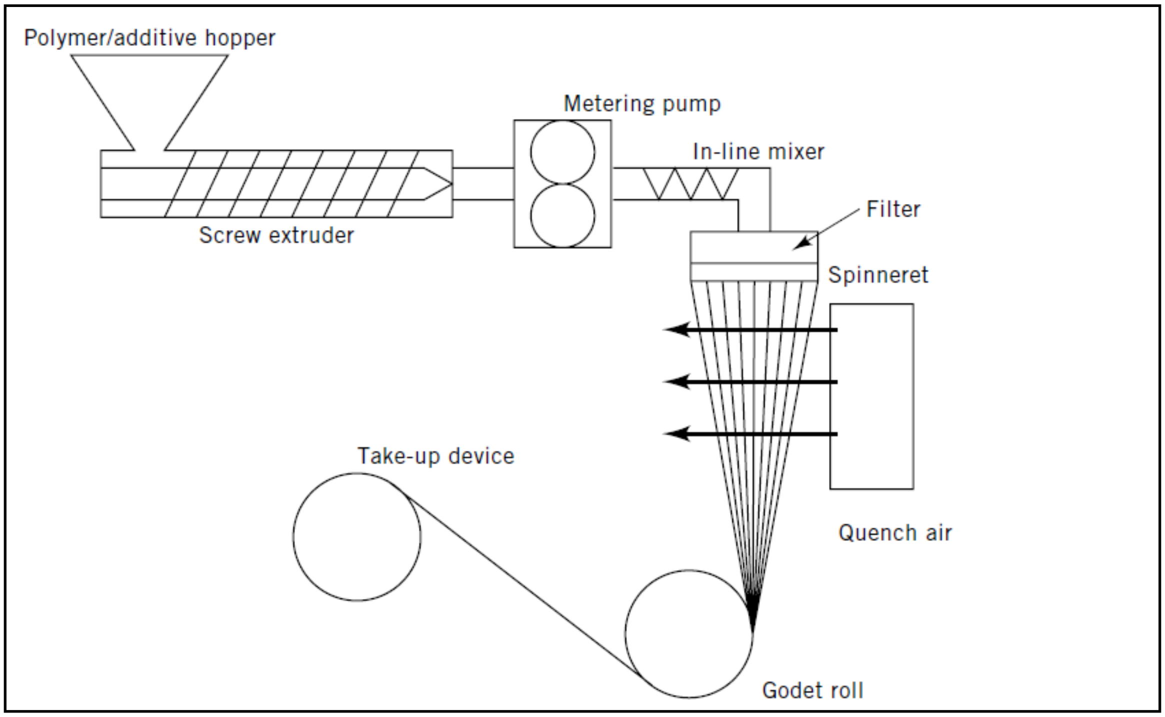


Figure 4.1: Generic Melt-Spinning Process (Wust 2004)

The polyethylene fibers are prepared for radiation-induced grafting. The first step in the process is irradiation via an electron beam accelerator (I). The irradiation process generates free radical sites for the subsequent grafting process. The irradiated fibers are placed into stirred tank reactors (L) on bobbins; the rectors are fed the following sequence of chemicals to graft an amidoxime group onto the radical sites on the polyethylene backbone:

1) 5 wt% surfactant (sodium lauryl sulfate) and 30wt% acrylonitrile in water,
2) dimethylformamide (DMF),
3) 3 wt% hydroxylamine in 1:1 water/methanol solution.

The grafted adsorbent fibers are subsequently woven around floats on a braiding machine (N) to complete the adsorbent manufacturing process.

### ***Size and Cost of Equipment: Spinning***

The spinning equipment costs were developed via reference plant costs and vendor quotes for a variety of melt spinning facilities. Table 4.9 lists the reference plant sources used to develop a cost estimate for the melt spinning process; Figure 4.2 depicts the cost scaling relationship derived from the reference data. Note that the data in the table and chart represent the total capital investment for the plant, including equipment.

Table 4.9: Melt Spinning Line Cost and Capacity Reference Data

| Year | Annual Capacity (metric tons) | Investment 2010 US$ | Material | Location | Source |
|---|---|---|---|---|---|
| 2011 | 65 | $1,930,007 | PAN | U.S.A | ORNL Carbon Fiber Pilot Facility |
| 2010 | 500,000 | $295,438,431 | N/A | China | (Jiangsu Challen Fiber S&T Co.,Ltd 2010) |
| 2008 | 160,000 | $38,302,561 | Polyester | China | (Zhejiang Huatesi Polymer Technical Co.,Ltd. n.d.) Phase 1 |
| 2010 | 180,000 | $32,498,227 | Polyester | China | (Zhejiang Huatesi Polymer Technical Co.,Ltd. n.d.) Phase 2 |
| 2003 | 200,000 | $74,489,823 | Polyester | China | Tongxiang Zhongxin Chemical Fiber Co., Ltd. (Xinfengming Group 2008) |
| 2007 | 200,000 | $68,917,413 | Polyester | China | Tongxiang Zhongchi Chemical Fiber Co., Ltd (Xinfengming Group 2008) |

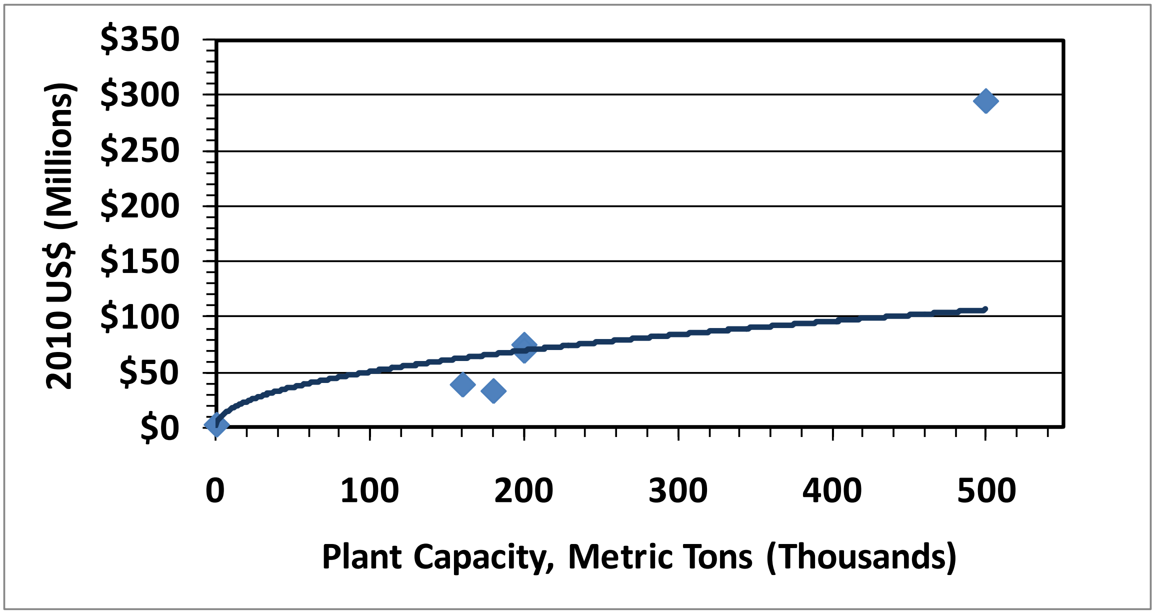


Figure 4.2: Cost Scaling Relationship for Melt Spinning Facilities

The cost scaling depicted by the trend line in Figure 4.2 is described by the following empirical relationship:

$$\boldsymbol{Plant\ Cost = 242,005 * Plant\ Capacity^{0.464}} \qquad \boldsymbol{R^2 = 0.87} \tag{4.11}$$

where

Plant Cost = Capital Investment in Melt Spinning Plant, 2010 US$

Plant Capacity = Melt spinning plant capacity, metric tonnes/year

The cost scaling equation in 4.11 was not used directly due to the lack of detail regarding the melt spinning facilities in China in Table 4.9. Instead the scaling exponent, 0.464, was used with the ORNL pilot facility data as a reference to obtain a $42.1 million (2010 US$) investment for the base case braid adsorbent production facility. The scale up from a small, custom pilot facility may introduce additional error, but the ORNL process can be verified through documentation and can be used as a starting point to develop detailed cost estimates (Oak Ridge National Laboratory 2010).

To support detailed cost estimation of the melt spinning facility in future work, major pieces of equipment in the melt spinning process were sized to provide a preliminary equipment list for the braid adsorbent production process. As mentioned, the first piece of equipment in adsorbent production is the single-screw extruder. The throughput of an extruder can be approximated by the drag flow rate through the extruder (neglecting pressure flow rate and leakage) (Rauwendaal 1987). Drag flow rate ($Q_D$) is given by:

$$\boldsymbol{Q_D = (4+n) * \frac{W*H*V_z}{10}} \tag{4.12}$$

$$\boldsymbol{V_z = \pi * D * N * \cos\varphi} \tag{4.13}$$

where

W = channel width

H = channel depth

$V_z$ = plastic velocity in channel

D = screw diameter

N = screw speed in rpm

$\varphi$ = helix angle

n = Power Law Index (1 for Newtonian Fluid; 0.5 for HDPE)

Figure 4.3 depicts the relevant dimensions of the extruder.

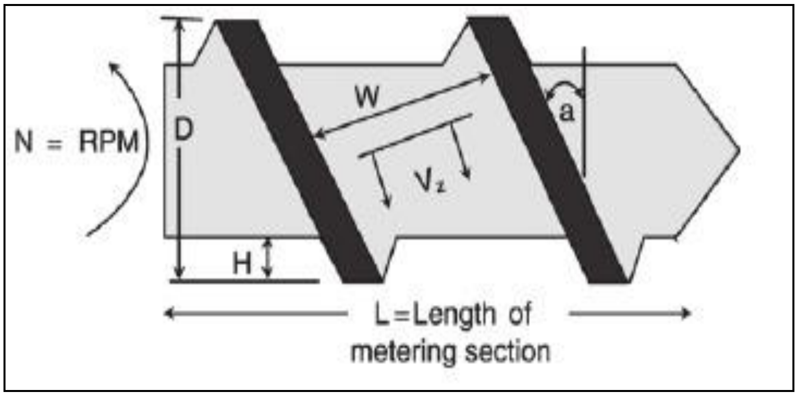


Figure 4.3: Single Screw Extruder Dimensions (Giles, Wagner and Mount 2005)

Detailed design is required to determine the drag flow from equations 4.12 and 4.13. However, in the case of scaling from one design to another, the drag flow can be approximated by the ratio of the diameters of the extruders (Rauwendaal 1987).

$$\boldsymbol{\frac{Q_{D2}}{Q_{D1}} \sim \left(\frac{D_2}{D_1}\right)^{(h+2+\nu)}} \tag{4.14}$$

$$\boldsymbol{h = \frac{1+n}{1+2n}} \tag{4.15}$$

$$\boldsymbol{\nu = -\frac{1+n}{1+2n}} \tag{4.16}$$

where

$Q_{D2}$ = Flow rate of design extruder (Unknown)

$Q_{D1}$ = Flow rate of reference extruder (380 kg/hr)

$D_2$ = Diameter of design extruder (250 mm)

$D_1$ = Diameter of reference extruder (150 mm)

h = Factor to represent channel depth (n = 0.5 for HDPE, h = 0.75)

ν = Factor to represent screw speed (n = 0.5 for HDPE, ν = -0.75)

The flow rates in equation 4.16 are volumetric flow rates; however, since the reference extruder and design extruder in this case are both based on HDPE (i.e. handling materials of the same density) mass flow rate can be substituted for $Q_{D1}$ and $Q_{D2}$. To perform this approximation, the extruders for the adsorbent production process are assumed to have a diameter of 250 mm; this was given by Fourne as the largest practical size in use for melt spinning processes (Fourne 1999). An extruder with a 150 mm diameter and mass flow rate of 380 kg HDPE per hour was selected from literature as the reference design for scaling (Hensen 1997). Based on this reference design and the scaling relationship in equation 4.14, the expected output for the 250 mm extruder is approximately 1056 kg/hr. To meet total throughput requirements for adsorbent production (50,000 tonnes/year HDPE), seven 250 mm extruders will be needed. This sizing information for the extruder is included in the summary equipment table at the end of this section.

Finally, the spinneret units and take-up equipment should be sized in tandem; the relationship between the speed and size of the polymer filaments leaving the spinneret and the final take-up speed after leaving the spinneret influences many of the final fiber characteristics, including strength and fiber diameter among others. Detailed discussion of fiber characteristics is beyond the scope of this analysis; however, recommended parameters from literature can be used to size the spinnerets and take-up equipment. Equation 4.16 describes the throughput for spinnerets in terms of the final take-up speed; an analogous polypropylene process was used as a reference to define the parameters (values in parentheses next to variable definition) in the equation (Fourne 1999):

$$\boldsymbol{TP_{SPIN} = ld * n_{holes} * i * \eta * v * \frac{1.44 * 10^{-4}}{24}} \qquad (4.17)$$

where

$TP_{SPIN}$ = Throughput of each spinneret, kg/hr

ld = Linear density, dtex or grams per 10,000 m

$n_{holes}$ = Holes per spinneret (200)

i = residual stretch (1.8)

$\eta$ = Efficiency of spinneret (97%)

v = Take-up speed, m/min (3330 m/min)

Based on a linear density of 3.96 dtex derived from the JAEA fiber diameter specification of 23 µm per filament, the throughput of each spinneret was determined as 27 kg/hr. To meet full line throughout requirements (~6400 kg HDPE/hour), 236 spinnerets are required; however, in spinning lines, spinnerets are organized in manifolds with a uniform number of spinnerets per extruder to balance polymer flow throughout the line. To ensure an equal number of spinnerets per extruder, 238 spinnerets are needed for the process (34 per extruder). In addition, as specified in equation 4.17, the take-up equipment should be expected to operate at approximately 3300 m/min. These values are summarized in the equipment table at the end of the section alongside all other adsorbent production equipment.

### *Size and Cost of Equipment: Irradiation*

The irradiation portion of the adsorbent production process contains the electron beam accelerator and its associated auxiliary equipment. The primary method of sizing and costing the electron beam accelerator was via a vendor quote based on a similar fiber irradiation process. Table 4.10 highlights the input data for the braid adsorbent irradiation process as well as the equipment specifications and cost provided by the vendor.

Table 4.10: Electron Beam Specifications and Vendor Quote

| | Parameter | Value | Unit |
|---|---|---|---|
| Input | Capacity | 50,000 | tonnes/year |
| | Dose | 50 | kGy |
| | Individual Fiber Diameter | 23 | µm |
| | Fiber Bundle Thickness | 1 | mm |
| | Operating Hours (@95% availability) | 8300 | kg/hr |
| Vendor Specifications | Parameter | Value | Unit |
| | Capacity | 44,000 | tonnes/year |
| | Energy | 0.8 | MeV |
| | Current | 160 | mA |
| | Power | 128 | kW |
| | Electrical Efficiency | 60% | N/A |
| | Annual Power Consumption | 2,000,000 | kWh |
| | Capital Cost- Accelerator | $2,250,000 | 2010 US$ |

The vendor quote will serve as the reference cost for scaling to meet requirements for the braid adsorbent process; in addition, the need for scaling and optimization as the adsorbent production process changes requires a model that ties the physical parameters of the electron beam accelerator to the cost and throughout of the equipment. Electron beam accelerators are classified by the energy of the beam (in electron volts, eV), the current of the beam (in amperes, A) and the resultant power (in kilowatts, kW). The power reflects the primary operating cost (electricity consumption) and will also serve as the basis for cost scaling when developing a capital cost estimate.

In addition, when considering grafting of a polymer, the dose (in grays, Gy or kGy) is a critical property. The dose reflects the amount of energy absorbed by a kilogram of the material; in the case of grafting, the dose must be sufficient to initiate the generation of free radicals in the polymer (reactive sites for grafting) yet cannot be so high that polymer degradation occurs. The previous economic analysis by JAEA cited an average dose of 50 kGy in the radiation grafting process (Tamada, et al. 2006); other sources cite a range from 20 kGy to 50 kGy for grafting processes (Cleland 2005). The current system will be designed at 50 kGy pending experimental data that identifies an optimal dose for the braid adsorbent application. The required dose must be optimized over the entire product thickness to ensure uniform grafting; this is controlled by the beam energy. The depth-dose distribution curves in Figure 4.4 depicts the energy deposition as a function of the product thickness for polyethylene for beam energies ranging from 5 to 10 MeV; similar curves can be found in Appendix for 0.4 to 0.8 MeV (Figure B.4.1) and 1 to 3 MeV (Figure B.4.2).

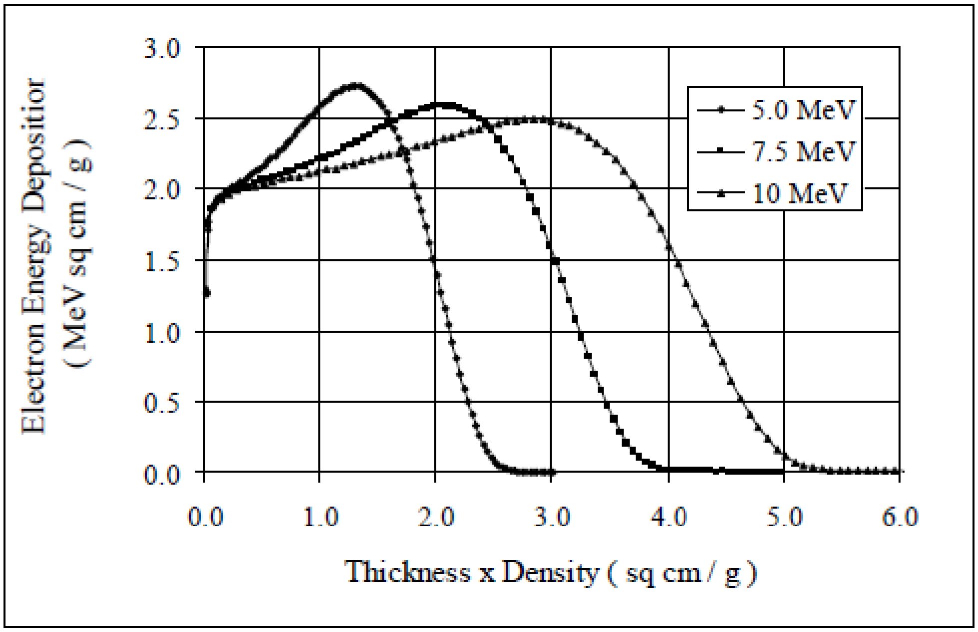


Figure 4.4: Electron Energy Deposition in Polyethylene, 5 to 10 MeV. 40µm titanium beam window thickness, 15 cm air gap at 0.0012 g/cm$^3$ (Cleland 2005)

The depth-dose distribution curves are used to empirically define an optimum thickness of the product to ensure that the exit dose is equal to the entrance dose (Cleland 2005):

$$\boldsymbol{R_{opt} = 0.404 * E - 0.161} \tag{4.18}$$

where

$R_{opt}$ = Optimum Product Thickness in g/cm$^2$

E = Beam Energy in MeV

In addition, the depth dose distribution curves define the area processing coefficient, K; this parameter includes the stopping power of the irradiated material for incident electrons and the energy dissipation function which defines the shape of the depth-dose curves above (see (Becker, et al. 1979) for more details). Table 4.11 provides area processing coefficients corresponding to the depth-dose curves above.

Table 4.11: Area Processing Coefficient at the Surface as a function of Beam Energy (Cleland 2005)

| **Electron Energy** | **$K_o$: Area Processing Coefficient** |
|---|---|
| **(MeV)** | **kGy $m^2$/mA min** |
| 0.4 | 29.778 |
| 0.6 | 22.770 |
| 0.8 | 17.894 |
| 1.0 | 15.301 |
| 1.5 | 12.710 |
| 2.0 | 11.795 |
| 3.0 | 11.324 |
| 5.0 | 11.159 |
| 7.5 | 11.159 |
| 10.0 | 11.270 |

The information from the depth-dose curves allows for optimization of the dose throughout the polyethylene fibers; however, it does not consider throughput requirements. An appropriate accelerator must maintain the required dose to generate reactive sites through the entire depth of the polymer product while maximizing throughput. The balance in dose distribution and throughput is controlled by the energy and current of the accelerator. The following equation illustrates the relationship between throughput and the beam characteristics (Cleland 2005):

$$\boldsymbol{I} = \left(\frac{\boldsymbol{D_0}}{\boldsymbol{F_i K_0}}\right) * \frac{\boldsymbol{A_p}}{\boldsymbol{T}} \tag{4.19}$$

where

$I$ = beam current in mA

$D_o$ = Surface Dose in kGy (50 kGy for this process)

$F_i$ = Beam Current Utilization Efficiency (0.8 to 0.9)

$K_o$ = Area Processing Coefficient in kGy*m$^2$/mA*min

$A_P/T$ = Area Throughput in m$^2$/min

As equation 4.19 shows, the current of the accelerator is directly proportional to the area throughput; as the amount of product passing the beam changes with time, the electron fluence (current) from the accelerator must change to ensure constant electron flux at the product surface. In addition, as the beam energy goes up (and area processing coefficient drops correspondingly), the current must go up as well to maintain a fixed throughput. As mentioned, beam energy and current ultimately determine the power of the accelerator as given by equation 4.20:

$$\boldsymbol{P} = \left(\frac{\boldsymbol{E}}{\boldsymbol{q}}\right) * \boldsymbol{I} \tag{4.20}$$

where

P = Beam power in kW (Output power after losses)

E = Beam Energy in MeV

q = Integer value of the elementary particle charge (q = -1 for electrons)

I = Beam Current in mA.

Finally, the power of the accelerator can be used in cost scaling with a reference design to provide a cost estimate for the current system design. Figure 4.5 includes cost data collected by Sandia National Laboratories over a range of accelerator power; the data also includes the vendor specifications in Table 4.10. Sandia reported roughly a fourth root relationship between power and cost (Kaye and Turman 1999). The data has been adjusted from 1999 to 2010 dollars using the M&S Equipment Index values in Table B.4.1.

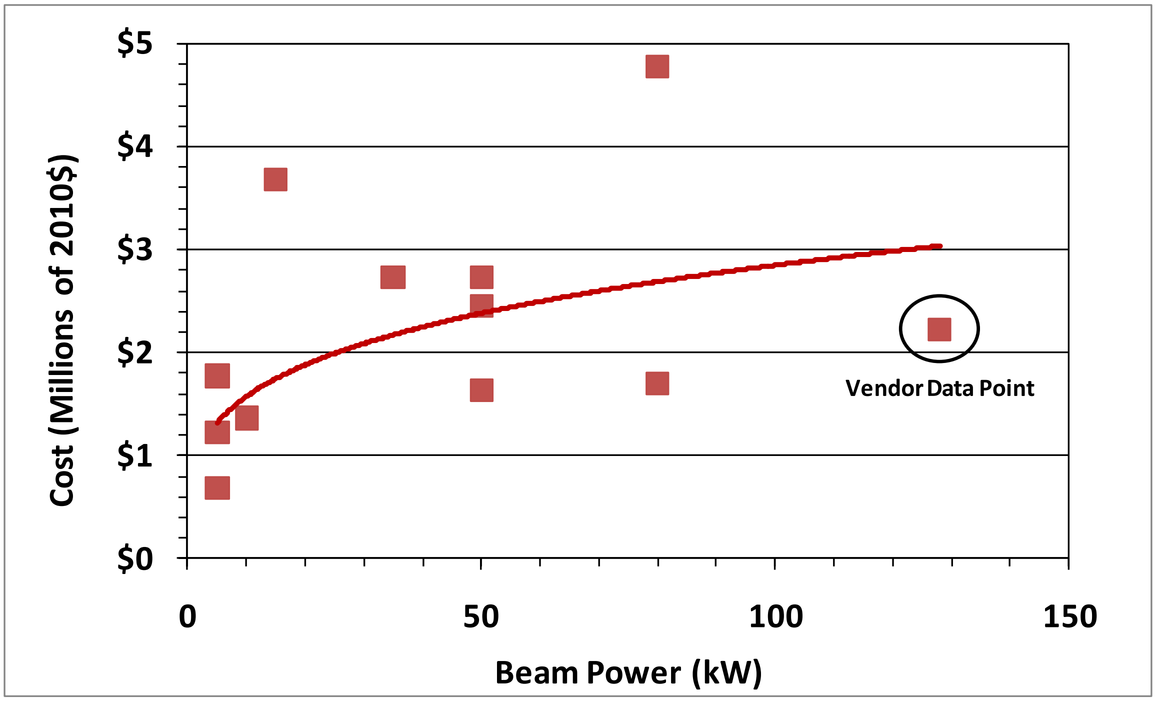


Figure 4.5: Electron Beam Cost as Function of Beam Power (Kaye and Turman 1999), with vendor data

The curve in Figure 4.5 represents the following cost scaling relationship for electron beam accelerators:

$$\boldsymbol{Cost\ of\ Accelerator} = \mathbf{869{,}096} * \boldsymbol{Power}^{0.2578} \tag{4.21}$$

where

Cost of Accelerator = Capital cost of accelerator, 2010 US$

Power = Beam Power in kW

Equations 4.19 and 4.20 were used to determine that a 145 kW accelerator would be required to meet throughout requirements for the braid adsorbent process. The vendor quote was used as a reference (due to similarity of irradiation application) with the cost scaling exponent from Equation 4.21 to develop a cost estimate of $2,300,000 (2010 US$) for an accelerator to meet base case process requirements.

The data shown in Figure 4.5 were also used with the e-beam throughput and dose distribution parameters discussed in this section to determine the final accelerator size and quantity; details of the optimization can be found in Appendix C. For comparison, Table 4.12 depicts the vendor specifications cost estimate alongside the optimization model results for the base case JAEA assumptions.

Table 4.12: Electron Beam Vendor Specification vs. Optimization Model Results (Base Case Conditions)

| **Parameter** | **Cost Scaling from Vendor Quote** | **Model Value** | **Unit** |
|---|---|---|---|
| Energy | 0.9 | 8.4 | MeV |
| Current | 160 | 17.2 | mA |
| Power | 145 | 145 | kW |
| Electrical Efficiency | 60% | 60% | N/A |
| Annual Power Consumption | 2,000,000 | 2,000,000 | kWh |
| Number of Accelerators | 1 | 1 | N/A |
| Capital Cost-Accelerator | $2,300,000 | $3,100,000 | 2010 US$ |

As the table shows, the optimization model predicts a higher energy system that also leads to a higher capital cost. It should be noted, however, that the optimization model is based on cost scaling data that was almost exclusively limited to high energy systems (> 5 MeV – the vendor data point was the only exception) and included only a single point beyond 80 kW; this limits the ability of the model to accurately predict high power, high throughput systems such as the one in this analysis. Additional cost data across various e-beam types (direct current (DC) and linear or radio frequency (RF)), energy ranges, and power ranges would enhance the optimization model.

### *Size and Cost of Equipment: Grafting and Braiding*

The grafting process was developed in Japan for large scale processing of irradiated fibers to produce the final amidoxime fiber adsorbents. Therefore, design data was directly adopted form the JAERI when available (i.e. equipment sizing). However, this was not sufficient to develop a full process flow diagram, so an independent flow diagram was developed for this analysis. Figure A.4.2 represents the process flow diagram for the grafting and braiding process. As the diagram shows, there are 4 primary types of equipment: solids conveying, grafting reactors, storage tanks, and braiders.

The solids conveying equipment is used to transport the irradiated fibers, now on bobbins, from the e-beam accelerator area to the reactor area. Without specific details on handling requirements, packaging, and facility layout, a detailed solids handling system cannot be specified. However, a basic belt conveyor system was assumed to allow a preliminary cost assessment. The belt conveyor is sized by speed and width of the belt, which together dictate throughput; Table 4.13 shows part of a belt conveyor specification table relevant to this analysis (Peters, Timmerhaus and West 2003):

Table 4.13: Belt Conveyor Sizing Table

| **Capacity of Belt Conveyors (kg/s)** | | **Belt Conveyor Speed (m/s)** | | |
|---|---|---|---|---|
| | | **0.75** | **1** | **1.3** |
| **Width (m)** | **0.4** | 15 | 21 | 26.5 |
| | **0.6** | 37.5 | 50 | 62.5 |
| | **0.75** | 60 | 80 | 100 |

Table 4.14: Belt Conveyor System Specifications – Grafting Area

| | | |
|---|---|---|
| Adsorbent Produced Annually | 100,000 | tonnes adsorbent/yr |
| Plant Uptime | 0.9 | Uptime |
| Operating Hours | 7,884 | Operating Hours/year |
| Mass Flow Rate | 12.7 | tons/hr |
| | 3.5 | kg/s |
| **Belt Width** | **0.4** | **meters** |
| **Transport Distance*** | **1,514** | **meters** |
| **Belt Incline** | **0.0** | **Degrees** |
| **Actual Belt Length** | **1,514** | **meters** |
| **Conveyor Destination Height** | **0.0** | **meters** |
| **Belt Speed** | **0.75** | **m/s** |

***Calculation basis from Peters, Timmerhaus and West (2003), p. 566-573***

****Transport Distance estimated as distance around perimeter of entire adsorbent production facility specified in JAEA analysis (143,215 $m^2$ facility)*** (Tamada, et al. 2006)

Table 4.14 shows the design parameters for the solids conveying system along with the selected sizing criteria for the conveying system. The mass flow rate or capacity required for the braid system dictates the use of the 0.4 m belt at the lowest operating speed of 0.75 m/s. With the belt width and the transport distance (see the table for an explanation of transport distance), the cost estimate for the belt conveyor was developed from the following cost scaling relationship (Peters, Timmerhaus and West 2003):

$$\boldsymbol{Cost\ of\ Conveyor = 1050 * Distance + 5884} \quad (4.22)$$

where

Cost of Conveyor = Capital cost of 0.4 m wide conveyor, 2002 US$

Distance = Transport length of conveyor system, m.

The same calculations will be used in the back end elution process for the solids handling of saturated adsorbent.

The grafting reactor data was taken from the JAEA cost estimate; the design assumptions for the grating reactors are summarized as follows:

Table 4.15: Grafting Reactor Sizing Data

| Parameter | Value | Units | Comments |
|---|---|---|---|
| **HDPE Grafted Annually** | 50,000 | tonnes/yr | 100,000 tons of adsorbent, 100% grafting |
| **Plant Uptime** | 0.9 | days/day | |
| **Daily Operating Hours** | 24 | hours/day | *9 hours assumed in JAEA |
| **Annual Operating Hours** | 7884 | hours/yr | |
| **Mass Flow Rate** | 6342 | tonnes/hr | |
| **Reaction Time** | 3 | hours | JAEA Assumption |
| **Reactions per day** | 8 | reactions/day/reactor | Operating Hours/Reaction Time |
| **Bobbins per Reactor** | 250 | bobbins | JAEA Assumption |
| **Weight per Bobbin** | 1 | kg | JAEA Assumption |
| **Reactor Volume** | 4 | $m^3$ | JAEA Assumption |

In order to develop independent assessments of the reactor volumes and times, the reaction kinetics of the grafting process must be fully understood; at this early stage, the reactor specifications from JAEA will be used directly. Work in Japan suggests that the reactors are actually custom modified fiber package dyeing equipment; however, a vendor quote could not be obtained for a custom system for this analysis. Therefore, the grafting reactors are treated as jacketed, stirred reactors for cost estimation purposes. The cost of jacketed stirred reactors can be estimated from the following empirical relationship (Peters, Timmerhaus and West 2003):

$$\boldsymbol{Cost\ of\ Tank = 21216 * Volume^{0.53}} \tag{4.23}$$

where

Cost of Tank = Capital cost of 316 SS, field erected tank, 2002 US$

Volume = Size of Tank, $m^3$.

Next, the grafting chemicals used in the process must be stored in bulk on site, particularly considering the large volumes and high throughout rates of the adsorbent production process. Each storage tank was sized to a 30 day capacity for each chemical. The annual chemical consumption rates were taken directly from the JAEA analysis, and converted to daily rates to estimate tank size by multiplying by 30. With tank volumes for each chemical, the following cost scaling relationship is used to cost the tanks (Peters, Timmerhaus and West 2003):

$$\boldsymbol{Cost\ of\ Tank = 163.3 * Volume + 63085} \tag{4.24}$$

where

Cost of Tank = Capital cost of 316 SS, field erected tank, 2002 US$

Volume = Size of Tank, $m^3$.

Finally, after the grafting process is complete, the multifilament bundles on the bobbins are braided around a central backbone that serves as a float for the adsorbents; the braiding is the final step of adsorbent production. As with the reactors, the braiding equipment was a custom design for the braid adsorbent process. Therefore, the price and quantity of braiders was taken directly from the JAEA analysis. Independent assessment of braiding must occur during detailed design or prototype phase.

Equipment costs for the grafting and braiding area are summarized in the following section.

### *Size and Cost of Equipment: Summary*

Table 4.16: Equipment Table with Delivered Equipment Costs, Grafting-Braiding Area

| ID (s) from PFD | Equipment | Type | QTY | Size | Unit | Total Purchased Equipment Cost 2010 US$ |
|---|---|---|---|---|---|---|
| A | Polymer Extruder | Single Screw | 7 | 250 | mm | See Melt Spinning Total |
| D | Spinneret | Melt Spinning | 238 | 200 | holes | See Melt Spinning Total |
| G | Final Take-Up | Roll/Winder | - | 3300 | m/ min | See Melt Spinning Total |
| N/A | Melt Spinning - All Equipment* | ALL | - | 50,000 | tonne/ year | $8,690,000 |
| I | Electron Beam Accelerator | Direct Current | 1 | 0.9<br>160<br>145 | MeV<br>mA<br>kW | $2,300,000 |
| K,M,O | Solids Conveying | Belt Conveyor | 1 | 1514 | m | $2,250,000 |
| L | Grafting Reactors | Jacketed, Stirred Reactors | 77 | 4 | m^3 | $4,490,000 |
| N | Braiders** | N/A | 1275 | N/A | N/A | $11,900,000 |
| N/A | Acrylonitrile Storage*** | Tanks (316 SS) | 2 | 2,007 | m^3 | $1,030,000 |

Table 4.16 (continued)

| | | | | | | |
|---|---|---|---|---|---|---|
| N/A | Surfactant Storage*** | Tanks (316 SS) | 1 | 312 | m^3 | $150,000 |
| N/A | Hydroxylamine Storage*** | Tanks (316 SS) | 1 | 2,024 | m^3 | $520,000 |
| N/A | DMF Storage*** | Tanks (316 SS) | 3 | 2,079 | m^3 | $1,590,000 |
| N/A | Water-Methanol Storage*** | Tanks (316 SS) | 3 | 2,027 | m^3 | $1,560,000 |
| **Total Delivered Equipment Cost (2010 US$)** | | | | | | **$37,200,000** |
| ***Source(s): Equipment Sizing and Reaction Data from JAEA Reference Design (Tamada, et al. 2006)***<br>****Melt Spinning Equipment cost calculated from Total Capital Investment Cost***<br>*****Braider quantity and cost taken directly from JAEA estimate***<br>******All storage tanks sized for 30 day inventory*** | | | | | | |

***Operating Costs: Operations and Management Staff***

Labor requirements and costs were estimated for the entire adsorbent production area via equations 4.3 through 4.5 in *Annualized Operation Cost Estimation* in section 4.3. The PFDs for the adsorbent production area (Figure A.4.1 and A.4.3) provide the number of major process steps in each PFD as well as a list of the steps. The labor requirements for the adsorbent production area are summarized in Table 4.17.

Table 4.17: Summary of Labor Requirements and Costs - Adsorbent Production Area

| **Labor Requirements**<br>**(@Design Capacity of 50,000 tonnes HDPE fiber/yr)** | | | | |
|---|---|---|---|---|
| | **Man-Hours Required** | **Operators Required** | **Annual Operator Salary** | **Total Cost (2010 US$)** |
| Melt Spinning and Irradiation | 103,000 | 53 | $83,000 | $4,390,000 |
| Grafting and Braiding | 51,600 | 27 | $83,000 | $2,240,000 |
| **Total for Adsorbent Production (2010 US$)** | | | | $6,630,000 |

***Operating Costs: Raw Materials and Utilities***

The raw materials and utilities consumption were taken directly from the JAEA assessment for the adsorbent production area; only the e-beam process has sufficient design detail to estimate electricity usage. Melt spinning, grafting, and braiding have basic equipment lists without detailed specifications for the equipment, streams or chemistry. A heat and material balance for this process area must be considered in future work.

Using the baseline consumption data from JAEA, price estimates for utilities (Table 4.7) and chemicals (Table B.4.4 in the Appendix) were developed and total raw materials and utilities costs for the adsorbent production area were estimated; the results are summarized in the following tables.

Table 4.18: Summary of Raw Material Costs - Adsorbent Production Area

| **Chemical Requirements (@Design Capacity of 50,000 tonnes fiber/year)** | | | |
|---|---|---|---|
| **Chemical** | **Annual Consumption** | **Unit Cost (2010 US$)** | **Total Cost 2010 US$** |
| High Density Polyethylene | 50,000 metric tons | $1,470/tonnes | $73,400,000 |
| 100% Hydroxylamine Hydrochloride | 56,400 metric tons | $3,080/tonnes | $174,000,000 |
| 100% Acrylonitrile | 35,400 metric tons | $1,330/tonnes | $47,200,000 |
| 100% Surfactant (Sodium Dodecyl Sulfate) | 3,450 metric tons | $2,100/tonnes | $7,240,000 |
| Methanol | 52,900 metric tons | $284/tonnes | $15,000,000 |
| Dimethylformamide | 64,800 metric tons | $1,250/tonnes | $80,700,000 |
| **Total for Adsorbent Production (2010 US$)** | | | $397,000,000 |

Table 4.19: Summary of Utility Costs - Adsorbent Production Area

| **Utility Requirements (@Design Capacity of 50,000 tonnes fiber/year)** | | | |
|---|---|---|---|
| **Utility** | **Annual Consumption** | **Unit Cost (2010 US$)** | **Total Cost 2010 US$** |
| Electricity | 620,000,000 kWh | $0.069/kWh | $42,900,000 |
| Process Water | 1,070,000 1000kg | $0.07/1000kg | $77,900 |
| Deionized Water | 444,000 1000kg | $1.08/1000kg | $480,000 |
| **Total for Adsorbent Production (2010 US$)** | | | $43,400,000 |

### *Operating Costs: Other Costs*

The remaining operating costs were estimated by the methods summarized in section 4.2 and Table 4.7. The costs are not listed in detail here, but can be found as part of the COA for the adsorbent production area in Appendix A (Table A.4.3)

### *Summary: Adsorbent Production Area*

The code of accounts for the adsorbent production area can be found in Table A.4.3. The summary reflects the base case results using the JAEA production parameters and design. The uncertainty in many of the parameters used in the cost estimation in this area will be evaluated as part of section 4.4. to develop a range around the figure of merit. The next chapter in the analysis will include sensitivity studies and alternative scenarios that modify many of the assumptions used to arrive at the baseline estimates in this section.

### 4.42 Mooring and Deployment

The mooring, deployment and retrieval) of the braid adsorbents at the selected coastal site requires design of an adsorbent field and specification of marine transportation and mooring equipment to ensure braid adsorbents can be recovered and re-deployed at rates consistent with the annual uranium production requirements. The following section highlights key design parameters and selection of appropriate equipment within design constraints.

#### ***Process Flow and Equipment***

The mooring area does not have a traditional process flow diagram since chemical unit operations are not employed. However, the design of the adsorbent field, recovery and deployment processes and equipment, and site selection will be evaluated to populate a code of accounts in much the same manner as the other process areas. The adsorbent field structure was developed by JAERI; the key design parameters and base case values from the Japanese analysis are summarized in Table 4.20.

Table 4.20: Adsorbent mooring field parameters, baseline values from Tamada, et al. 2006

| Parameter | Value | Units | Notes |
|---|---|---|---|
| **Adsorbent Deployment** | 100,000 | tonnes/year | Based on 1200 tonnes per year U requirement, 2 gU/kg Ads capacity, 60 day campaigns, and 6 reuses of adsorbent |
| **Adsorbent Linear Density** | 1 | kg/meter | |
| **Braid Length** | 60 | meters | See figure below |
| **Braids Required** | 1,670,000 | braids | |
| **Braid Spacing** | 8 | meters | Prevent entanglement |
| **Length of Individual Chains** | 2,120 | meters | |
| **Chain End Length** | 100 | meters | Unencumbered ends of chain for handling |
| **Braids per Chain** | 240 | braids | Based on spacing and end requirements |
| **Chains Required** | 6,976 | chains | To moor complete 100,000 tonnes of adsorbent |

Based on the chain requirements to moor the 100,000 tonnes of adsorbent, JAEA developed the field design depicted in Figure 4.6.

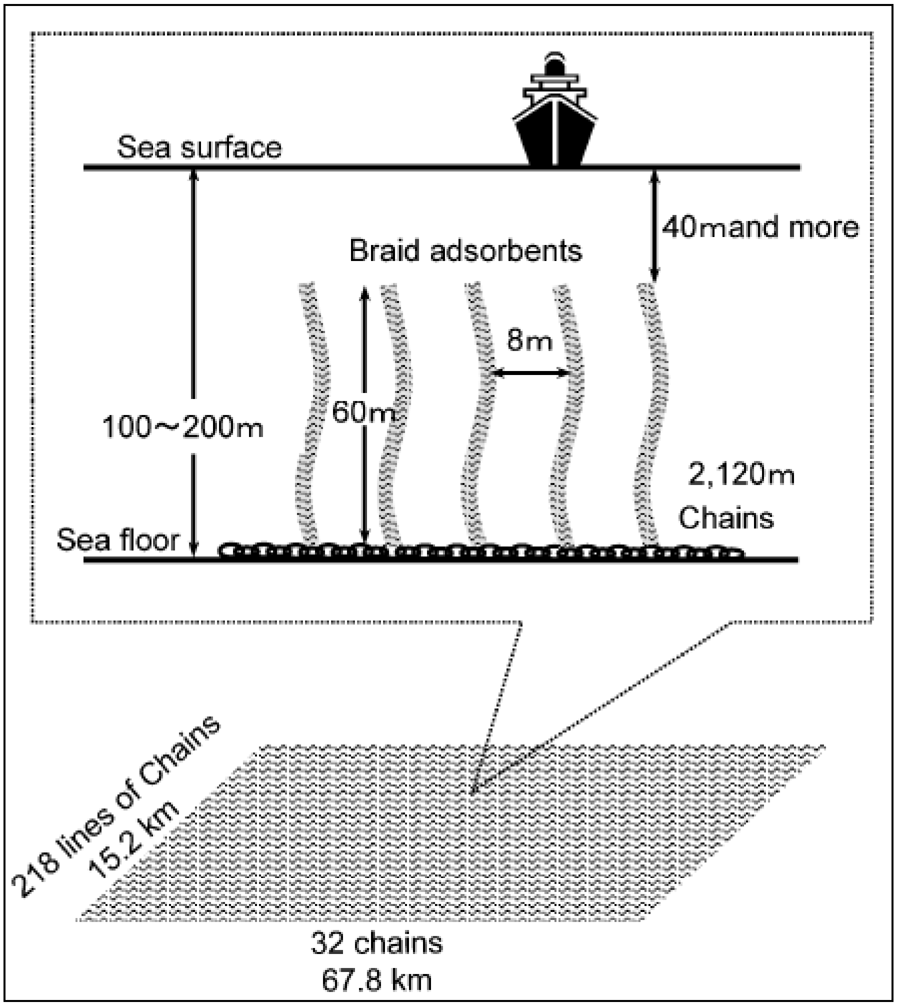


Figure 4.6: Braid Adsorbent Mooring Field (Tamada, et al. 2006)

The mooring chains (stud-link anchor chains) are central to the Japanese system and design. The chains serve as the anchor for the braid adsorbents which are buoyant due to the embedded float in the backbone of each adsorbent unit. The selection of chain size to serve this primary function of providing counter-weight to the buoyant force of the adsorbent units is discussed in detail in the subsequent section. The chain also dictates the method and apparatus to recover saturated braid adsorbent from the field for the subsequent elution and uranium purification steps. An anchor windlass (a specialized class of winch designed specifically for stud-link chain recovery) is needed to pull the chain up from the ocean floor to allow removal of saturated adsorbents and replacement with fresh adsorbents. The speed with which the windlass can recover the chain is a critical rate-limiting design parameter; the windlass speed determines how much adsorbent each ship can recover in a given period of time and ultimately the minimum number of ships required to recover the braid adsorbent. The windlass recovery speed is discussed in subsequent sections as well. Finally, ships are required to transport the adsorbent to and from on-shore facilities, carry required work crew for recovery operations, and to house the anchor windlass for chain recovery. The ships are defined by their carrying capacity in deadweight tonnes (dictates the amount of adsorbent each ship can carry) and brake horsepower. Ship selection is discussed with windlass selection due to the relationship between windlass recovery speed and number of ships required.

### *Size and Cost of Equipment: Chains*

A simple analysis of static forces in the underwater environment can reveal the weight requirement of the stud-link anchor chains. Figure 4.7 depicts force vectors in the braid-chain system.

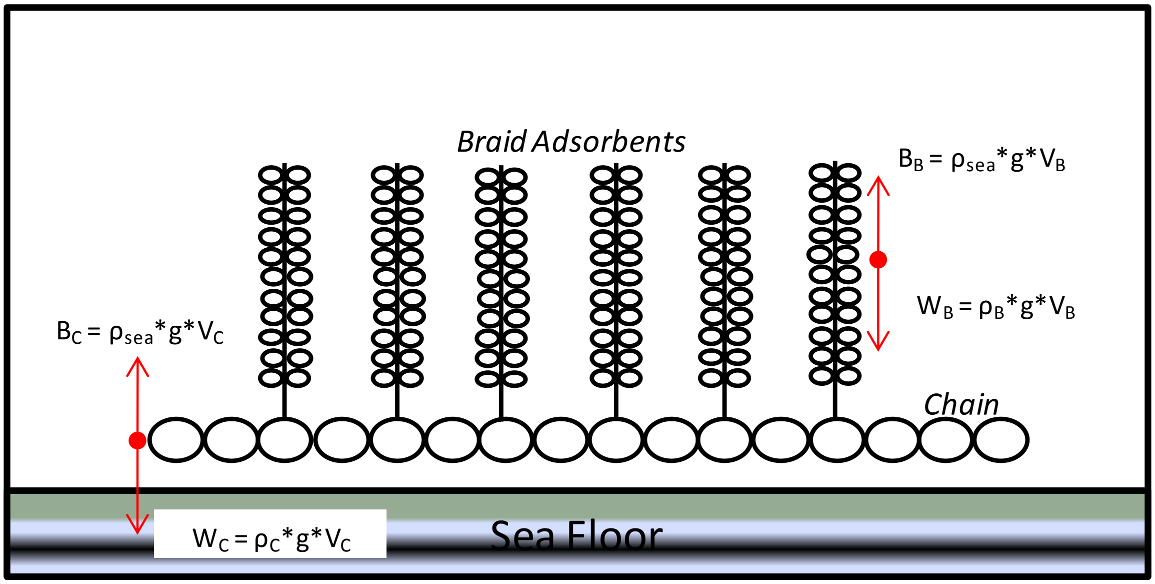


Figure 4.7: Static force vectors in chain mooring of adsorbent braids

As the diagram shows, the primary static forces in the mooring system are the buoyant forces on the chain and braids, respectively, in opposition to the weight of the chain and braids (vectors in the direction of the sea floor). The design parameter of interest is the weight of the chains; when the system is neutrally buoyant with no net acceleration (sum of static forces is zero with no normal force by the sea floor on the chain), the weight of the chains can be expressed as follows::

$$\boldsymbol{W_C = n_B B_B + B_C - n_B W_B} \tag{4.25}$$

where

$W_C$ = Weight of Chain, N

$n_B$ = Number of braids per chain (240)

$B_B$ = Buoyant force on braids = $\rho_{sea}*g*V_B$

$\rho_{sea}$ = Density of Seawater, kg/m$^3$ (1025 kg/m$^3$ @ 20°C and 35 g/kg salinity)

g = Gravitational acceleration, m/s$^2$ (9.8 m/s$^2$)

$V_B$ = Volume of Braids, $m^3$ = $L_B$ * $Wd_B$ *$Tk_B$

$L_B$ = Length of Braid, m (60 m)

$Wd_B$ = Width of Braid, m (0.2 m)

$Tk_B$ = Thickness of Braid, m (0.002 m – Thickness of 7400 multifilament bundle)

$B_C$ = Buoyant force on chains = $\rho_{sea}$*g*$V_C$

$V_C$ = Volume of chains, $m^3$

$W_B$ = Weight of Braids = $\rho_B$*g*$V_B$

$\rho_B$ = Density of Braids, kg/$m^3$ (953 kg/$m^3$, density of HDPE)

The weight in water of stud link anchor chains is known to be 0.87 times the weight in air, accounting for the buoyant force on the chains (Myers, Holm and McAllister 1969). There must be a net downward force on the system in the static case to ensure the entire mooring apparatus sinks to the ocean floor; the simplified static force analysis provides an approximation of the minimum weight of the chain required to moor a given number of braid adsorbents. Based on the static analysis, the full length chain weight should be about 12,300 N or about 0.6 kg/m.

Table B.4.5 in Appendix B relates chain diameter, the primary measure defining stud-link anchor chain types, to the weight of the chains; the table indicates that the smallest chain size has a linear density of 4 kg/m, nearly seven times the requirement from the static calculations. The JAERI chain was sized at 44 mm with a linear density 70 times greater than the weight requirement. The simplified static force analysis does not account for all of the forces acting the system; ocean currents generate additional force vectors which may impact the braids, and in turn, the chain. However, the large margin between calculated linear density requirements and properties of the chain selected by JAERI indicates that buoyancy effect may not impose the limiting sizing factor.

The chain must also be able to withstand the tension applied during recovery by the anchor windlass. Table B.4.5 also provides the working, proof, and break loads of each chain diameter and each grade of chain. Design loads should not exceed the working loads to ensure safety of the system.

One component of the tension during recovery is the drag force on the chains and braids.The drag-force is quantified as follows:

$$\boldsymbol{F_D = \frac{1}{2} * \rho_{sea} * u^2 * C_D * A} \tag{4.26}$$

where

$F_D$ = Drag force on mooring structures, N

u = Velocity of fluid relative to solid body, m/s

$C_D$ = Drag coefficient

A = Projected area or Skin Area (Tangential Drag), $m^2$

Further, the drag force must be considered as a component of the total load on the chain as the load on the given chain size and grade must not exceed the working load limit. The total load on the chain, can be summarized as:

$$\boldsymbol{F_{TL} = W_{Chains} + n_{Braids} W_{Braids} + F_{DW} + F_{DC} - (n_{Braids} B_{Braids} + B_{Chains})} \tag{4.27}$$

where

$F_{TL}$ = Total Load on chain and windlass during recovery (N)

$F_{DW}$ = Drag Force due to the windlass (from relative velocity of chain to water)

$F_{DC}$ = Drag Force due to ocean current (conservatively assumed at 2 m/s and tangential to recovery direction)

Drag coefficients were obtained from Driscoll (1982); in the base case of the windlass operating at 4 m/min and a worst case scenario of ocean current at 2 m/s acting tangentially to the chain recovery path, a total load of 543 kN was obtained. The working load (safety limit) for a 44 mm, Grade 3 chain (from Table B.4.5) is 539 kN. The working load limit on a chain one size smaller (42 mm) is 490 kN while the new load is 535 kN, exceeding the limit by nearly 10%. These preliminary calculations support the JAEA specification of a 44 mm chain.

***Size and Cost of Equipment: Anchor Windlass***

As mentioned, the anchor windlass is a critical component in the sizing of the mooring system. The recovery speed of the chains and associated adsorbent braids must meet capacity requirements to ensure expected annual production of uranium. Given that the entire braid adsorbent field must be recovered over the course of a campaign, the following set of equations derives the speed and number of the anchor windlasses from the reference adsorbent field size.

$$\boldsymbol{N_C = N_{Braids} \Big/ \left[\frac{(L_C - 2*End\ Spacing)}{Braid\ Spacing}\right]} \tag{4.28a}$$

where

$N_C$ = Total number of chains required to moor full field of adsorbents (6976),

$N_{Braids}$ = Number of braids in adsorbent field (1,670,000)

$L_C$= Length of an individual chain, m (2120m), End Spacing = Empty space at ends of a single length of chain, m (100 m each end)

Braid Spacing = Spacing between individual braids to prevent tangling, m (8 m)

$$\boldsymbol{R_{CR}} = \frac{\boldsymbol{N_C}}{\boldsymbol{Campaign\ Length}} \tag{4.28b}$$

where

$R_{CR}$ = required daily chain recovery rate (chains per day)

Campaign Length = Days in each production campaign (60)

$$\boldsymbol{N_{Windlass}} = \frac{\boldsymbol{R_{CR}}}{\boldsymbol{OH_{Daily} * 60 * R_{Windlass}}} \tag{4.28c}$$

where

$N_{Windlass}$ = number of windlasses required

$OH_{Daily}$ = Operating hours of mooring system per day (9 hours in base case)

$R_{Windlass}$ = Operating speed of windlass, m/min (4 m/min).

The operating speed of the windlass is determined in a trade-off with the allowable payload weight (in this case, the weight of the chain and adsorbents); lower gear ratios in the windlass allow for higher recovery speeds but also reduce the allowable payload.

In addition, the speed is further limited by the fact that the effective payload is increased by drag force on the chain and adsorbents as they are recovered. This drag force was quantified in the previous section as part of the chain tension calculations.

Once an appropriate windlass recovery speed and the corresponding load on the chain are determined, the windlass can be sized according to the power required to drive the equipment (Driscoll 1982) :

$$\boldsymbol{P = \frac{Line\ Pull * R_{windlass}}{60}} \tag{4.29}$$

where

P = Nameplate power of windlass (W)

Line Pull = Design load for windlass system –Includes $F_{TL}$ plus a safety margin, N

The power of the windlass was estimated at 36 kW using the base case the load calculations described above. However, the sizing is simply for reference; the cost of the windlass will be assumed to be included in the total ship cost (discussed in the next section) as is standard practice in commercial vessels. Custom windlass requirements may add costs that should be considered during the design phase of the project.

***Size and Cost of Equipment: Ships***

The ships required for adsorbent deployment and recovery are directly related to the number of windlasses required as derived in equation 4.28c:

$$\boldsymbol{N_{Ships} = \frac{N_{Windlass}}{N_{Windlass-Ship}}} \tag{4.30}$$

where

$N_{\text{Windlass-Ship}}$ = number of windlasses per ship

The JAERI analysis does not explicitly refer to a windlass; instead, the speed of chain recovery is assigned to the ship itself under the assumption that each ship has one windlass to recover chains. Equations 4.28c and 4.30 generalize the ship requirement to account for any feasible number of windlass units per ship.

Next, given the number of ships, the size of the ship is expressed in terms of its carrying capacity, or deadweight capacity. The deadweight capacity indicates the amount of cargo the ship can carry when fully loaded. Given the total amount of adsorbent recovered (entire field recovered during a campaign) and the number of ships required to recover the adsorbent over the course of a single campaign, the deadweight capacity of each individual ship can be calculated as follows:

$$\boldsymbol{DW_{Ship} = \frac{M_{Adsorbent}}{N_{Ships}}} \tag{4.31}$$

where

$DW_{Ship}$ = Deadweight capacity of each ship (deadweight tonnes or DWT),

$M_{Adsorbent}$ = Total mass of loaded adsorbent field (tonnes).

Note that this calculation includes an assumption that the recovery ships do not return to shore during the course of the campaign, requiring the fleet to have sufficient capacity to carry the entire field. This also creates a lag time in uranium recovery as loaded adsorbent is at sea for the duration of the campaign after its recovery. This is an area of potential operational optimization for the mooring and recovery operations.

The deadweight capacity of ships has been correlated to the capital cost of the ship in past analyses for a wide range of cargo and transport vessels; initial work was based on the simple relationship between building material required and cost of the ship (Thorburn 1960):

$$\text{Cost} \propto \text{Surface Area}$$

$$\text{Surface Area} \propto \text{Volume}^{0.67}$$

$$\text{Cost} \propto \text{Volume}^{0.67}$$

$$\text{Cost} \propto \text{DW}_{\text{ship}}{}^{0.67}.$$

Several empirical studies confirmed the "two-thirds" rule for cost scaling of ships, but work by Cullinane and Khanna provided the highest degree of correlation ($R^2 = 0.93$) to a large dataset of ships (n=153) (Cullinane and Khanna 1999):

$$\mathbf{ln}(\boldsymbol{ship\ price}) = \mathbf{4.8097} + \mathbf{0.759} * \mathbf{ln}\ (\boldsymbol{NTEU}) \qquad (4.32)$$

where

Ship Price = New-building contract prices (1000 US$, 1996),

NTEU = Nominal twenty-foot equivalent unit = 14 DWT.

The regression analysis dataset leading to eq. 4.32 covered ships from roughly 2800 DWT to 84,000 DWT (Cullinane and Khanna 1999). Despite the fact that the ships covered in the Cullinane and Khanna analysis are larger than the base estimate for the Japanese ship (1000 DWT), the regression will be used as the basis for cost estimation in this analysis. As no equivalent correlation limited to smaller vessels could be found in the literature. The shipping size specifications are summarized in Table 4.21.

Table 4.21: Mooring vessel requirements and sizing specifications

| Item | Value | Unit | Comments |
|---|---|---|---|
| **Length of Campaign** | 60 | days | JAEA Assumption |
| **Required Daily Chain Recovery** | 116 | chains/day | Based on exchange of all adsorbent over the campaign (continuous operation or steady-state assumption) |
| **Chain Recovery Speed** | 4 | m/minute | JAEA Assumption |
| **Boat Operation/Day** | 9 | hours | Implicit Assumption in JAEA Calculations |
| **Time to Recover One Chain** | 9 | hours | Calculated - 1 boat |
| **Total Boats Required** | 116 | N/A | Calculated |
| **Loaded Adsorbent Weight** | 107,000 | metric tons | Weight of Adsorbent + 2 x weight of known adsorbed metals |
| **Boat Capacity (Dead Weight)** | 1000 | deadweight tonnes | Calculated from Adsorbent Transported per Ship |
| **Ship Brake Horsepower** | 861 | BHP | Calculated from empirical relationship developed by Cullinane and Khanna 1999 |

***Size and Cost of Equipment: Summary***

Table 4.22 summarizes all of the required mooring equipment and associated costs based on the base case conditions.

Table 4.22: Equipment Table with Delivered Equipment Costs, Mooring Area

| **Equipment** | **Type** | **QTY** | **Size** | **Unit** | **Total Purchased Equipment Cost 2010 US$** |
|---|---|---|---|---|---|
| Mooring Chains | Stud Link Anchor Chain | 6976 | 44 | mm | $1,430,000,000 |
| Windlass | N/A | 116 | 36 | kW | Included in Ship Costs |
| Ships | Cargo | 116 | 1000<br>861 | DWT<br>BHP | $510,000,000 |
| **Total Delivered Equipment Cost (2010 US$)** | | | | | **$2,130,000,000** |

### *Operating Costs: Utilities*

The mooring and recovery portion of the operation consumes fuel oil. Work by Cullinane and Khanna related fuel consumption to the installed brake horsepower of the ship and in turn statistically correlated brake horsepower to ship size. Therefore, for a given ship size, fuel consumption can be estimated as follows:

$$\mathbf{FO} = \frac{\mathbf{BHP*SFOC*U*OH_{Daily}}}{\mathbf{1{,}000{,}000}} \qquad (4.33a)$$

where

FO = Daily fuel oil consumption (tonnes/day)

BHP = Installed brake horsepower (bhp)

SFOC = Specific Fuel Oil Consumption (gal/bhp-hr)

U = Utilization of engine capacity to maintain service speed (~80%)

and

$$\ln(BHP) = 2.6308 + 0.967 * \ln(NTEU) \qquad R^2 = 0.94 \qquad (4.33b)$$

An average value of specific fuel oil consumption of large displacement marine engines was estimated in an EPA supported marine emissions study at 0.219 kg/kWh or 163 gal/bhp-hr (Environ International Corporation 2002). It should be noted that SFOC will vary with engine operation, technology development over time, and specific engine designs and models. Using the daily fuel oil consumption, the number of ships, and the price of fuel oil #2 as listed in Table 4.7, annual fuel costs can be obtained.

Table 4.23: Summary of Utility Costs – Mooring Area

| **Utility Requirements (@Design Capacity of 100,000 tonne adsorbent field)** | | | |
|---|---|---|---|
| **Utility** | **Annual Consumption** | **Unit Cost (2010 US$)** | **Total Cost 2010 US$** |
| No. 2 Fuel Oil | 12,000,000 gal | $2.12/gal | $25,400,000 |
| **Total for Mooring and Recovery (2010 US$)** | | | $25,400,000 |

### *Operating Costs: Operations and Management Staff*

Crew requirements are not well correlated to ship size, and thus an empirical estimate cannot be used to determine crew size. In lieu of empirical data, the following heuristics developed by Cullinane and Khanna will be used to estimate labor requirements:

Table 4.24: Labor requirements on ships as a function of deadweight capacity

| Ship Size (DWT) | Crew Size |
|---|---|
| 0 to 7000 | 16 |
| 7000 to 11,200 | 20 |
| > 11,200 | 24 |

One of the crew members on the vessel will be assumed to be the captain while the remainder will be standard sailors; using the salary requirements from the United States Bureau of Labor Statistics presented previously in Table 4.6, total labor costs can be developed for each ship and the mooring and deployment area.

Table 4.25: Summary of Labor Costs – Mooring Area

| **Labor Requirements (@Design Capacity of 100,000 tonne adsorbent field)** | | | |
|---|---|---|---|
| | **Total Fleet Requirement** | **Annual Salary** | **Total Cost (2010 US$)** |
| Ship Captains | 116 | $108,000 | $12,600,000 |
| Sailors/Workers | 1,856 | $58,500 | $109,000,000 |
| **Total for Mooring and Recovery (2010 US$)** | | | $121,000,000 |

***Operating Costs: Site Selection***

One unique aspect of the mooring area is the need for seabed leasing rights. In addition to the costs associated with obtaining offshore space to operate the adsorbent field, the conditions of specific sites may impact performance of the adsorbent or feasibility of the mooring system due to temperature, depth, or other mitigating circumstances. Therefore, as part of the preliminary cost analysis, five coastal regions in the United States were evaluated for potential lease cost, depth/terrain of water in coastal areas, and temperature of water as a function of depth in potentially feasible areas. The five locations are highlighted in Figure 4.8.

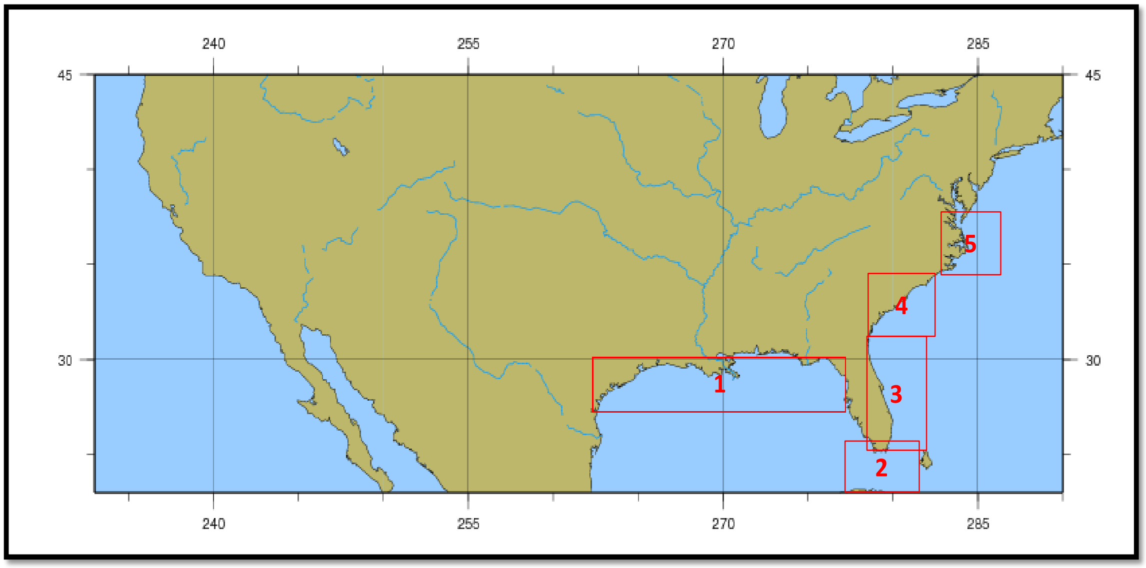


Figure 4.8: Five potential regions for offshore sites: 1 – Main Gulf, 2 – South Florida, 3 – South Atlantic, 4 – Mid-Atlantic, and 5 – North Atlantic.

The areas generally correspond to active offshore lease areas (in oil and gas exploration) and represent feasible areas for sites in terms of depth, access and temperature. Figures B.4.3 through B.4.6 in the Appendices depict coastal relief charts for each of the five regions; specifically the maps highlight depths from 0 to 300 meters underwater (NOAA National Geophysical Data Center 2011). Beyond 300 meters, depths (and corresponding temperatures) drop off rapidly, and the slope may become severe as the edge of the continental shelf is approached. The analysis by JAERI indicated that 100 meters was a minimum depth for mooring 60 meter high system to allow surface ship clearance.

Using the data associated with the coastal relief models, depth statistics (average, median, etc.) were generated in the 0 to 300 meter region for all five areas. In addition using depth-temperature data in the same regions, a weighted average temperature was developed for all five regions in 0 to 300 meter waters (Locarnini, et al. 2010). The weighted average temperature for each area was calculated as follows:

$$\boldsymbol{T_{Avg} = T_{Avg\,1-2} * \frac{M_{1-2}}{M_{Total}} + T_{Avg\,2-3} * \frac{M_{2-3}}{M_{Total}} \ldots + T_{Avg\,n-n+1} * \frac{M_{n-n+1}}{M_{Total}}} \tag{4.34}$$

where

$T_{Avg}$ = Weighted average temperature for a region

$T_{Avg\ n-n+1}$ = Average temperature from depth n to depth n+1

$M_{n-n+1}$ = Number of depth measurements between n and n+1

$M_{Total}$ = Total number of depth measurements for region between 0 and 300 m

Equation 4.34 does not reflect a true depth averaged temperature, but does provide a reasonable proxy for early screening and evaluation of sites alongside other data and considerations.

Finally, offshore lease data was evaluated for each of the regions to determine the average expected price for offshore leases in the area. Data is provided for auction prices and rental or lease payments, but only the lease payments will be considered in the economic analysis; auction data showed high variability related to the value of underlying oil and gas resources. In addition, adsorbent field operations would represent a lease, not a purchase of underlying resource rights. This is the type of arrangement pursued for offshore wind farms, which utilize seabed in a manner analogous to the uranium recovery system. For example, the Cape Cod wind lease in 2010 resulted in an annual payment of $1,363 per square kilometer in addition to operating fees; the land was not purchased via auction (U.S. Department of the Interior 2010). This lease price is seen to be comparable to the average historic lease prices in the ensuing tables for the five regions in this analysis. It will be treated as an operating cost under the raw materials category in the mooring area COA.

Tables 4.26 through 4.30 summarize the financial and physical parameters discussed thus far for each of the five regions. Lease price data was obtained from the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) (Bureau of Ocean Energy Management, Regulation and Enforcement 2010).

Table 4.26: Mooring Site Selection, Region 1 Data

| **Region 1 : Main Gulf** | | |
|---|---|---|
| ***Economic Parameters*** | | |
| **Item** | **Value** | **Unit** |
| Average Annual Rental Price | **$1,805** | 2010 US$/km^2 |
| Standard Deviation | $402 | 2010 US$/km^2 |
| ***Physical Parameters (Restricted to 0 to 300 meters depth region)*** | | |
| **Item** | **Value** | **Unit** |
| Average Depth | -52.0 | meters |
| Standard Deviation | 60.4 | meters |
| Median Depth | -31.1 | meters |
| Depth Averaged T | 22.0 | °C |

Table 4.27: Mooring Site Selection, Region 2 Data

| **Region 2 : South Florida** | | |
|---|---|---|
| ***Economic Parameters*** | | |
| **Item** | **Value** | **Unit** |
| Average Annual Rental Price | **$1,854** | 2010 US$/km^2 |
| Standard Deviation | $430 | 2010 US$/km^2 |
| ***Physical Parameters*** ***(Restricted to 0 to 300 meters depth region)*** | | |
| **Item** | **Value** | **Unit** |
| Average Depth | -53.8 | meters |
| Standard Deviation | 79.0 | meters |
| Median Depth | -15.4 | meters |
| Depth Averaged T | 24.7 | °C |

Table 4.28: Mooring Site Selection, Region 3 Data

| **Region 3 : South Atlantic** | | |
|---|---|---|
| ***Economic Parameters*** | | |
| **Item** | **Value** | **Unit** |
| Average Annual Rental Price | **$2,236** | 2010 US$/km^2 |
| Standard Deviation | $479 | 2010 US$/km^2 |
| ***Physical Parameters*** ***(Restricted to 0 to 300 meters depth region)*** | | |
| **Item** | **Value** | **Unit** |
| Average Depth | -51.7 | meters |
| Standard Deviation | 70.2 | meters |
| Median Depth | -26.2 | meters |
| Depth Averaged T | 23.9 | °C |

Table 4.29: Mooring Site Selection, Region 4 Data

| **Region 4 : Mid-Atlantic** | | |
|---|---|---|
| ***Economic Parameters*** | | |
| **Item** | **Value** | **Unit** |
| Average Annual Rental Price | **$2,236** | 2010 US$/km^2 |
| Standard Deviation | $479 | 2010 US$/km^2 |
| ***Physical Parameters*** ***(Restricted to 0 to 300 meters depth region)*** | | |
| **Item** | **Value** | **Unit** |
| Average Depth | -51.3 | meters |
| Standard Deviation | 68.8 | meters |
| Median Depth | -25.1 | meters |
| Depth Averaged T | 22.5 | °C |

Table 4.30: Mooring Site Selection, Region 5 Data

| **Region 5 : North Atlantic** | | |
|---|---|---|
| ***Economic Parameters*** | | |
| **Item** | **Value** | **Unit** |
| Average Annual Rental Price | **$2,236** | 2010 US$/km^2 |
| Standard Deviation | $479 | 2010 US$/km^2 |
| ***Physical Parameters (Restricted to 0 to 300 meters depth region)*** | | |
| **Item** | **Value** | **Unit** |
| Average Depth | -32.3 | meters |
| Standard Deviation | 36.1 | meters |
| Median Depth | -25.0 | meters |
| Depth Averaged T | 17.0 | °C |

***Operating Costs: All Other Costs***

Several previous studies used 3 to 5% of the initial capital cost as an estimate for all other operating costs (including maintenance, taxes and insurance, administration, etc.).[7] A nominal value of 4% will be used in this analysis while the range will be used in analysis of uncertainty in costs as discussed in subsequent sections.

---

[7] See **Invalid source specified.**, **Invalid source specified.**, and **Invalid source specified.**

### *Summary: Mooring Area*

The code of accounts for the adsorbent production area can be found in Table A.4.4 in the Appendices.

## 4.43 Elution and Purification

The recovery of the uranium from the adsorbents entails two processes: elution of metals from the adsorbent and purification of uranium to produce purified ammonium diuranate (ADU) or yellowcake. The elution process was developed in Japan specifically for the recovery and separation of uranium from amidoxime adsorbents while the purification process is analogous to refining processes used in conventional uranium production.

### *Process Flow and Equipment*

The elution and purification processes are divided into three separate PFDs. Figure A.4.3 represents the PFD for the elution process and Table A.4.5 is the associated equipment and stream table for the PFD. The loaded adsorbent is removed from the recovery ships and transported to the first elution tank (A); in this stirred reactor vessel, the alkali and alkali earth metals present in the adsorbent are eluted with 0.01 M hydrochloric acid. After the initial wash, the adsorbent is transferred to a second elution tank; the uranium in the adsorbent is eluted via 0.1 M nitric acid.8 The fractional elution process was developed by Japanese researchers, including JAERI, to isolate uranium from the other constituents adsorbed from seawater. The stripped adsorbent then proceeds

---

[8] The process configuration for elution has not been optimized for this analysis; in this case, the adsorbent is processed in two reactor vessels operating in series and the adsorbent material is transported between vessels. However, solids transport may be a difficult operation with the saturated adsorbent; an optimized design may include sequential elution in a single reactor (hydrochloric acid followed by nitric acid after purging in the same reactor vessel). The adsorbent would remain in a single vessel for the entire elution process.

to an alkali wash to remove residual acid and regenerate the adsorbent prior to recycle to the sea (F).

Following the elution, the uranium, now in solution as uranyl nitrate, is pumped to a storage/surge tank (G) followed by a precipitation tank (H); ammonia is added to the tank to precipitate uranium from solution as crude ADU which requires further purification. First, the ADU is sent to a thickener (I) and centrifuge (J) to remove any excess liquids or contaminants prior to further processing. Finally, the ADU is dried (L) and prepared for purification depicted in Figure A.4.5 (with Table A.4.7).

The crude ADU is re-dissolved in concentrated nitric acid in a stirred tank (N) to once again form uranyl nitrate that serves as the initial feed for the purification circuit The purification process is analogous to uranium refining processes used for conventionally mined ores; specifically, the process used in this design will be a tri-butyl phosphate (TBP) – hydrocarbon diluent and nitric acid solvent extraction process. Many variants of the reference solvent extraction process used here have been developed; these are candidates for consideration in subsequent process design work. The reference process flow, depicted in Figure A.4.5[9], from an existing refinery is the basis for the subsequent economic analysis.

The key components of the process flow are summarized as follows (relevant stream and equipment IDs listed in parentheses):

1. Uranyl nitrate slurry (21) from the digestion tanks is extracted by diluted TBP (36) via a pulse column (P).
2. The loaded organic extract (23) from the extraction column is subsequently scrubbed in a pulse column (Q) with a portion of the aqueous product stream

---

[9] The refinery design chosen is based on the Fernald Refinery that was located in Ohio and used TBP-Kerosene for solvent extraction and purification of a variety of ore blends (Catalytic Construction Company 1952), **Invalid source specified.**.

(25) from the stripping section (sometimes called the OK liquor) to remove metallic impurities.

3. The loaded organic solution (24) leaves the scrubbing column and enters the stripping pulse column (R) where de-ionized water (27) (or dilute nitric acid) is used to re-extract the uranium from the organic phase. A purified, loaded aqueous uranyl nitrate product stream is formed (25-b).
4. The newly formed aqueous product stream is then sent to the TBP removal area (S) to remove residual organic solvent and wastes from the product stream.
5. The stripped organic solvent (28) from the strip pulse column is combined is washed with sodium carbonate in the solvent wash area (T). The regenerated organic solution (31) is recycled back to the extraction process.
6. The uranyl nitrate product stream (35) is sent back to the precipitation area to recover purified ADU.

As seen in the PFD (Figure A.4.5), several support processes are not depicted or discussed in the main process flow (i.e. raffinate treatment, sump recovery, and acid recovery). However, these additional process areas are included in the cost estimation scope.

### *Size and Cost of Equipment: Elution*

As mentioned, the elution process is unique to amidoxime adsorbent. Therefore, an existing industrial flow sheet cannot serve as the reference design for the process. The PFD in Figure A.4.3 was developed from the process description given by JAERI;

equipment sizing will be taken directly from the Japanese cost estimation. However, independent equipment costs will be developed.

The equipment in the elution area includes solids conveying via a belt conveyor, two large elution tanks with agitators, and storage tanks. The belt conveyor system was discussed in detail in the grafting section; Table 4.13 and equation 4.22 in that section covered sizing and cost scaling of the belt conveyors. Table 4.31 summarizes the specifications of the solids conveying system in the elution area.

Table 4.31: Belt Conveyor System Specifications – Grafting Area

| | | |
|---|---|---|
| Adsorbent Processed (Field Size x Campaigns) | 600,000 | tonnes adsorbent/yr |
| Loading with Known Metals | 22,394 | t adsorbent/yr |
| Adsorbent Loaded (Double Known Metals) | 644,787 | t adsorbent/yr |
| Plant Uptime | 0.9 | Uptime |
| Operating Hours | 7,884 | Operating Hours/year |
| Mass Flow Rate | 81.8 | tonnes/hr |
| | 22.7 | kg/s |
| **Belt Width** | **0.4** | **meters** |
| **Transport Distance** | **3,000** | **meters** |
| **Belt Incline** | **0.0** | **Degrees** |
| **Acutal Belt Length** | **3,000** | **meters** |
| **Conveyor Destination Height** | **0.0** | **meters** |
| **Belt Speed** | **1.30** | **m/s** |
| ***Calculation basis from Peters et al 2003, p. 566-573*** | | |

Several differences from the grafting area specifications in Table 4.14 are apparent; the repeated processing in the elution area leads to a significantly higher annual solids handling rate (6 times the grafting area); the rate is even higher when considering the loading of the adsorbent.[10] Additional transport distance is also considered in the elution area due to potential long distance transport to and from a coastal recovery point; the length was assumed as twice that of the grafting area for initial calculations. Ultimately, the belt width is still 0.4 m, but the operating speed of the belt is higher in the elution area.

The elution and storage tanks are field erected tanks which were described in the grafting area as well; Equation 4.24 provides the cost scaling relationship for the field erected tanks. The solvent storage tanks are sized for 30 day supply in the elution area just as in the grafting area. The elution tank sizing is directly adopted from JAEA, but the tanks are also equipped with agitators for mixing during processing. The following relationship describes the cost scaling of the agitation propeller (Peters, Timmerhaus and West 2003):

$$\boldsymbol{Cost\ of\ Agitator = 3365 * Power^{0.1732}} \tag{4.35}$$

where

Cost of Agitator = Capital cost of 316 SS, propeller type agitator, 2002 US$

Power = Rated power of agitator motor, kW.

A value of 3 kW for agitator size was used for the initial cost analysis based on similar tanks used in the purification area (Catalytic Construction Company 1952).

---

[10] In this analysis, the weight of loaded adsorbent includes not only the weight of the uranium adsorbed, but also eight other metals identified with distribution coefficients in Tamada, et al. (2006). A factor of two is applied to allow for additional elements that have not been measured, residual water weight, and as a worst case scenario for additional loading.

Elution equipment costs are summarized in the equipment table at the end of the end of the elution-purification section.

### *Sizing and Cost of Equipment: Purification*

As mentioned, the basis for the purification process used in this analysis is the Fernald refinery. A detailed equipment list in excess of 300 pieces of equipment was obtained for the Fernald refinery from a design report developed during refinery start-up (Catalytic Construction Company 1952). The report and equipment list did not include costs and due to the time elapsed between the report and this current analysis, scaling costs directly would introduce a large level of uncertainty. As an alternative approach, a cost was assigned to each piece of equipment using the cost scaling relationships in Peters, Timmerhaus and West (2003). The sum of costs across the equipment list provided a proxy for a modern refinery cost configured as the Fernald refinery. The total refinery cost can then be scaled to the 1200 tonnes of uranium capacity for the current evaluation using a cost scaling exponent of 0.73 for solvent extraction facilities in equation 4.1 (Remer and Chai 1993a). The Fernald refinery had a reported capacity of 7,640 tonnes of uranium per year for the digestion area and 5804 tonnes of uranium per year for the solvent extraction area; the digestion area was over-sized to allow for flexibility in processing a variety of ores and, therefore does not match the capacity of the rest of the facility (Catalytic Construction Company 1952). Details of the equipment list and cost scaling relationships have been excluded here due to the size of the list of equipment; the Fernald design report can be consulted to obtain a full list and description of equipment. The cost scaling relationships are analogous to those used throughout the report. The purification area equipment costs are summarized as a single plant cost in the equipment table at the end of this section.

### ***Sizing and Cost of Equipment: Precipitation***

The precipitation area, as described in Figure A.4.4, followed a similar cost estimation process to that of the purification area. An equipment list for the purification area was obtained from a Canadian report in an OECD proceeding regarding uranium processing economics (Campbell, Kelly and Craigen 1983). The equipment costs were developed from the cost scaling data in Peters, Timmerhaus and West (2003) in most cases; where equipment sizing was insufficient for the estimation methods, costs were provided in the original Candian report; these costs were scaled for inflation via the Marshall and Swift Equipment Cost Index (Table B.4.1). The total purification plant cost was adjusted from the reference capacity of 278 tonnes of uranium per year to the 1200 tonne basis in this analysis.

### *Sizing and Cost of Equipment: Summary*

Table 4.32: Equipment Table with Delivered Equipment Costs, Elution-Purification Area

| ID (s) from PFD | Equipment | Type | QTY | Size | Unit | Total Purchased Equipment Cost 2010 US$ |
|---|---|---|---|---|---|---|
| A,C,E,K | Solids Conveying | Belt Conveyor | 1 | 3,000 | m | $4,450,000 |
| B, D | Elution Tanks | Field Erected Tanks w/ agitator | 2 | 642<br>3 | $m^3$<br>kW | $454,000 |
| N/A | Nitric Acid Storage Tank | Field Erected Tanks | 3 | 1,752 | $m^3$ | $1,380,000 |
| N/A | Hydrochloric Acid Storage Tank | Field Erected Tanks | 12 | 2,467 | $m^3$ | $7,380,000 |
| See Table A.4.4 | Purification Area | Multiple | - | 1,200 | tonnes U per year | $4,520,000 |
| See Table A.4.5 | Precipitation Area | Multiple | - | 1,200 | tonnes U per year | $4,270,000 |
| | | | | | **Total Delivered Equipment Cost (2010 US$)** | **$24,700,000** |

***Operating Costs: Operations and Management Staff***

Labor requirements and costs were estimated for the entire back end process area using equations 4.3 through 4.5 in *Annualized Operation Cost Estimation* in section 4.3. The PFDs (Figure A.4.3 through A.4.5) provide the number of major process steps in each PFD. The labor requirements for the elution-purification area are summarized in Table 4.33.

Table 4.33: Summary of Labor Requirements and Costs – Elution-Purification Area

| **Labor Requirements (@Design Capacity of 1200 tonnes U/year)** | | | | |
|---|---|---|---|---|
| | **Man-Hours Required** | **Operators Required** | **Annual Operator Salary** | **Total Cost (2010 US$)** |
| Elution | 31,600 | 17 | $83,000 | $1,400,000 |
| Purification | 101,000 | 52 | $83,000 | $4,300,000 |
| Precipitation | 62,400 | 32 | $83,000 | $2,700,000 |
| **Total for Elution and Purification (2010 US$)** | | | | $8,370,000 |

***Operating Costs: Raw Materials and Utilities***

Raw materials and utilities consumption were taken directly from the JAEA assessment for the elution portion of the process; however, the Fernald design report included raw materials and utilities consumption values that were used as the basis for the purification operating costs. To scale the raw materials and utility consumption for the purification area to the 1200 tonne per year basis, consumption was assumed to scale linearly. In reality, a detailed process model is needed to accurately predict raw materials and utilities at different scales.

For the precipitation area, detailed utility costs were not available; as a preliminary estimate, utility costs for the precipitation area were estimated as 4% of the delivered equipment cost. This matches the ratio of the utilities to equipment costs for the purification area. Raw materials consumption (ammonia) was taken directly from the JAEA assessment.

Price estimates for utilities (Table 4.7) and chemicals (Table B.4.4 in the Appendix) were used to estimate total raw materials and utilities costs for the back end processes.

Table 4.34: Summary of Raw Material Costs – Elution-Purification Area

| Chemical Requirements<br>(@Design Capacity of 1200 tonnes U/year) | | | |
|---|---|---|---|
| **Chemical** | **Annual Consumption** | **Unit Cost (2010 US$)** | **Total Cost 2010 US$** |
| 67% Nitric Acid | 5,180 tonnes | $284/tonne | $1,470,000 |
| 36% Hydrochloric Acid | 383 tonnes | $148/tonne | $56,600 |
| Sulfuric Acid, 66°Be | 73 tonnes | $63/tonne | $4,600 |
| Sodium Carbonate | 7 tonnes | $149/tonne | $1,040 |
| TBP | 4 tonnes | $6420/tonne | $25,100 |
| Kerosene | 11 tonnes | $553/tonne | $6,000 |
| Filter Aid | 0.07 tonnes | $325/tonne | $22 |
| Magnesium Oxide | 61 tonnes | $598/tonne | $36,500 |
| Ammonia | 0.45 tonnes | $341/tonne | $153 |
| Calcium Oxide (Lime) | 27 tonnes | $107/tonne | $2,900 |
| **Total for Elution-Purification (2010 US$)** | | | $1,610,000 |

Table 4.35: Summary of Utility Costs – Elution-Purification Area

**Utility Requirements**
**(@Design Capacity of 1200 tonnes U/year)**

| Utility | Annual Consumption | Unit Cost (2010 US$) | Total Cost 2010 US$ |
|---|---|---|---|
| Electricity | 2,840,543 kWh | $0.069/kWh | $196,000 |
| Process Water | 304,000 1000kg | $0.07/1000kg | $22,000 |
| Deionized Water | 184,000 1000kg | $1.08/1000kg | $199,000 |
| Steam | 1,630 1000kg | $32/1000kg | $52,200 |
| Cooling Water | 741 1000$m^3$ | $16.01/1000m^3 | $11,900 |
| Purification - All (4% of Delivered Equipment Cost) | N/A | N/A | $188,000 |
| **Total for Elution-Purification (2010 US$)** | | | $669,000 |

### *Operating Costs: Other Costs*

The elution-purification costs include disposal of the adsorbent at the end of its lifetime. The cost is treated as a fee-for-service or one-time operating cost for incineration of the adsorbent. Details of disposal are not included in this work, but previous analysis utilized a charge $0.36/kg adsorbent as a conservative estimate (Schneider and Sachde, Cost and Uncertainty Analysis of an Adsorbent Braid System for Uranium Recovery from Seawater 2011). The remaining operating costs were estimated by the methods summarized in section 4.2 and Table 4.7. The costs are not listed in detail here, but can be found as part of the COA for the elution-purification area in Appendix A.

***Summary: Elution-Purification Area***

The code of accounts for the elution-purification area is summarized in Table A.4.8. The summary reflects the base case results using the JAEA production parameters.

## 4.6 CONNECTING THE CODE OF ACCOUNTS TO LIFE CYCLE DISCOUNTED CASH FLOW ANALYSIS

The life cycle discounted cash flow (LCDCF) methodology was detailed in section 3.31.The LCDCF method was applied to the data from the code of accounts in an analogous manner to the previous chapter.

The code of accounts provides project costs by category in annualized expenses (e.g. annual operating costs or amortized capital costs). And will not account for the time value of money or other important system parameters that vary with time, such as adsorbent performance or degradation. LCDCF normalizes the annual costs to one tonne of adsorbent in the system.

To associate the annual costs from the COA with a single tone of adsorbent, two steps are taken (as in Chapter 3):

3) The costs in the two digit accounts are converted to annual costs by amortization (in the case of capital costs) and divided by the total annual uranium production. This results in a unit annual cost for each account.
4) The uranium unit cost can be associated with a tonne of adsorbent and its life cycle via the adsorption capacity. Adsorption capacity is given in kg U per tonne of adsorbent and is associated with a period of one recycle or campaign (i.e. 60 days in the base case). By multiplying the unit production cost of each COA category with the capacity of a tonne of adsorbent, the annual costs have been converted to a cost per recycle of a ton of adsorbent.

The COA costs can then be represented as a cash flow with each period being a recycle of adsorbent and the LCDCF methodology can be applied as before.

### 4.7 EVALUATION OF UNCERTAINTY

The methodology developed thus far employs a deterministic approach to cost estimation; in reality, however, many of the heuristics, scaling assumptions, and process inputs used to develop cost estimates are not known with certainty. Much of the data is accompanied by a range of feasible values or takes the form of a mean or expected value derived from underlying datasets. These uncertainties in input variables must be propagated through the analysis to provide a realistic depiction of the uncertainty associated with the metric of interest, the uranium production cost. To properly assess uncertainty associated with the cost model, it is important to first make distinctions amongst model inputs (Frey 1992).

- Decision Variables: This includes any variable that the modeler or estimator controls and defines to set the scope of the analysis. For example, the annual uranium production capacity for the system is a specific, point value defined by the modeler (1200 tonnes per year in the base case). This variable is NOT treated probabilistically; to analyze the impacts of decision variables on system costs, sensitivity analysis that defines specific cases of practical interest or significance is the appropriate approach.
- Value Parameters: As with decision variables, these parameters are selected by the analyst. Value parameters are not process variables, but rather represent

preferences or norms in design or cost estimation. Discount rate is one example of a value parameter. These parameters should be handled in sensitivity analysis as well.

- Empirical Quantities: These parameters are measurable process inputs and are the main focus of uncertainty characterization. Examples include performance parameters such as adsorbent capacity or equipment parameters such as maintenance costs or sizing. The cost estimation methodology in this chapter has largely focused on empirical quantities.

Empirical quantities come from a large range of sources (e.g. laboratory experiments, cost estimation literature, previous designs, etc.) and the data and associated uncertainty may take many forms. Three specific cases are used in this analysis to describe the state of information regarding uncertainty associated with input variables depending on the source of the input variables:

1) Explicitly provided range via literature (or experts in the field),
2) Calculated from a sample set of values or data,
3) Point estimate only; no uncertainty information provided (requires analyst judgment).

In all three cases, the uncertainty associated with a variable can be represented by an underlying probability distribution; this distribution can be used to develop a distribution for the final cost estimate that incorporates the uncertainty in input variables. In this analysis, all distributions will be treated as normal distributions unless sufficient empirical data exists to support another choice. At this early stage of development, many of the variables lack empirical data or even experience-based judgment, so alternate distributions often cannot be validated or justified. Additionally, the combination of a large set of input uncertainties will approach a normal distribution depicting the output parameter uncertainty (consistent with the Central Limit theorem)[11]. The normal distribution probability density function is parameterized by the mean and standard deviation:

$$\boldsymbol{f(x) = \left(\frac{1}{\sqrt{2\pi\sigma^2}}\right) e^{-\frac{(x-\mu)^2}{2\sigma^2}}} \tag{4.36}$$

where

$\mu$ = Population mean

$\sigma$ = Population standard deviation

x = Individual value from distribution or data set

The following sections describe the parameterization of probability distributions by defining the mean and standard deviation for each of the three forms of input data discussed previously.

### 4.7.1 Input parameter with explicitly provided range

In this scenario, the input variable used in the cost estimate includes a range of possible values; a mean value (point estimate) may or may not be explicitly stated. To develop a probability distribution for the variable, the point estimate and range must be

---

[11] The approximation to a normal distribution assumes the input uncertainties follow the same distribution and no single parameter dominates the overall uncertainty. The limited data at this early stage of process development justifies adhering to these basic assumptions until data shows other distributions are appropriate.

treated as parameters of a normal distribution. The point estimate (if given) will be treated as the mean of the distribution; if no point estimate is cited, the midpoint of the range will be treated as the mean. The specified upper and lower limits will be assumed to represent a two standard error displacement from the mean corresponding to a 95% confidence interval.

$$\boldsymbol{CI_{upper} = \mu + n\sigma} \tag{4.37a}$$

and

$$\boldsymbol{CI_{lower} = \mu - n\sigma} \tag{4.37b}$$

where

CI = Confidence Interval (upper and lower correspond to the bounds of the interval)

n = Number of standard deviations from the mean (N=2 for 95% confidence intervals)

Given an input parameter is provided as a range with a lower bound of A and an upper bound of B, the mean and standard deviation of a normal distribution would be calculated as follows:

$$\boldsymbol{\mu = \frac{A+B}{2}} \tag{4.38a}$$

and

$$\boldsymbol{\sigma = \frac{\mu-A}{n}} \tag{4.38b}$$

or

$$\boldsymbol{\sigma} = \frac{\boldsymbol{B-\mu}}{\boldsymbol{n}} \tag{4.38c}$$

A = Lower bound of given parameter range;

B = Upper bound of given parameter range;

A parameter that was previously described by an explicitly provided range can now be expressed as a normal distribution described by a mean and standard deviation using equation 4.19 in conjunction with 4.20 and 4.21.

### 4.7.2 Input Parameter from a sample set of data

In this case, the input parameter is derived from an existing sample set of data from experimentation or from literature; two possible scenarios exist for deriving a parameter from an existing dataset:

1) The sample set of data represents the underlying distribution of the point estimate used in the analysis. Examples include average electricity or chemical prices derived from a historical dataset.
2) The sample set of data is *correlated* to the relevant input parameter; the input parameter is derived via regression analysis of the dataset. Examples include the cost scaling exponents regressed from historical data or performance parameters such as the capacity of the adsorbent regressed from experimental data.

The two cases require different approaches in deriving the uncertainty associated with the estimated input data.

***Input data derived directly from sample data set***

To evaluate the uncertainty associated with an average value taken from a sample set of data, simple statistical techniques to calculate the sample mean and variance can be used:

$$\overline{x} = \sum_{i=1}^{N} \frac{x_i}{N} \tag{4.39a}$$

And

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \overline{x})^2} \tag{4.39b}$$

where

$\bar{x}$ = Sample mean,

s = sample standard deviation

$x_i$ = Individual sample data points

N = Sample size

The sample mean and sample standard deviation are approximations of the population mean (μ) and population standard deviation (σ) in equation 4.19 and can be used to define a normal distribution (or other distribution if justified) for the input parameter.

### *Regressed Input Parameter*

Some input parameters are derived via regression from experimental or historical data. However, the regression models and equations will not explain all of the variability in the data set; a residual error will remain. A basic linear regression model illustrates the empirical estimation of an input parameter from a dataset:

$$y = \beta_0 + \beta_1 x_1 + \cdots + \beta_i x_i \quad (i = 1\ to\ N) \tag{4.40}$$

where

y = Dependent variable (Input variable estimated for this analysis)

x = Independent variable

$\beta i$ = Regression fit parameter

N = Observations in the dataset

Each regression fit parameter, $\beta_i$, has an associated uncertainty that must be propagated to the input variable of interest. The general error propagation equation can be used to propagate uncertainty in a regression model (expressed here in terms of the linear regression model):

$$\delta y = \sqrt{\left(\frac{\partial y}{\partial \beta_i} * \delta \beta_i\right)^2} \quad (i = 1\ to\ N) \tag{4.41}$$

where

$\delta y$ = Uncertainty in the dependent variable

$\delta \beta i$ = Uncertainty in regression parameter

The standard error associated with the regression parameter (often reported in regression analysis software) can be used in equation 4.x to determine the uncertainty in the input parameter used in the cost model. The uncertainty in y can then be used as the standard deviation to develop a representative normal distribution for the parameter. The least squares method of regression presented here assumes that the independent parameter (x) is a deterministic value and has no associated uncertainty (Golberg and Cho 2004). Cases may arise where the independent variable is uncertain or contains measurement error; this situation requires alternate methods, such as error in variables regression. However, those methods are not considered in this analysis, and the independent values are taken as constant.

### 4.7.3 Input Parameter with no information about uncertainty

In the case of input parameters that are only available as a point estimate, an estimation of the uncertainty must still be developed using analyst judgment or experience. This analysis will assume any point estimate parameters without information regarding uncertainty will have a range of +/- 30% around the point estimate; the range is consistent with the uncertainty typical for order of magnitude cost estimates (see Table 4.4). The range around the point estimate is used just as in the previous section where the range was explicitly provided. The upper and lower bounds of the range can be substituted into equations 4.21a-c to derive the mean and standard deviation of the probability distribution that describes the input parameter.

### 4.7.4 Propagation of Uncertainty: Monte Carlo Method

Table 4.36 summarizes all relevant input parameters and the mean and standard deviation of each distribution representing the parameter. All parameters in the table were treated as normal distributions.

Table 4.36: List of variables included in Monte Carlo Analysis with mean and standard deviation

| Item | Mean | Standard Deviation |
|---|---|---|
| Cost of Electricity ($/kWh) | 0.069 | 0.0022 |
| #2 Heating Oil ($/gal) | 2.12 | 0.28 |
| Nitric Acid ($/tonne) | 284 | 47 |
| Ammonia ($/tonne) | 341 | 148 |
| Hydrochloric Acid ($/tonne) | 148 | 58 |
| Sulfuric Acid ($/tonne) | 63 | 20 |
| Tributyl Phosphate ($/tonne) | 6419 | 1848 |
| Kerosene | 1.70 | 0.69 |
| Filter Aid (Diatomite) ($/tonne) | 325 | 59 |
| Magnesium Oxide ($/tonne) | 598 | 121 |
| Calcium Oxide (Lime) ($/tonne) | 107 | 15 |
| Polyethylene (HDPE) ($/tonne) | 1467 | 280 |
| Acrylonitrile ($/tonne) | 1331 | 587 |
| Dimethylformamide ($/tonne) | 1245 | 591 |
| Hydroxylamine ($/tonne) | 3077 | 411 |
| Methanol ($/tonne) | 284 | 127 |
| Surfactant (Sodium Dodecyl Sulfate) ($/tonne) | 2101 | 642 |
| Sodium Carbonate ($/tonne) | 149 | 43 |
| Land (% of FCI) | 0.015 | 0.0025 |
| Plant Licensing (% of FCI) | 0.03 | 0.015 |
| Chemical Plant - Cost Scaling | 0.67 | 0.13 |
| Solvent Extraction Cost Scaling | 0.73 | 0.1095 |
| Direct supervisory and clerical labor Estimation Factor (% of OL Cost) | 0.175 | 0.0375 |
| Maintenance Estimation Factor (% of FCI) | 0.06 | 0.02 |

Table 4.36 (continued)

| | | |
|---|---|---|
| Operating Supplies Estimation Factor (% of FCI) | 0.011 | 0.0045 |
| Local Taxes and Insurance Estimation Factor (% of FCI) | 0.032 | 0.009 |
| Mooring and Deployment: Other Operating Cost Factor (% of FCI) | 0.04 | 0.005 |
| Purchased Equipment Delivered | 100% | 15% |
| Melt Spinning Cost Scaling Exponent | 0.46 | 0.09 |
| E-Beam Cost Scaling Exponent | 0.26 | 0.11 |
| Disposal Cost Uncertainty | 0.36 | 0.054 |
| Adsorbent Degradation (% per recycle) | 0.05 | 0.025 |
| Adsorbent Capacity (kg U/t adsorbent) | 2.0 | 0.5 |

With probability distributions defined for all relevant input parameters, the impact of the uncertainty around input parameters on the final cost estimate must be quantified. Due to the large set of input parameters and complex final cost function derived from those input parameters, standard error propagation methods would present many challenges; the method requires a detailed account of all calculations performed on input parameters as part of their propagation to a final cost estimate. Instead, a Monte Carlo stochastic estimation approach will be used. A random number will be generated for every input parameter and used to derive corresponding value for of the input parameter from the associated probability density function. The newly generated input values will be used to calculate a point estimate for the cost. The process will then be repeated with a new set of random numbers for the input parameters; several iterations will be performed until the final cost estimate is represented by a distribution of values corresponding to the varying input parameters. This iterative process conceptually describes the Monte Carlo method of uncertainty propagation. By using a repeated series of deterministic calculations, step by step error calculations are avoided; each iteration is treated as if only a point estimate was provided.

# Chapter 5: Results and Discussion

## 5.1 BASE CASE RESULTS

The base case for the current analysis was defined in terms of several key input parameters initially developed in JAEA cost estimation work (Tamada, et al. 2006). Table 5.1 summarizes the input parameters alongside the original values used in the work by JAEA.

Table 5.1: Base case parameter comparison with JAEA Analysis (Tamada, et al. 2006)

| **Parameter** | **JAEA** | **Current Analysis** | **Unit** |
|---|---|---|---|
| Annual Uranium Production | 1200 | 1200 | metric ton/year |
| Seawater Temperature | 25 | 25 | °C |
| Adsorption Capacity | 2 | 2 | kg U/ t adsorbent |
| Length of Mooring Campaign | 60 | 60 | days |
| Adsorbent Recycles | 6 | 6 | N/A |
| **Adsorbent Degradation Rate** | **0%** | **5%** | **% per recycle** |
| **Discount Rate** | **0%** | **7%** | **annual rate** |
| **Interest Rate of Capital** | **3%** | **10%** | **annual rate** |
| Amortization Period: Buildings | 30 | 30 | years |
| Amortization Period: Equipment | 15 | 15 | years |
| **Interest During Construction** | **No** | **Yes** | **N/A** |
| **Disposal Costs** | **No** | **Yes** | **N/A** |

Key differences from the JAEA analysis include a 5 percent degradation rate of the adsorbent per recycle; the assumption is based on previous work in Japan where 20%

loss in adsorbent capacity was observed after 5 recycles due to repeated acid elution (Sugo, et al. 2001).

The financial assumptions in Table 5.1 also differ from previous work. JAEA focused on annual costs and did not consider the time value of money; to implement the discounted life cycle cash flow methodology in this assessment, a 7 percent discount rate was assumed. The choice of discount rate will be considered in sensitivity analyses. In addition, interest rate of capital in the JAEA analysis was fixed at 3%. To reflect a representative rate of private financing in the United States, 10% was chosen for this work; this assumption will also be considered in sensitivity analysis.

Finally, the current analysis includes costs for interest during construction and disposal of adsorbent that were not part of the JAEA analysis. Specifics for interest during construction and disposal costs are covered in Appendix C.

The results of the analysis using the methodology described in chapter 4 are first compared alongside the JAEA analysis presented in chapter 3 in detail. The costs from the code of accounts were aggregated to match the JAEA capital and operating costs as closely as possible. Table 5.2 summarizes these results.

Table 5.2: Results comparison with JAEA by process area and aggregate cost categories (Tamada, et al. 2006)

<table>
<tr><th colspan="5">Adsorbent Production Costs</th></tr>
<tr><th rowspan="2">Items</th><th>JAEA Estimate</th><th>Current Analysis</th><th rowspan="2">Notes</th><th rowspan="2">COA Reference Accounts</th></tr>
<tr><th>2010 US$</th><th>2010 US$</th></tr>
<tr><td><b>Annual Amortized Capital Costs</b></td><td>$27,500,000</td><td>$27,100,000</td><td>Current Analysis Includes Interest During Construction</td><td>Accounts 1-6</td></tr>
<tr><td><b>Annual O&M Expenses</b></td><td>$103,000,000</td><td>$115,000,000</td><td>All operating costs excluding chemicals</td><td>Accounts 7 and 9 (excl. 74)</td></tr>
<tr><td><b>Chemicals and Materials</b></td><td>$607,000,000</td><td>$397,000,000</td><td>Same chemicals and consumption in both analyses. Difference in chemical prices.</td><td>Account 74</td></tr>
<tr><th colspan="5">Mooring and Deployment Costs</th></tr>
<tr><th rowspan="2">Items</th><th>JAEA Estimate</th><th>Current Analysis</th><th rowspan="2">Notes</th><th rowspan="2">COA Reference Accounts</th></tr>
<tr><th>2010 US$</th><th>2010 US$</th></tr>
<tr><td><b>Annual Amortized Capital Costs</b></td><td>$149,000,000</td><td>$353,000,000</td><td>Current Analysis Includes Interest During Construction</td><td>Accounts 1-6</td></tr>
<tr><td><b>Annual O&M Expenses</b></td><td>$163,000,000</td><td>$257,000,000</td><td>Current Analysis includes seabed leasing cost</td><td>Accounts 7 and 9</td></tr>
</table>

Table 5.2 (continued)

| Elution-Purification Costs | | | | |
|---|---|---|---|---|
| **Items** | **JAEA Estimate** | **Current Analysis** | **Notes** | **COA Reference Accounts** |
| | **2010 US$** | **2010 US$** | | |
| **Annual Amortized Capital Costs** | $11,000,000 | $17,600,000 | Current Analysis Includes Interest During Construction | Accounts 1-6 |
| **Annual O&M Expenses** | $10,000,000 | $25,700,000 | N/A | Accounts 7 and 9 |
| JAEA numbers derived from Tamada et al., 2006. Values were converted from Japanese yen to US$ using the 2005 exchange rate of 110 yen per US Dollar. Capital costs associated with adsorbent production and elution were inflated with the Chemical Engineering Price Index (Appendix B). All other values inflated using the general CPI (Appendix B) | | | | |

As expected, the costs vary between the assessments due to methodological differences, unique assumptions in process and equipment specification, and independent sources of cost data. Potential sources of difference are briefly highlighted in the table, but are not the focus of this assessment.

Figure 5.1 depicts the base case cost estimation results as a histogram accounting for uncertainty in the cost estimate. The uncertainty associated with the expected value was derived via Monte Carlo propagation of uncertainty around several input variables as discussed in the previous chapter. The expected value of the base case scenario (all parameters fixed at their respective mean or expected values as summarized in Table 4.36) is $1230 per kg U extracted. However, the figure depicts the associated uncertainty with the expected value; a two sigma range (approximating a 95% confidence interval) corresponds to a cost estimate of [$689/kg U to $2850/kg U].

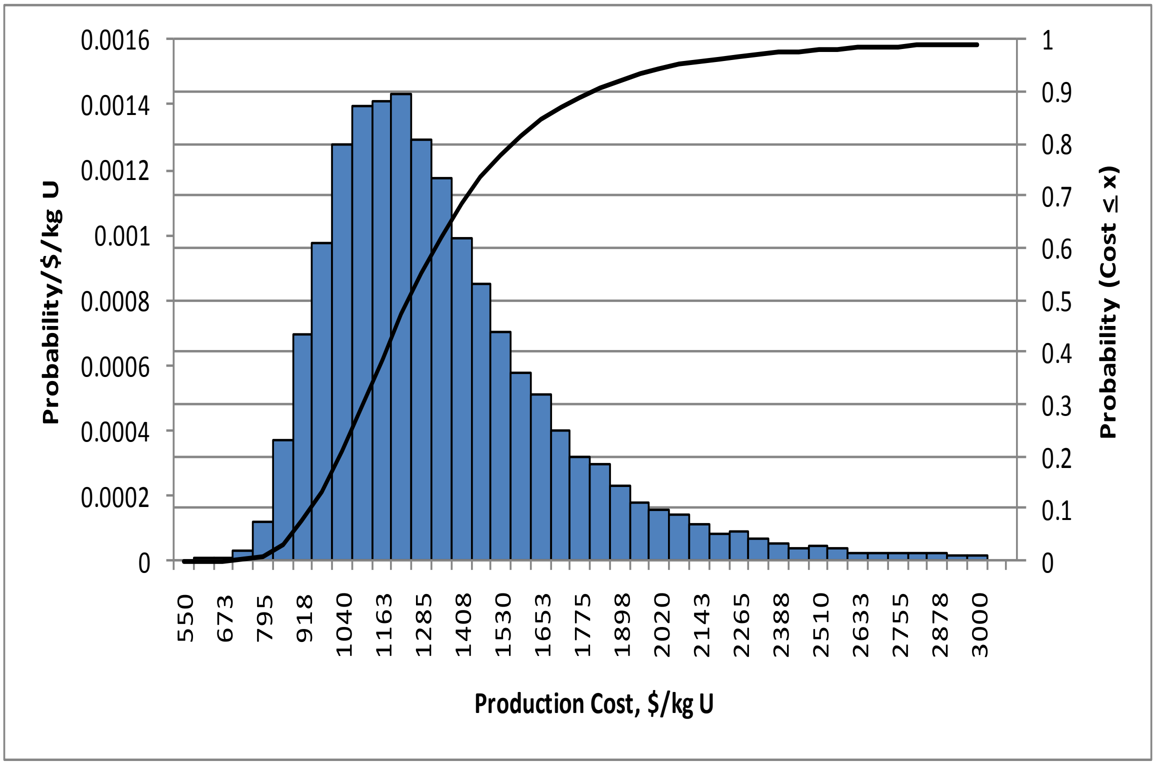


Figure 5.1: Histogram and cumulative probability curve of base case cost estimate

The figure includes two measures of probability assessment for uranium production cost. The primary axis (to the left of the figure) is associated with the height of the individual histogram bars and is scaled to reflect the relative likelihood of a Monte Carlo assessment falling within the defined bin. The secondary axis (to the right) is associated with the cumulative probability curve in the figure; the curve indicates that the probability that production costs will be less than or equal to a given value. For example, the cumulative probability curve for the base case indicates near 0 probability for production costs below \$550/ kg U. The cumulative probability distribution is a powerful tool for decision-makers. Once a specific criterion for investment is defined (e.g. return on investment), the probability for specific uranium production costs from the cumulative distribution can be used with the investor’s risk preference to evaluate the investment decision without an absolutely certain deterministic value for production costs.

The skewed nature of the distribution can be explained by the uncertainty in adsorbent capacity; the unit production cost of uranium is calculated by dividing total production costs by the quantity of uranium recovered. Therefore, a drop in adsorbent capacity has a proportionally larger impact on unit production costs than an equivalent relative increase in capacity. The distribution for the expected value provides evidence that the capacity is the dominant uncertainty in the analysis; a normal distribution would be expected for an analysis with identical input distributions without a dominant variable. Further evaluation of the Monte Carlo results confirms the adsorbent capacity as the primary source of uncertainty in uranium production costs. Table 5.3 provides the expected value for the uranium production cost with associated uncertainty and key components comprising the uncertainty. The asymmetrical range for the two sigma interval around the cost estimate is a reflection of the distribution in Figure 5.1.

Table 5.3: Base case cost estimate results with categorized uncertainty

| Capacity (kgU/t ads) | Recycles | Cost (2010 US$/kgU) | +/- 2σ | Component Uncertainty | | |
|---|---|---|---|---|---|---|
| | | | | ± Capacity[1] | ± Degradation[2] | ± Cost[3] |
| 2 | 6 | 1230 | +1620 | +1230 | 72 | 124 |
| | | | -541 | -410 | | |

1. Capacity refers to uncertainty in adsorbent performance at varying temperatures.
2. Degradation rates have only been quantified as point estimates. A ± 50% standard deviation interval was assumed.
3. Cost uncertainty includes variability in prices of equipment, chemicals, and estimation techniques.

The results in Table 5.3 have important ramifications for future work and assessment of the viability of uranium extraction from seawater. The uncertainty in capacity is primarily a function of a limited empirical data to quantify adsorbent performance in field conditions. In the current analysis, a regression model was developed to assess adsorbent performance as a function of time and temperature; the model was presented in section 3.4.1 (see Figure 3.8 and Table 3.11). The standard deviation for adsorbent capacity was derived from the standard error associated with regression coefficients in the time-temperature regression model via error propagation methods reviewed in section 4.7.2. A mean value of 2 kgU/t adsorbent with a standard deviation of 0.5 kg U/ t adsorbent was used to parameterize a normal distribution for adsorbent capacity. If the adsorption capacity could be treated as constant in the analysis, the 2 sigma range around the expected value of $1230 kg U/ t adsorbent would drop from [$689/kg U, $2850/kg U] to [$1030/kg U, $1430/kg U].

Finally, Figure 5.2 is the discounted cash flow diagram for the base case process at 6 recycles.

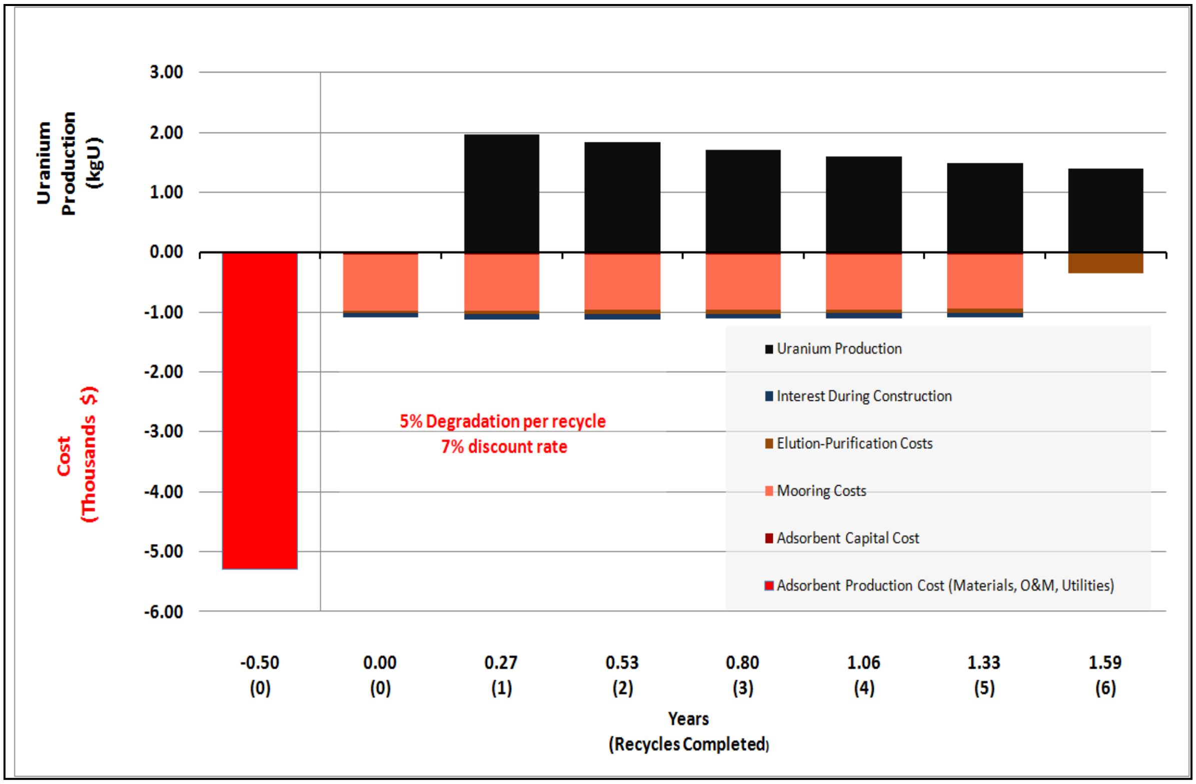


Figure 5.2: Life cycle discounted cash flow diagram for base case analysis at 6 recycles

The declining uranium production (in black) reflects the effect of adsorbent performance degradation and discounting. The chart also highlights adsorbent production as a key cost driver; the large initial investment prior to operations emphasizes the importance of the timing of uranium production to provide return on the investment.

### 5.2 SENSITIVITY ANALYSES

The production cost estimates of several alternative adsorbent performance scenarios are summarized in Table 5.4; the base case estimate is reproduced in the table for comparison.

Table 5.4: Summary of uranium production cost estimation results for base case and alternatives including uncertainty quantification.

| **Capacity (kgU/t ads)** | **Recycles** | **Cost (2010 US$/kgU)** | **+/- 2σ** | **Component Uncertainty** | | |
|---|---|---|---|---|---|---|
| | | | | **± Capacity[1]** | **± Degradation[2]** | **± Cost[3]** |
| **2** | **6** | **1230** | **+1620** | **+1230** | **72** | **124** |
| | | | **-541** | **-410** | | |
| 2 | 18 | 1180 | +2000 | +1180 | 346 | 66 |
| | | | -668 | -393 | | |
| 4 | 6 | 659 | +864 | +659 | 38 | 64 |
| | | | -288 | -220 | | |
| 4 | 18 | 642 | +1100 | +642 | 192 | 36 |
| | | | -366 | -214 | | |
| 6 | 6 | 482 | +630 | +482 | 32 | 42 |
| | | | -210 | -161 | | |
| 6 | 18 | 484 | +828 | +484 | 144 | 28 |
| | | | -276 | -161 | | |

1. Capacity refers to uncertainty in adsorbent performance at varying temperatures.
2. Degradation rates have only been quantified as point estimates. A ± 50% standard deviation interval was assumed.
3. Cost uncertainty includes variability in prices of equipment, chemicals, and estimation techniques.

The alternative scenarios in Table 5.4 correspond to cases considered in the cost estimation work by JAEA; their analysis recognized 4 kg U per tonne of adsorbent as a feasible capacity and viewed the 6 kg U capacity and 18 recycles as an optimistic case (Tamada, et al. 2006). The table spans the range of these performance variables to provide insight into the impact on cost and uncertainty. To evaluate adsorbent capacity uncertainty at the varying nominal capacities listed in the table, the uncertainty ( or standard deviation) was assumed to scale linearly from the base estimate 2 ± 0.5 kg U/ t adsorbent. For example, the standard deviation at 4 kg U/ t adsorbent would be 1. All other parameters from the base case are held constant in the analysis in Table 5.4. It is important to note that the increase in uranium production in each scenario reflects inherent improvement in technology; parameters such as immersion time and temperature are considered in separate sensitivity analyses that follow. In addition, the improvement in capacity does not impact the costs associated with the system; this condition should be tested as improved technology develops to allow a full evaluation of improved performance.

The table reveals several important trends. First, as the number of recycles increases for a given capacity, the uncertainty around the expected production cost increases correspondingly. The increase in uncertainty is driven by the growing importance of degradation with the number of recycles. As the cash flow diagram in Figure 5.2 illustrated, degradation imposes a penalty on repeated use of adsorbent material. Quantifying the degradation is critical to identifying the optimal number of recycles for an adsorbent material; uncertainty in degradation makes it difficult to distinguish the benefit of the high recycle cases in Table 5.3 and, in turn, makes decisions about adsorbent production strategies difficult (e.g. high cost, long-life materials vs. low cost “throw away” materials.)

Table 5.5 evaluates several system parameters over a range of values to identify key cost drivers for the braid adsorbent extraction process. All parameters are evaluated in terms of percent change in production cost relative to the base case expected value of \$1230/ kg U.  All other system variables are held constant at the base case conditions in Table 5.1 during variation of a given parameter.

Table 5.5: Summary of parameter sensitivity analyses

| **Variable** | **Low Cost Point** | ***% Change*** | **Base Case Values*** | ***%Change*** | **High Cost Point** |
|---|---|---|---|---|---|
| Discount Rate (%) | 0% | *-5.89%* | 7% | *6.75%* | 15% |
| Interest Rate of Capital | 3% | *-12.46%* | 10% | *10.35%* | 15% |
| Recycles | 18 | *-4.38%* | 6 | *32.61%* | 3 |
| Seawater Temperature | 30 °C | *-10.31%* | 25 | *43.25%* | 15 °C |
| Adsorbent Performance Loss (%/Recycle) | 0% | *-11.46%* | 5% | *12.76%* | 10% |
| Adsorption Capacity (g-U/kg-ads) | 6 | *-60.88%* | 2 | *95.05%* | 1 |
| Annual Consumption of Hydroxylamine | 28K metric tons | *-8.09%* | 56K metric tons | *15.25%* | 110K metric tons |
| Annual Consumption of Acrylonitrile | 17K metric tons | *-2.27%* | 35K metric tons | *4.25%* | 70K metric tons |
| Annual Consumption of DMF | 32K metric tons | *-3.78%* | 65K metric tons | *7.51%* | 130K metric tons |

Table 5.5 (continued)

| | | | | | |
|---|---|---|---|---|---|
| Size of Mooring Chain | 38 mm | *-3.43%* | 44 mm | *5.58%* | 50 mm |
| Annual Uranium Production Capacity | 4800 metric tons | *-3.45%* | 44 mm | *22.43%* | 300 metric tons |

*Base Case conditions (2 g U/kg ads, 6 recycles, 5% degradation) for all parameters not included in sensitivity analyses. All percentages are differences from the expected uranium production costs at the base case conditions, $1230/kg U (2010 US $)

As expected performance parameters such as recycles, degradation, and adsorption capacity (and the related effect from seawater temperature) are dominant cost drivers. This is consistent with the sensitivity results on the JAEA cost model in Table 3.12; however, the table again emphasizes the importance of degradation on recycles. The addition of the 5% degradation rate to the base case in this analysis dampens the benefits of increased recycling. In addition, the consumption of grafting chemicals is highlighted. A 50% reduction in hydroxylamine consumption, for example, provides 8% reduction in costs; while reducing consumption for a single chemical by half may not reflect a feasible scenario, the aggregate impact of reduction to all of the grafting chemicals in Table 5.5 could be potentially significant. To quantify the impact, production scale consumption of chemicals must be understood. Finally, the last row in Table 5.5 reflects the incorporation of economies of scale in the cost methodology used in this analysis. Specifically, a small benefit is accrued in unit production costs for a major scale up of uranium production while a significant penalty is imposed for a drop in scale. This will be an important consideration as the process approaches the design and investment stage.

### 5.2.1 Financial Parameters

Figures 5.3 and 5.4 consider the impact of discount rate in tandem with a change in number of recycles. Figure 5.3 reflects the base case of 5% degradation while Figure 5.4 assumes no degradation.

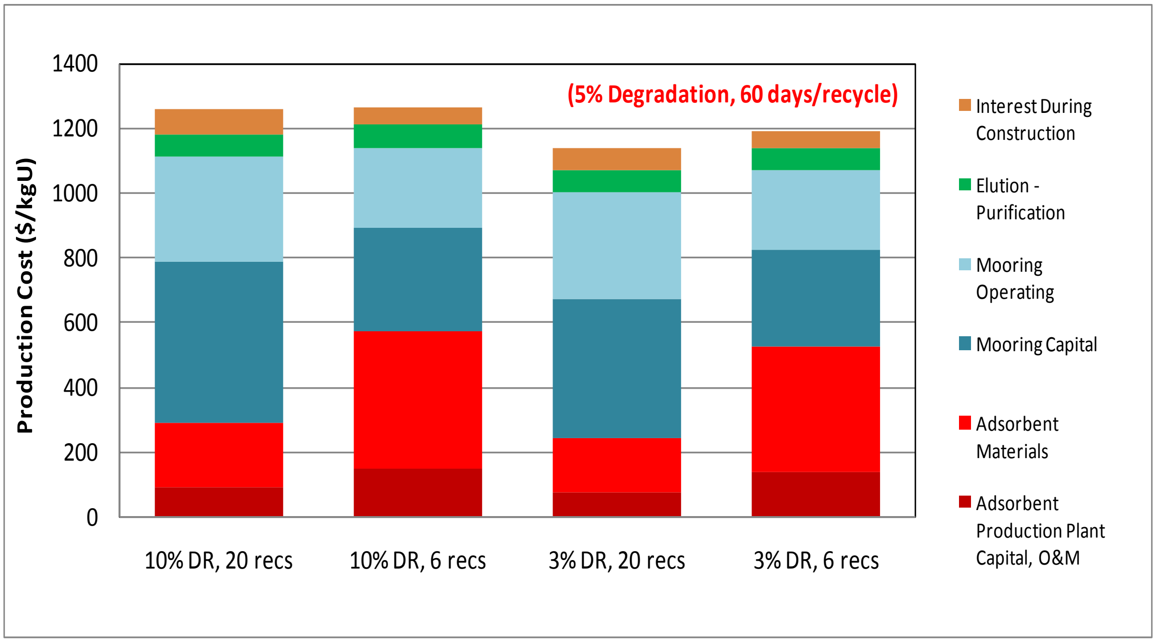


Figure 5.3: Components of uranium production cost, varying discount rate and recycles, 5%degradation rate

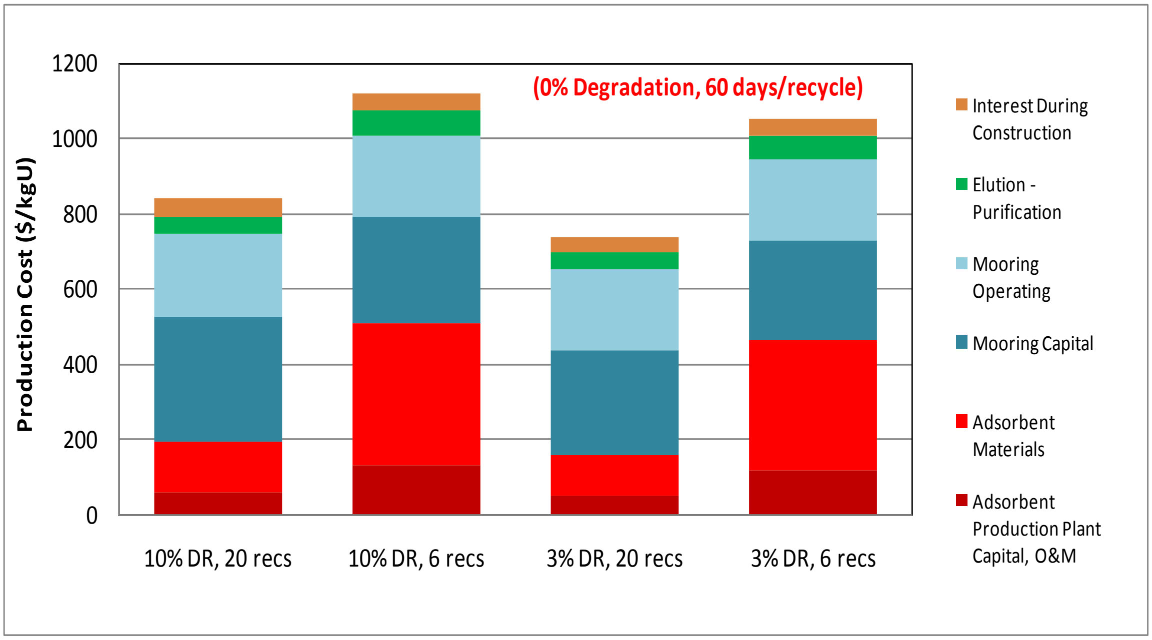


Figure 5.4: Components of uranium production cost, varying discount rate and recycles, 0%degradation rate

Increased discount rates penalize deferred benefits and provide a potential deterrent to long term recycling. However, comparison of the two figures reveals that the effect of degradation dominates the economics of recycling over time, the benefit of increased recycles is evident at 3% and 10% in Figure 5.4 (no degradation); the incorporation of degradation makes the recycle scenarios nearly indistinguishable. To isolate the effect of discount rate, adsorbent production costs (in red) can be considered. Comparing cases of a common number of recycles but differing discount rates (e.g. 6 recycles at 3% vs. 6 recycles at 10%) in either figure reveals that adsorbent production costs become more significant at higher rates. The discount rate impact may be an important consideration during investment and is a function of the individual investor (opportunity cost for that investor).

Next, Figure 5.5 considers the impact of interest rate of capital. The two points indicated with labels and error bars in the diagram reflect the low-end assumption in the JAEA analysis and the high end assumption used in this analysis. The bounds also reflect the range of rates that might be expected in projects supported or funded by government to projects fully funded by private investment.

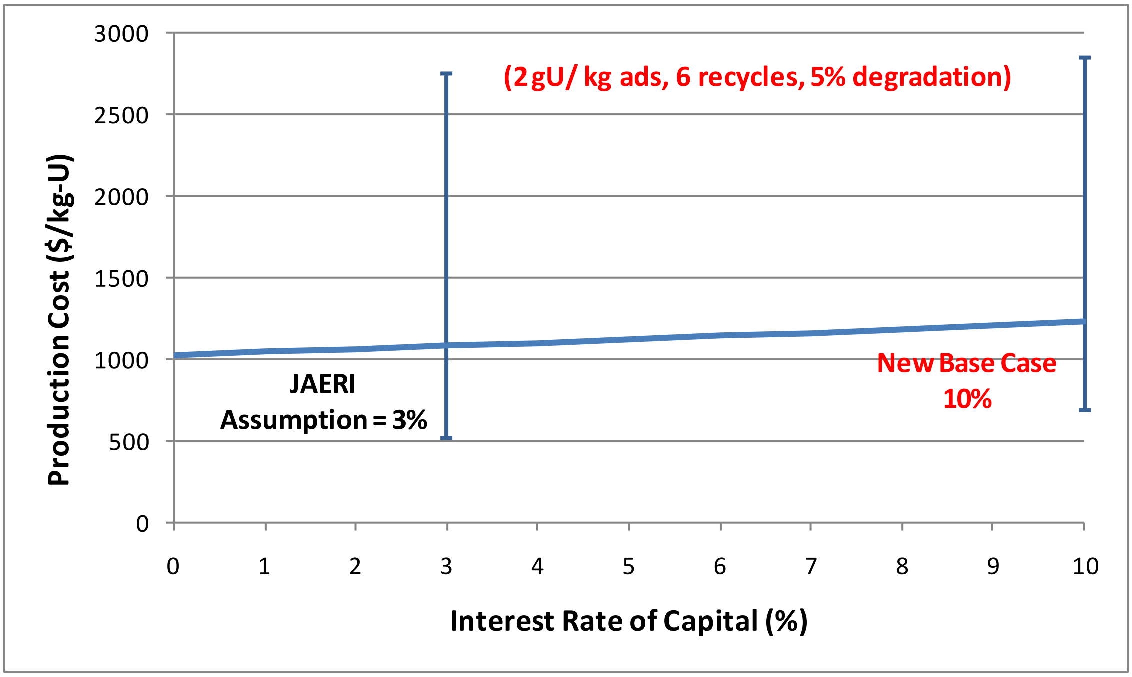


Figure 5.5: Change in production cost with varying interest rate of capital

As the figure depicts, interest rate of capital is not a major cost driver – the range from 3 to 10% represents a change of about $150/kg U in production cost – but is still important as part of the initial investment decision. The error bars in the chart, which include all sources of error in this analysis and represent a two sigma range, reveal a potentially valuable insight as well. The range in uncertainty is so large at this early stage of development that the difference in interest rates is negligible relative to the uncertainty; the practical implication is that investment decisions cannot be made with the current level of uncertainty in production costs.

### 5.2.1 Performance Parameters

Figure 5.6 is based on the time-temperature relationship to adsorption capacity discussed previously. The figure depicts the production cost of uranium with increasing time at sea and at temperatures ranging from 15°C to 25°C. The temperature range depicted roughly corresponds to the range exhibited in the five regions along the United States coastline identified as potential mooring areas (see section 4.42).

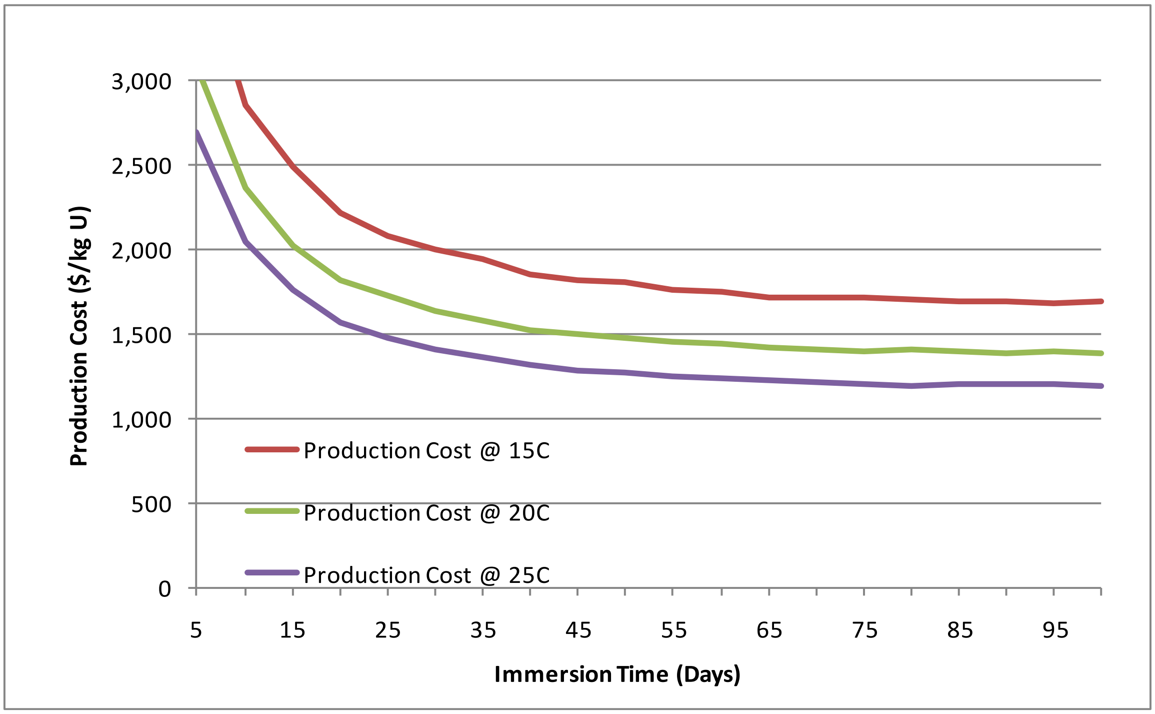


Figure 5.6: Production cost as a function of immersion time and seawater temperature

As expected, after an initial drop in costs with immersion time each curve flattens over time. The adsorbent eventually approaches saturation and the marginal benefit of an additional day at sea approaches zero.

Based on the figure, the base case of 60 days and 25°C is in the flat cost region representing a minimum among the three curves. Therefore, based on the current knowledge of the kinetic and thermodynamic behavior via empirical data, the base case conditions are justified.

Figure 5.7 illustrates the idea of an optimal number of recycles for the braid adsorbents. The plot includes adsorption capacities from 2 kg U/ t adsorbent up to 8 kg U/ t adsorbent and uses base case conditions for all other parameters. At every capacity, the optimal number of recycles appears to be near 11 recycles. Specifying the rate of degradation with certainty is important to developing optimal recycle estimates; Figure 5.7 assumes degradation is constant at 5%. The rate of degradation ultimately determines the point at which the reduced uranium production in additional recycles outweighs the fixed costs of the system, such as mooring and deployment of the adsorbent.

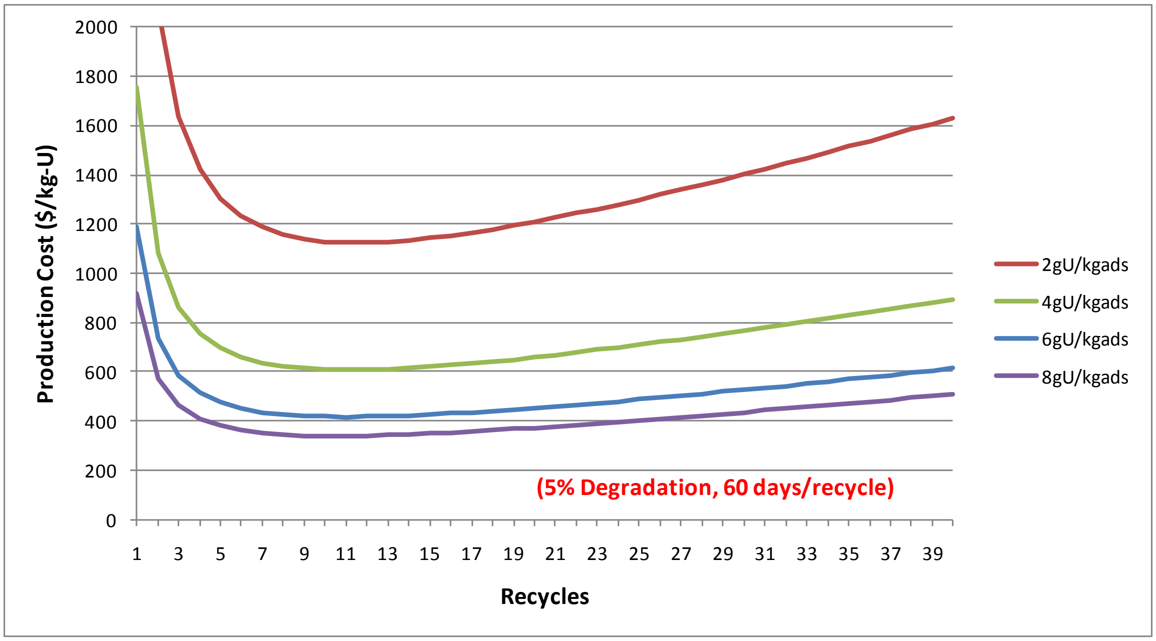
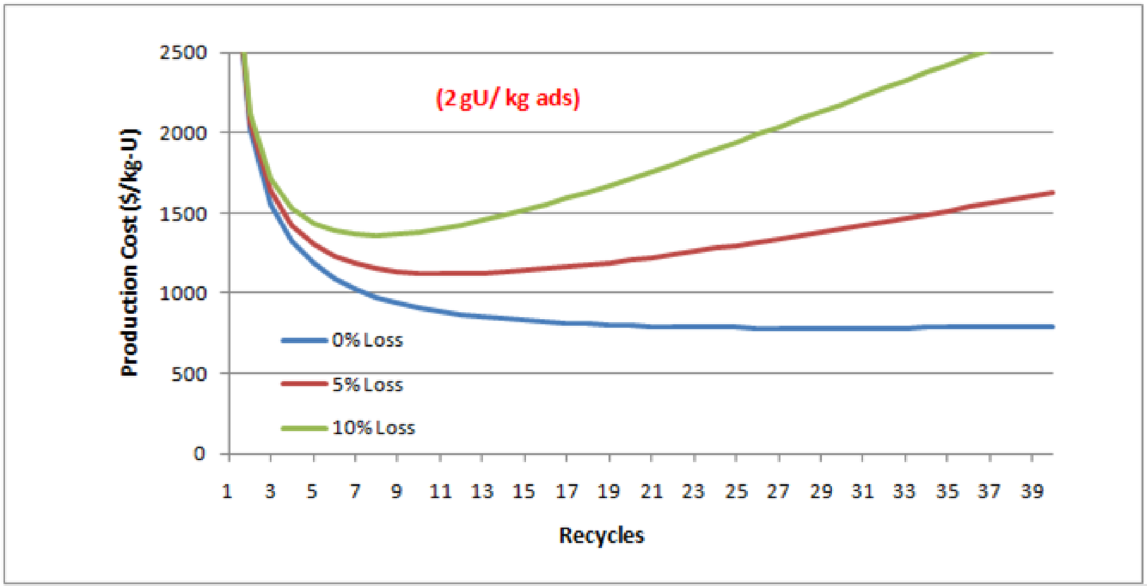
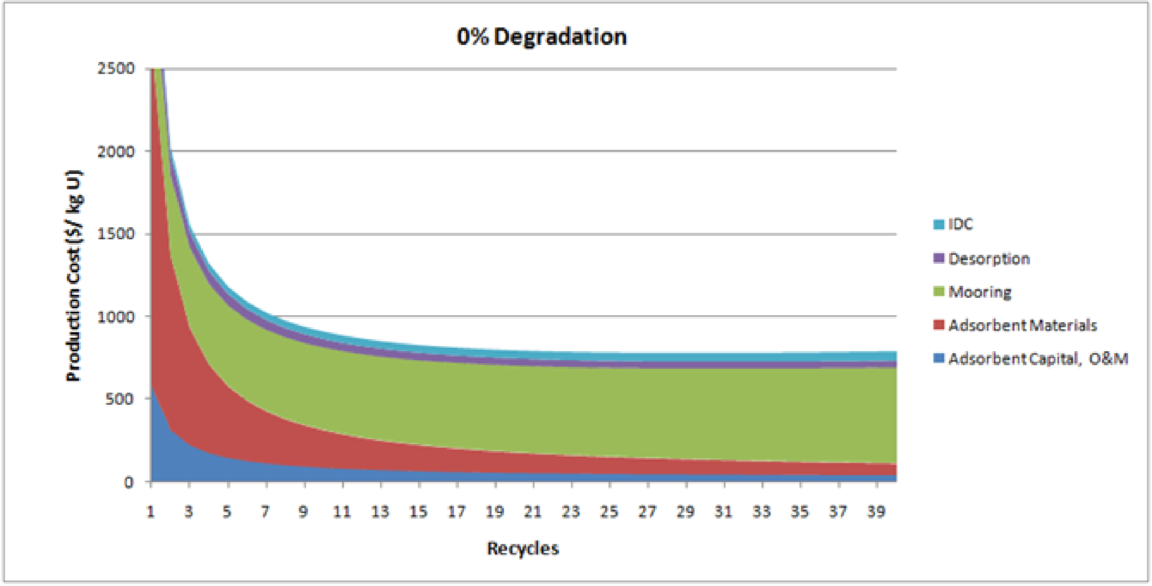


Figure5.7: Production cost with varying recycle lifetime and adsorption capacity, base case conditions

Finally, Figure 5.8 provides an alternate view optimal recycles. In this case, the adsorption capacity is held constant at 2 kg U / t adsorbent and degradation rate is varied from 0 to 10%. The chart illustrates the idea that lost adsorbent capacity is a major limiting factor in developing braid adsorbents; the 0% case indicates continuous cost reduction with increased recycles. The 5% case limits optimal recycles to 11 and 10% degradation limits recycles to approximately 7 to achieve minimum cost. In addition, for each level of degradation, the figure breaks out the total unit production cost into costs by area. The results indicate that additional recycles increase the relative cost of mooring and deployment, while adsorbent production becomes less significant. As mentioned, this is due to the fact that the high mooring capital costs are continuous over the lifetime of the adsorbent while adsorbent production costs are incurred only at the start of the lifetime. The mooring costs serve as a minimum cost for a system regardless of improvements in adsorbent performance.





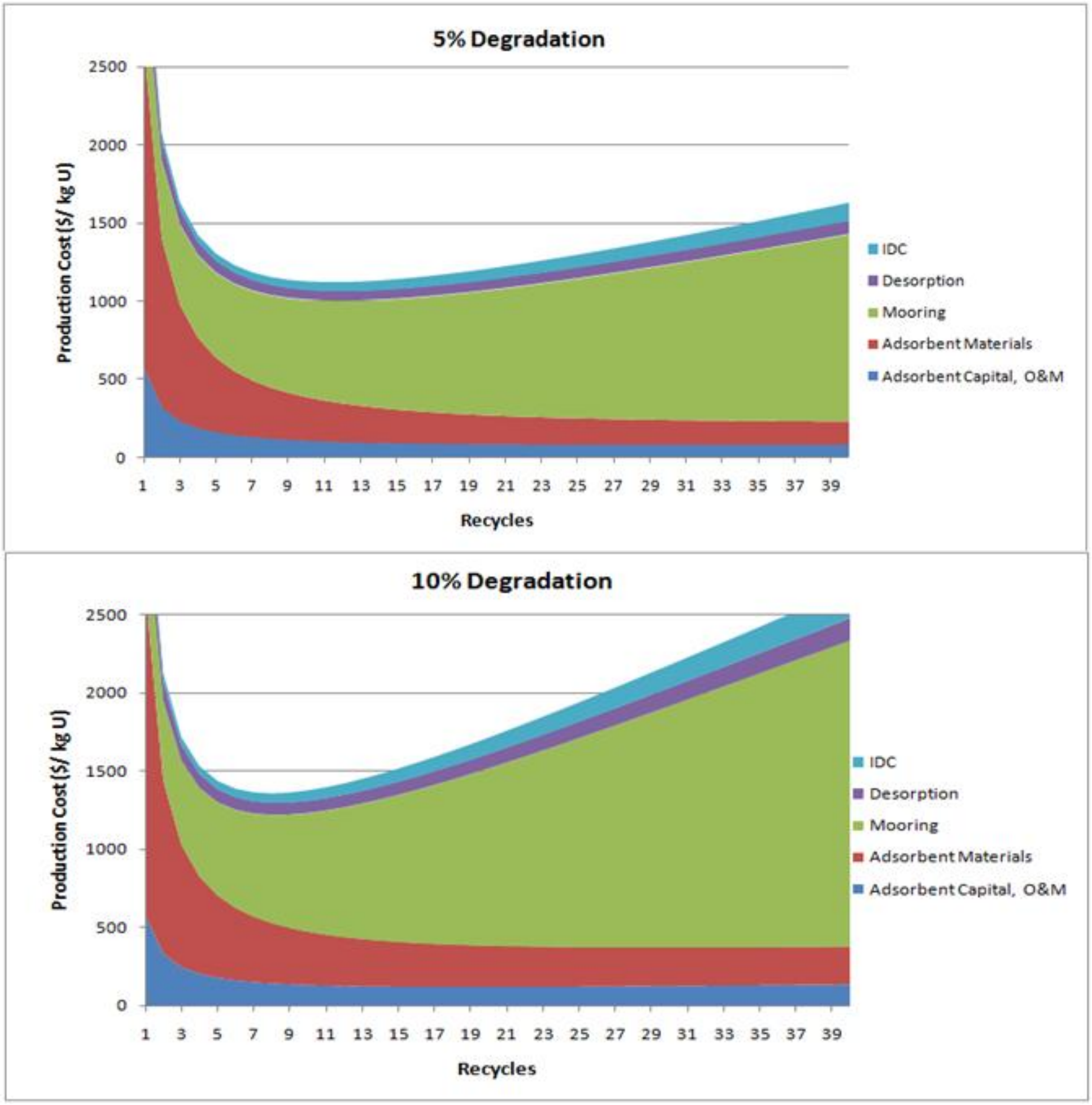


Figure 5.8: Optimal recycles of adsorbent given varying degradation rates

## 5.3 KEY SYSTEM ALTERNATIVES

The cost assessment in this work focused on the baseline design developed by JAEA; however, in all areas of the process, alternative configurations and optimization are possible and should be evaluated in detail to refine the initial cost estimate developed here. Several alternatives became evident during the preliminary cost analysis and merit further consideration:

1) Alternative grafting chemistry (Area: Adsorbent Production)
2) Alternative mooring configuration/optimization of equipment requirements and back end refining at sea (Area: Mooring and Deployment)
3) Alternative elution chemistry (Area: Elution and Purification)
4) Co-product Recovery during purification (Area: Elution and Purification)

These highlighted alternatives are discussed individually in the following sections to develop a starting point for detailed development of the alternatives and to identify research needs in each area; where possible, potential cost impacts of alternative configurations are included.

### Alternative Grafting Chemistry

Figure 5.9 depicts the distribution of unit uranium production cost into major cost categories for the base case conditions in this analysis.

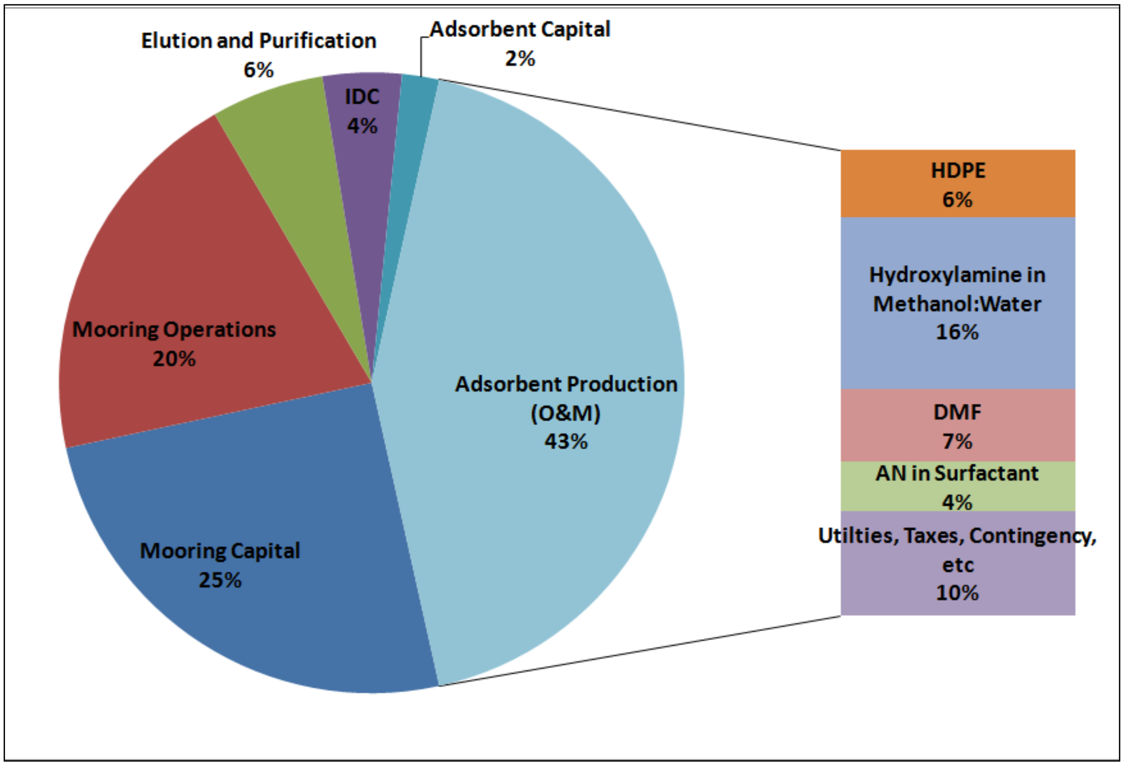


Figure 5.9: Distribution of uranium production cost by major cost categories with a focus on adsorbent production

Adsorbent production costs, largely consisting of grafting chemicals consumption, represent a significant portion of the project costs and thus a potential obstacle to the development of the amidoxime adsorbent fibers. However, the cost assessment only reflects one potential route to adsorbent production and the associated performance characteristics with the specific adsorbent production chemistry. Current bench-scale work includes evaluation and development of modified adsorbent production chemistry based on research completed in Japan.[12] Table 5.6 provides a comparison of the reference design process chemistry and the alternative under consideration in experimental work.

---

[12] See the following for examples of research in Japan: (Kawai, et al. 2000) and (M. Tamada 2009).

Table 5.6: Comparison of grating methods and chemicals required

| **AN/DMF Grafting Pathway (Used in this analysis)** | | |
|---|---|---|
| **Chemical** | **Role of Chemical** | **Annual Consumption*** |
| Acrylonitrile (AN) | React with irradiated polymer backbone to provide cyano groups for subsequent amidoximation step | 35,000 tonnes |
| Surfactant (i.e. Sodium Lauryl Sulfate) | Stabilize emulsion of acrylonitrile monomer in solution with water/prevent phase separation due to acrylonitrile polymerization | 3,500 tonnes |
| Dimethylformamide (DMF) | Wash fibers to remove unreacted monomers | 65,000 tonnes |
| Hydroxylamine | Functionalize cyano groups on acrylonitrile grafted chains to form amidoxime groups | 56,000 tonnes |
| Methanol | Dispersal of hydroxylamine during final grafting step as part of 1:1 solution with water | 53,000 tonnes |
| **Alternate Grafting Pathway (AN-MAA/DMSO)** | | |
| **Chemical** | **Role of Chemical** | **Annual Consumption*** |
| Acrylonitrile (AN) | Same as above | 35,000 tonnes |
| **Dimethylsulfoxide (DMSO)** | **Serves dual function of stabilizing acrylonitrile monomer in solution (removing the need for surfactant) and removing unreacted monomer after process** | 44,000 tonnes |
| Hydroxylamine | Same as above | 56,000 tonnes |
| **Methacrylic Acid (MAA)** | **Co-grafted with acrylonitrile to improve polymer backbone contact with water (hydrophilic group)** | 8,900 tonnes |
| Methanol | Same as above | 53,000 tonnes |

* Consumption for AN/DMF pathway is based on base case for this analysis. Consumption for alternate pathway was derived by scaling based on a fixed amount of AN in the process.

As an initial assessment of the economic impact of the alternate grafting system, consumption numbers were estimated for DMSO and MAA while the surfactant was removed from the system cost. In the alternate process, AN and MAA form a 50/50 solution by weight with DMSO; the monomers are in an 80/20 ratio by weight. (M. Tamada 2009). Using the assumption that the AN consumption remained the same (to ensure the same amidoxime group concentration in the adsorbent) in the alternate process as in the base case process, the required quantity of DMSO and MAA could be back calculated from the weight ratios in solution. The analysis revealed approximately 1 percent increase in uranium production cost for the alternate process from the base case chemistry; however, given the volatility of chemical prices and lack of detailed knowledge of consumption in the grafting systems, the difference should be considered negligible. The preliminary economic analysis could not account for true reactant consumption or impact on adsorbent performance from the different grafting procedures; the relationship between chemical consumption, cost of chemicals and adsorbent performance is the critical optimization for the grafting area.

To facilitate more detailed economic analyses, several items are needed:

1) Correlate chemical consumption to degree of grafting, specifically to determine optimum chemical consumption,
2) Disaggregate degree of grafting/co-grafting into concentration of amidoxime groups and hydrophilic groups. Within degree of grafting, acrylonitrile grafting must be viewed separately and correlated to amidoxime group formation while grafting of MAA or hydrophilic functional groups should be linked to water uptake and contact. The distinctions allow for correlation to

performance via the functional mechanism of each chemical. Previous work has analyzed the functional groups separately (Kawai, et al. 2000).

3) Use the understanding of grafting behavior of monomer groups and chemicals required to achieve range of grafting results to make final correlation to adsorbent performance (capacity).

Detailed understanding of reaction performance and final adsorbent performance together allow for optimization of chemicals consumption in the grafting area.

### Alternative Mooring Deployment

The cost analysis of the mooring and deployment area revealed several areas for potential optimization and improvement. First, as was mentioned in the methodology section, the current system is designed for the ships to stay at sea for the duration of a mooring campaign (60 days in the base case). Therefore, the ships are sized to the recovery of a fully loaded field of adsorbent. Two potential issues arise; first, despite the economies of scale present in the ships, they may potentially be oversized because of the limitation of storing adsorbent during the campaign. Secondly, uranium recovery is delayed; on average, a braid adsorbent will spend half of the campaign length in boat storage awaiting return to shore for processing. Therefore, a detailed optimization should be performed on the mooring operation. This may include moving the elution and/or refining facility offshore to a central ship or platform. While adding to the capital cost of those processes, the offshore processing unit would allow ships to offload cargo at regular intervals and allow continuous uranium recovery. A detailed cost-benefit analysis should be considered for this option.

In addition, the data on depth and temperature by location off the United States coastline reveals another important design decision. As seen in sensitivity results, temperature is a critical variable for adsorbent performance. While specific locations may have the highest depth averaged temperature to 300 m (South Florida region in this analysis), the data does not give a full picture of temperature profile with depth in each area. To fully optimize with temperature, the length of the braids, depth of mooring, and temperature-depth profile must all be considered together; this allows analysis of the temperature actually observed by the adsorbent and also allows the design to be modified to best leverage seawater conditions at a specific site.

### Alternative Elution Chemistry

Degradation of the adsorbent is a critical variable in the analysis of the seawater extraction system. Preliminary research in Japan identified hydrochloric acid as an eluting agent due to its selective removal of uranium relative to other metals in the adsorbent; however, it was also recognized that the elution process damages hydrophilic groups in the adsorbent, reducing adsorptive capacity of the material (Hirotsu, et al. 1987). Alternative elution chemistry was investigated to mitigate the damage to the adsorbent while retaining high recovery rates of uranium. Potential alternatives include sodium carbonate (Hirotsu, et al. 1987), and several organic acid alternatives - tartaric acid, oxalic acid, malic acid, maleic acid, phthalic acid, and formic acid have been studied previously (Seko, et al. 2005).

The elution process must be considered in tandem with the specific grafting chemistry optimization discussed previously; trade-offs may exist in initial adsorbent performance versus performance over the lifetime of the adsorbent. For example, the

MAA in the alternative grafting chemistry discussed previously improves contact with water, but may have specific interactions with elution chemistry that are not present in the baseline system considered in this analysis. The economic model in this work included a 5% degradation rate per recycle and the results highlight the impact of degradation on the economics of the system. Incorporating uranium recovery efficiency, degradation rates, and initial adsorption capacity into a single model can allow much deeper analysis of optimal economic scenarios for the braid adsorbent system.

### Co-Product Quantification

In this analysis, uranium extraction was the focus of the braid adsorbent system. However, previous work has indicated that other valuable metals such as vanadium are co-extracted with uranium (Suzuki, et al. 2000). The by-products of the uranium extraction process may have significant value that can offset some of the costs associated with the extraction process. As research progresses in adsorbent development, field performance, and elution processes, co-products should be quantified and the impact of design changes on co-product extraction capacity should be considered.

## 5.4 HIGH PRIORITY DATA REQUIREMENTS

The uncertainty associated with the cost estimate provided in Table 5.2 indicates the need for an improved understanding of the design and operation of a braid adsorbent system. The following items have been identified as critical steps in advancing system analysis of uranium extraction from seawater:

1) Development of process models: The current analysis assumes linear scaling of chemicals and utilities with production scales; in reality, process models that include dynamic heat and material balance applications are required to understand the change in raw materials and energy consumption with scale. For the areas of the extraction process that are well-established manufacturing technologies (e.g. melt spinning or uranium refining), models may be readily available.

2) Development of kinetic and thermodynamic models: The effect of time and temperature on adsorbent performance was incorporated in this analysis via regression of limited field data; this resulted in a high level of uncertainty regarding adsorbent performance in response to time and temperature. Future analysis requires thermodynamic and kinetic models of the adsorption process to accurately depict adsorbent performance in field conditions. This is a critical item in the economic analysis as it impacts the optimization and design of all process areas (adsorbent production, mooring and elution-purification).

As details of adsorbent production and performance are added to the model, additional sensitivity analyses, optimization, and uncertainty reduction and quantification can be performed to inform decision makers regarding seawater extraction economics.

# Chapter 6: Conclusions and Recommendations

The renewed interest in uranium extraction from seawater in the United States and elsewhere mirrors many of the concerns over resource scarcity, energy security, and environmental issues during the 1970s. This time period coincides with the development of much of the economic theory regarding backstop technologies in the energy sector. As discussed, funding of research and development (R&D) in uranium extraction from seawater may return long term benefits when the technology serves as an upper limit on conventional uranium prices. However, the debate over exhaustible resources in the 1970's and beyond revealed that the costs and potential benefits from backstop technologies are highly uncertain. For uranium, part of this uncertainty includes the supply of conventional resources; though these resources have some physical exhaustion limit, it is ultimately unimportant in economic analysis. Therefore, the role of seawater uranium is as a long-term economic substitute for conventional uranium. The viability and timing of the implementation of the backstop technology will be dependent on the cost of the technology rather than a physical exhaustion limit. Further, the uncertainty in the production cost of uranium from seawater is directly linked to risk assessment in planning and decision-making regarding long-term uranium supply. The improvement of the long-term uranium resource picture, and its ramifications for nuclear energy R&D broadly, provided the core motivation for the analysis in this work.

The central findings of the cost assessment include identification of the most influential cost drivers in the system and a quantified range of uncertainty in production cost estimates disaggregated into major contributing categories. In addition, the methodology used in the cost estimation provides the first independent, component level cost estimate relevant to the United States with sufficient transparency to allow reproduction and continuous revision of results with new information.

Sensitivity studies confirmed key cost drivers including adsorbent capacity, degradation and number of adsorbent recycles. For example, an optimistic case of 6 kgU/t adsorbent and 20 recycles would reduce uranium production costs from $1230/kg U in the reference case to $299/kg U. The identification of these cost drivers provides a roadmap for future R&D investment. In addition, the analyses identified potential optimization around key cost drivers; for example, the illustration of an optimal number of adsorbent recycles given adsorbent degradation connects potentially disparate research areas. In the base case with 5% degradation, production costs were minimized at approximately 11 recycles. Investment in

Uncertainty quantification identified adsorbent capacity as dominant contributor to uncertainty in the process. As a primary cost driver, much focus has centered on improvement of adsorbent technology; however, as the analysis showed, persistent uncertainty surrounding the true performance of the technology, as measured by the capacity of the material to adsorb uranium, drives uncertainty in the production costs. As noted, the two standard deviation range for the production cost of uranium is [$689/kg U, $2850/kg U]; without uncertainty in adsorbent capacity, the range drops to [$1030/kg U, $1430/kg U]. Therefore, reduction in the uncertainty associated with adsorbent capacity has immediate (and quantifiable) value to decision-makers. In addition, the presence of this dominant uncertainty limits meaningful analysis of other system parameters; this was evident in the case of financial parameters which were dominated by the uncertainty in performance parameters.

Uncertainty in another performance parameter, adsorbent capacity degradation was an important finding in the analysis. Limited empirical data exists on performance degradation, yet system optimization is strongly influenced by degradation. The high initial costs of adsorbent production can be mitigated by repeated use of a durable adsorbent; however, as discussed, if performance degradation steadily reduces uranium production over the life of the adsorbent, the optimal strategy for production and deployment of the adsorbent changes. The risk of underestimating the influence of degradation is R&D investment in sub-optimal design and diminished return on investment.

The range of uncertainty around the expected value for seawater extraction is more important than the expected value itself. The range provides investors and planners with the information needed to perform a cost benefit analysis of further development of the current extraction technology and to assess the potential risk associated with any investment. The combination of key cost drivers and uncertainty in costs provides decision-makers with a full picture of the current status of seawater extraction technology and allows design of optimal R&D strategy.

## 6.1 POLICY RECOMMENDATIONS

The cost analysis at the center of this thesis has important implications for policy makers. The seawater extraction process is in early development relative to commercial scale investment, and therefore the primary path to improving technology and/or reducing costs is via R&D. For policy makers, R&D investment is governed by cost-benefit analysis; at each stage of technology development, decision makers can choose to continue funding and development of a specific technology or abandon the project. They must re-assess the potential benefits of the technology against the current understanding of costs (both in terms of investment costs and costs to society or end-users).

Fundamentally, the continuous evaluation of R&D investment makes the process an exercise of information gathering and measuring the value of information.

The wide uncertainty bands seen in this analysis would make investment decisions challenging and technology development paths difficult to define (e.g. optimization of adsorbent recycle and durability). Considering the potential role of uranium from seawater as a long-term backstop technology, two important and related objectives exist for future development. First, planning and prediction of the viability of uranium from seawater (as a backstop or as an alternative to address concerns with conventional uranium) requires a detailed understanding of the uncertainty in extraction costs. Planners and investors will ultimately rely more on the plausible range of potential production costs for uranium than a single point estimate. Second, continued assessment of the uncertainty in extraction costs can in turn guide innovation in system design to reduce costs or improve performance.. For example, understanding the effects of temperature on adsorbent performance to reduce the uncertainty in adsorbent capacity may yield important information on the mechanisms that drive the adsorption of uranium. The iterative process of uncertainty reduction and process improvement can guide research from the preliminary assessment provided in this thesis.

In addition, environmental and energy impacts of the seawater extraction process should be researched in detail; while these parameters may not directly lead to cost reductions, they may be as important for viability of the extraction process as the performance parameters of the system. Uranium from seawater may provide societal value (which can be quantified) by preserving land that would potentially be used for conventional mining, mitigating environmental impacts, reducing price volatility in energy resources, and providing countries with a secure, stable supply of energy resources. These impacts must be evaluated alongside the potential detrimental impacts of the seawater extraction system; at the early stages of development, environmental issues have not been considered in detail. However, they contribute to the uncertainty in cost estimation (e.g. in potential seabed lease prices or uncertainty in regulatory costs) and therefore should be considered early in technology development.

Finally, understanding the conventional resource base and demand are critical to defining the value of the backstop technology. Without an accurate representation of the needs and supply conditions for nuclear power, the benefits associated with a backstop technology may never become quantifiable.

## 6.2 RECOMMENDATIONS FOR FUTURE WORK

A discussion of process alternatives and data requirements was included in chapter 5. Process modeling was mentioned in the previous chapter as an important tool to provide data regarding scaling and performance of the entire seawater extraction process. Trials in seawater are crucial to understanding and developing the extraction technology and cannot be replaced by lab or simulation data; however, these trials are expensive, time consuming, and lack the flexibility to perform wide ranging parametric analysis that is an important part of economic evaluation of engineering systems. Therefore, the development of tools such as process models provides an intermediate source for data, uncertainty reduction, and technology development between trials. Furthermore, the process modeling activities can inform and direct field trials and pilot scale development by focusing trials on parameters deemed critical to process performance or costs by the process model. The models also provide a means to more accurately represent the cost model of the system by simulating real process performance as part of the cost analysis.

One implication of the recommendation to develop process models is the need to understand the fundamental thermodynamics, kinetics and reaction mechanisms associated with adsorption of uranium in seawater. As highlighted by uncertainty in adsorbent performance, limited data or incomplete understanding of adsorbent performance propagates to the final cost estimate and can severely hinder decision-making and planning. The development of empirical models that accurately reflect the fundamental physical processes driving adsorbent performance would provide immediate reduction of uncertainty in current cost estimates and thus provide value to decision makers and investors without technology improvement or process cost reduction. This makes the development of basic chemical and physical models a top priority in seawater research.

Future cost studies may also include more detailed uncertainty quantification and assessment. For example, this analysis considered the uncertainty in chemical prices via historical data. Future analysis might include connecting each process chemical to raw material inputs and market demand to develop a better understanding of chemical price volatility. This type of analysis also allows for the consideration of correlation between variables in uncertainty analysis; providing more detailed assessment of uncertainty can then feed specific research requirements. The need for process models or kinetic models can be further focused by identifying parameters with large contributions to uncertainty (such as adsorbent capacity in this work).

Finally, the energy return on investment (EROI) should be considered in future analysis as a more fundamental measure of process viability. Cost assessment can be affected by many exogenous variables that have little to do with the actual extraction process and performance. Previous seawater extraction processes were eliminated from consideration due to the prohibitive energy consumption required in pumping seawater

(Best and Driscoll 1980). Evaluation of energy return reduces the analysis to performance and production parameters and eliminates uncertainty from costs. The independent cost assessment and associated methodology in this work can serve as a framework to evaluate energy return on investment.

# Appendix A: Process Flow Diagrams and Code of Accounts

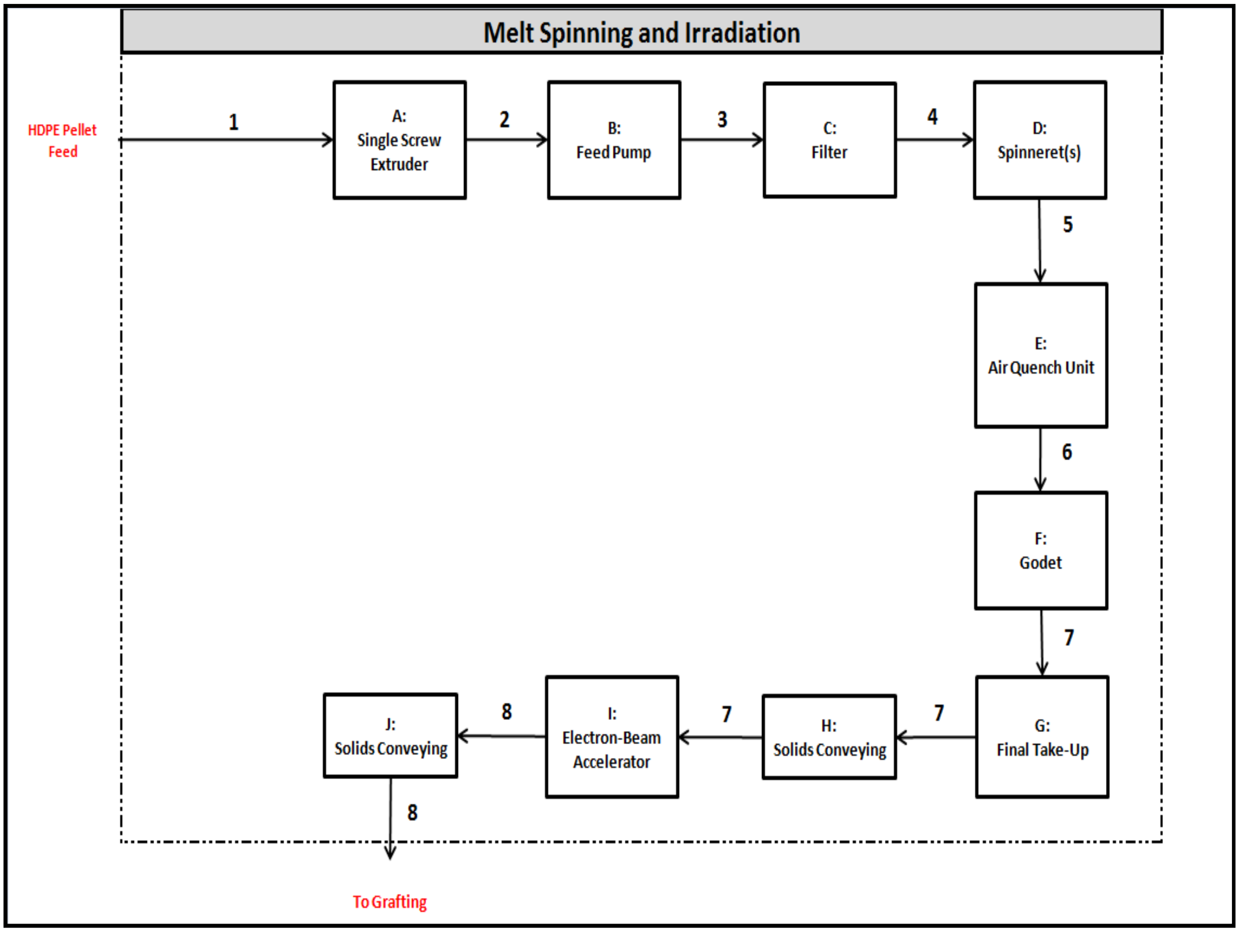


Figure A.4.1: Process Flow Diagram – Melt Spinning and Irradiation

Table A.4.1: Equipment and Stream Table for Melt Spinning and Irradiation Process Flow Diagram

| PFD Table | | |
|---|---|---|
| **Equipment** | | |
| **ID** | **Equipment Type** | **Description** |
| A | Single Screw Extruder | Melt and mix HDPE pellets for subsequent spinning steps |
| B | Feed Pump | Meter and dispense polyethylene melt |
| C | Filter | Remove impurities and residual solids in melt |
| D | Spinneret | Arranged in manifold to receive portion of extruder feed; extrudes fibers from melt feed via holes in spinneret head |
| E | Air Quench Unit | Cools and crystallizes fibers |
| F | Godet | Works in tandem with take up roll to draw fiber to final length and wind for final processing |
| G | Final Take-Up | Final fiber winding |
| H | Belt Conveyor | Moves fiber spools from spinning line to e-beam accelerators |
| I | Electron Beam Accelerator | Irradiates HDPE trunk polymer to generate free radicals for polymerization |
| J | Belt Conveyor | Moves irradiated fibers on bobbins to grafting area |
| **Streams** | | |
| **ID** | **Components** | **Description** |
| 1 | HDPE Pellets | Bulk HDPE pellets |
| 2 | HDPE Melt | HDPE melt at 170°C to 190°C |
| 3 | Pressurized HDPE Melt | HDPE melt at high pressure for spinning |
| 4 | Pressurized HDPE Melt | HDPE melt with impurities and solids removed |
| 5 | HDPE Melt | Individual streams of HDPE melt formed by spinneret |
| 6 | Crystallized HDPE fibers | Cooled fibers formed by extrusion and cooling |
| 7 | HDPE Fibers | Fibers drawn down to final diameter and length |
| 8 | Irradiated Fibers | Fibers with free radicals from e-beam irradiation |
| **Total Major Process Steps*** | | **4** |
| ***Major Process Steps are Extrusion (A), Spinning (B-D), Cooling and Take-Up (E-G) and Irradiation (I)** | | |

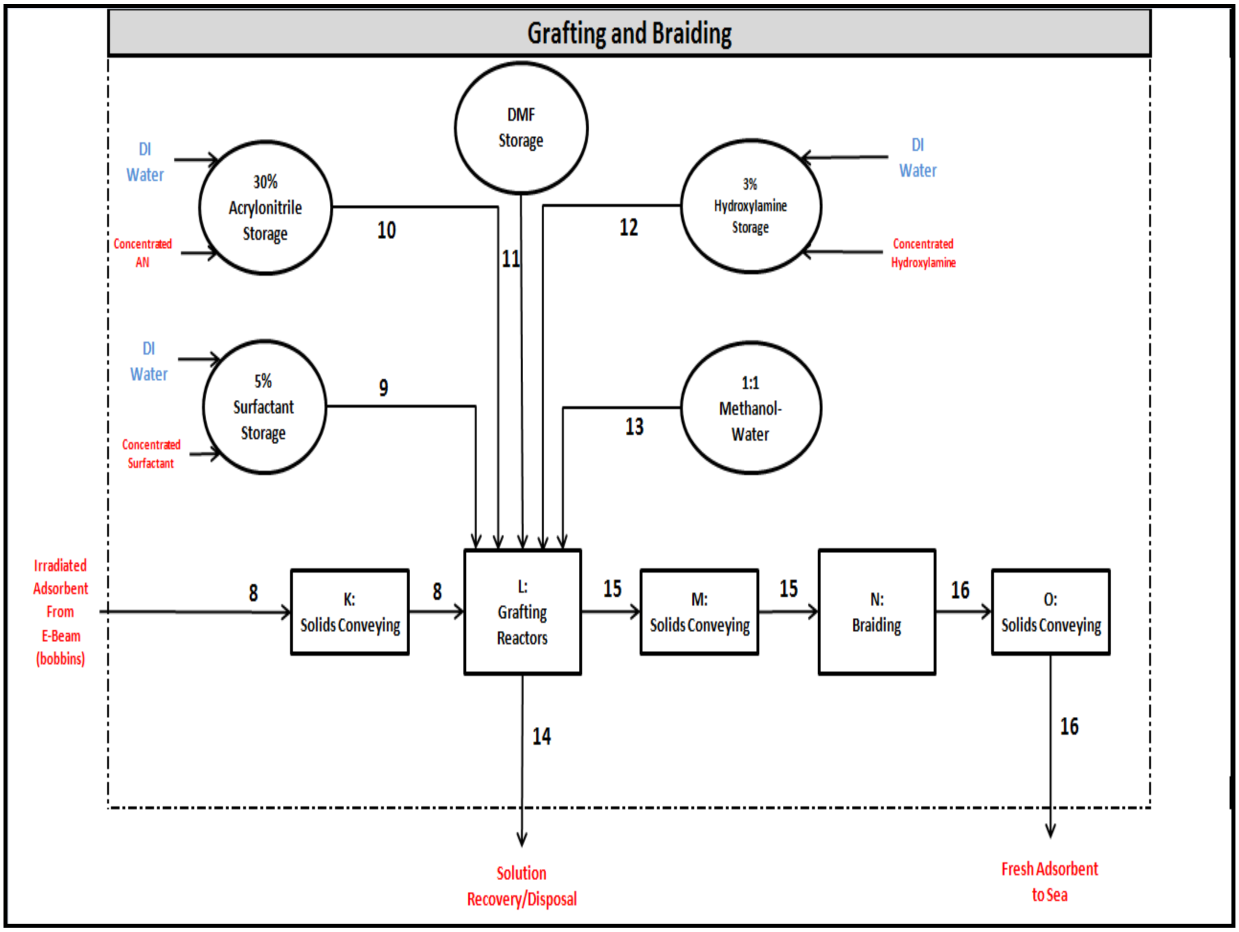


Figure A.4.2: Process Flow Diagram – Grafting and Braiding

Table A.4.2: Equipment and Stream Table for Grafting and Braiding Process Flow Diagram

| PFD Table | | |
|---|---|---|
| **Equipment** | | |
| **ID** | **Equipment Type** | **Description** |
| K | Belt Conveyor | Carry irradiated multifilament bundles to chemical grafting step |
| L | Jacketed Stirred Reactor | Grafting of amidoxime groups onto free radical sites of HDPE fibers |
| M | Belt Conveyor | Carry amidoxime fibers to braiders for final processing |
| N | Fiber Braider | Braid 4 multifilament bundles around hollow core (float) |
| O | Belt Conveyor | Transport finished braid adsorbent for loading/transport to sea |
| ETC. | Storage Tanks | 30 day bulk chemical storage |
| **Streams** | | |
| **ID** | **Components** | **Description** |
| 8 | HDPE fibers | 50,000 tonnes/year of irradiated HDPE from e-beam |
| 9 | 5% Sodium Dodecyl Sulfate | Surfactant solution to stabilize emulsion during grafting |
| 10 | 30% Acrylonitrile Solution | Monomer that grafts onto free radical sites on polymer backbone |
| 11 | Dimethylformamide | Solvent wash to remove unreacted monomer in reactor |
| 12 | 3% Hydroxylamine | Converts cyano group of grafted monomer into amidoxime group |
| 13 | 1:1 Methanol-Water | Disperses hydroxylamine during final grafting reaction step |
| 14 | Wash Solution | Unused/Unreacted chemicals from grafting reactors |
| 15 | Amidoxime Fibers | Amidoxime-grafted fiber adsorbent |
| 16 | Braid Adsorbent | Final braided adsorbent formed from 4 multifilament bundles |
| **Total Major Process Steps** | | **2** |
| ***Major Process Steps are Grafting (L) and Braiding (N)** | | |

Table A.4.3: Code of Accounts – Adsorbent Production Area

| EMWG Acct # | Account Title | Total Cost (2010 US$) | Specific Annual Cost ($/kg U/yr) |
|---|---|---|---|
| **1** | **Capitalized Pre-construction Costs (Subtotal)** | **$2,511,158** | **$0.22** |
| **10 series** | | | |
| **11** | **Land and land rights** | $2,511,158 | $0.22 |
| **12** | **Site permits** | $0 | |
| **13** | **Plant licensing** | $0 | |
| **14** | **Plant permits** | $0 | |
| **15** | **Plant studies** | $0 | |
| **16** | **Plant reports** | $0 | |
| **17** | **Other Pre-Construction Costs** | $0 | |
| **18** | **Reserved for other activity as needed** | $0 | |
| **19** | **Contingency on Pre-Construction Costs (aggregated below)** | $0 | |
| **2** | **Capitalized Direct Costs (Subtotal)** | **$133,624,715** | **$13.87** |
| **20 series** | | | |
| **21** | **Structures and Improvements** | $36,443,104 | $3.22 |
| **22** | **N/A** | $0 | $0.00 |
| **23** | **Process Equipment** | $74,404,671 | $8.15 |
| **24** | **Electrical equipment** | $3,796,157 | $0.42 |
| **25** | **Heat Rejection System** | $0 | $0.00 |
| **26** | **Miscellaneous plant equipment** | $18,980,783 | $2.08 |
| **27** | **Special materials** | $0 | |
| **28** | **N/A** | $0 | |
| **29** | **Contingency on Direct Costs (aggregated below)** | $0 | |
| **Sum 1-2** | **TOTAL DIRECT COST** | | |
| | | | |
| **3** | **Capitalized Indirect Services (Subtotal)** | **$32,267,332** | **$3.54** |
| **30 series** | | | |
| **31** | **Field indirect costs (rentals, temp facil, etc)** | $20,119,630 | $2.20 |
| **32** | **Construction supervision** | $12,147,701 | $1.33 |
| **33** | **Commissioning and Start-Up Costs** | $0 | $0.00 |

| | | | |
|---|---|---|---|
| 34 | **Demonstration Test Run** | $0 | $0.00 |
| **Sum 1 - 34** | **TOTAL FIELD COST** | | |
| 35 | **Design Services Offsite** | $0 | |
| 36 | **PM/CM Services Offsite** | $0 | |
| 37 | **Design Services Onsite** | $0 | |
| 38 | **PM/CM Services Onsite** | $0 | |
| 39 | **Contingency on Indirect Services (aggregated below)** | $0 | |
| **Sum 1-3** | **BASE CONSTRUCTION COST** | | |
| **4** | **Capitalized Owner's costs (Subtotal)** | **$1,518,463** | **$0.17** |
| **40 series** | | | |
| 41 | **Staff recruitment and training** | $0 | |
| 42 | **Staff housing facilities** | $0 | |
| 43 | **Staff salary-related costs** | $0 | |
| 44 | **Reserved** | $0 | |
| 45 | **Reserved** | $0 | |
| 46 | **Other Owners' capital investment costs** | $1,518,463 | $0.17 |
| 47 | **Reserved** | $0 | |
| 48 | **Reserved** | $0 | |
| 49 | **Contingency on Owner's Costs (aggregated below)** | $0 | |
| **5** | **Capitalized Supplementary Costs (subtotal)** | **$0** | 0 |
| **50 series** | | | |
| 51 | **Shipping & transportation costs** | $0 | |
| 52 | **Spare parts and supplies** | $0 | |
| 53 | **Taxes** | $0 | |
| 54 | **Insurance** | $0 | |
| 55 | **N/A** | $0 | |
| 56 | **Reserved** | $0 | |
| 57 | **Reserved** | $0 | |
| 58 | **Decommissioning Costs** | $0 | |
| 59 | **Contingency on supplementary costs** | $0 | |
| **Sum 1-5** | **OVERNIGHT CONSTRUCTION COST** | | |
| **CONT** | **Total contingency:accts 19+29+39+49+59** | **$16,992,167** | **$1.86** |

| | | | |
|---|---|---|---|
| **OVNT** | **Overnight cost** | **$186,913,834** | **$19.65** |
| | | | |
| **6** | **Capitalized Financial Costs (subtotal)** | **$0** | **$0.00** |
| **60 series** | | | |
| **61** | **Escalation** | $0 | |
| **62** | **Fees/Royalties** | $0 | 0 |
| **63** | **Interest during construction** | $0 | |
| **64** | | $0 | |
| **65** | | $0 | |
| **66** | | $0 | |
| **67** | | $0 | |
| **68** | | $0 | |
| **69** | **Contingency on financial costs** | $0 | |
| **Sum 1-6** | **TOTAL CAPITAL INVESTMENT COST** | | |
| | **Total Capitalized Cost (TCIC)** | **$186,913,834** | **$19.65** |
| **Annualized Costs** | | | |
| | | | |
| **7** | **Annualized O&M Cost (subtotal)** | **$512,147,463** | **$426.79** |
| **70 series** | | | |
| **71** | **Operations Staff** | $6,630,303 | $5.53 |
| **72** | **Management Staff** | $1,160,303 | $0.97 |
| **73** | **Salary-Related Costs** | $0 | $0.00 |
| **74** | **Raw Materials** | $397,120,081 | $330.93 |
| **75** | **Spare Parts** | $0 | $0.00 |
| **76** | **Utilities, Supplies and Consumables** | $55,320,779 | $46.10 |
| **77** | **Capital Plant Upgrades** | $0 | $0.00 |
| **78** | **Taxes and Insurance** | $5,357,136 | $4.46 |
| **79** | **Contingency on O&M Cost** | $46,558,860 | $38.80 |
| **9** | **Annualized Financial Costs (subtotal)** | **$0** | 0 |
| **90 series** | | | |
| **91** | **Escalation** | $0 | |
| **92** | **Fees** | $0 | |
| **93** | **Cost of Money** | $0 | |
| **94** | | $0 | |
| **95** | | $0 | |

|  |  |  |  |
|---|---|---|---|
| **96** |  | $0 |  |
| **97** |  | $0 |  |
| **98** |  | $0 |  |
| **99** | **Contingency on Financial Costs** | $0 |  |

Table A.4.4: Code of Accounts – Mooring and Deployment Area

| **EMWG Acct #** | **Account Title** | **Total Cost (2010 US$)** | **Specific Annual Cost ($/kg U/yr)** |
|---|---|---|---|
| **1** | **Capitalized Pre-construction Costs (Subtotal)** | **$0** | **$0.00** |
| **10 series** |  |  |  |
| **11** | **Land and land rights** | $0 | $0.00 |
| **12** | **Site permits** | $0 |  |
| **13** | **Plant licensing** | $0 |  |
| **14** | **Plant permits** | $0 |  |
| **15** | **Plant studies** | $0 |  |
| **16** | **Plant reports** | $0 |  |
| **17** | **Other Pre-Construction Costs** | $0 |  |
| **18** | **Reserved for other activity as needed** | $0 |  |
| **19** | **Contingency on Pre-Construction Costs** | $0 |  |
| **2** | **Capitalized Direct Costs (Subtotal)** | **$2,134,405,779** | **$233.85** |
| **20 series** |  |  |  |
| **21** | **Structures and Improvements** | $0 | $0.00 |
| **22** | **N/A** | $0 | 0 |
| **23** | **Process Equipment** | $2,134,405,779 | $233.85 |
| **24** | **Electrical equipment** | $0 | $0.00 |
| **25** | **Heat Rejection System** | $0 | $0.00 |
| **26** | **Miscellaneous plant equipment** | $0 | $0.00 |
| **27** | **Special materials** | $0 |  |
| **28** | **N/A** | $0 |  |
| **29** | **Contingency on Direct Costs** | $0 |  |
| **Sum 1-** | **TOTAL DIRECT COST** |  |  |

|  |  |  |  |
|---|---|---|---|
| **2** |  |  |  |
|  |  |  |  |
| **3** | **Capitalized Indirect Services (Subtotal)** | **$0** | **$0.00** |
| **30 series** |  |  |  |
| **31** | **Field indirect costs (rentals, temp facil, etc)** | $0 | $0.00 |
| **32** | **Construction supervision** | $0 | $0.00 |
| **33** | **Commissioning and Start-Up Costs** | $0 | $0.00 |
| **34** | **Demonstration Test Run** | $0 | $0.00 |
| **Sum 1 - 34** | **TOTAL FIELD COST** |  |  |
| **35** | **Design Services Offsite** | $0 |  |
| **36** | **PM/CM Services Offsite** | $0 |  |
| **37** | **Design Services Onsite** | $0 |  |
| **38** | **PM/CM Services Onsite** | $0 |  |
| **39** | **Contingency on Indirect Services** | $0 |  |
| **Sum 1-3** | **BASE CONSTRUCTION COST** |  |  |
| **4** | **Capitalized Owner's costs (Subtotal)** | **$0** | **$0.00** |
| **40 series** |  |  |  |
| **41** | **Staff recruitment and training** | $0 |  |
| **42** | **Staff housing facilities** | $0 |  |
| **43** | **Staff salary-related costs** | $0 |  |
| **44** | **Reserved** | $0 |  |
| **45** | **Reserved** | $0 |  |
| **46** | **Other Owners' capital investment costs** | $0 | $0.00 |
| **47** | **Reserved** | $0 |  |
| **48** | **Reserved** | $0 |  |
| **49** | **Contingency on Owner's Costs** | $0 | - |
| **5** | **Capitalized Supplementary Costs (subtotal)** | **$0** | 0 |
| **50 series** |  |  |  |
| **51** | **Shipping & transportation costs** | $0 |  |
| **52** | **Spare parts and supplies** | $0 |  |
| **53** | **Taxes** | $0 |  |
| **54** | **Insurance** | $0 |  |
| **55** | **N/A** | $0 |  |
| **56** | **Reserved** | $0 |  |

| | | | |
|---|---|---|---|
| **57** | **Reserved** | $0 | |
| **58** | **Decommissioning Costs** | $0 | |
| **59** | **Contingency on supplementary costs** | $0 | |
| **Sum 1-5** | **OVERNIGHT CONSTRUCTION COST** | | |
| **CONT** | **Total contingency:accts 19+29+39+49+59** | **$213,440,578** | **$23.38** |
| **OVNT** | **Overnight cost** | **$2,347,846,357** | **$257.23** |
| | | | |
| **6** | **Capitalized Financial Costs (subtotal)** | **$0** | **$0.00** |
| **60 series** | | | |
| **61** | **Escalation** | $0 | |
| **62** | **Fees/Royalties** | $0 | 0 |
| **63** | **Interest during construction** | $0 | |
| **64** | | $0 | |
| **65** | | $0 | |
| **66** | | $0 | |
| **67** | | $0 | |
| **68** | | $0 | |
| **69** | **Contingency on financial costs** | $0 | |
| **Sum 1-6** | **TOTAL CAPITAL INVESTMENT COST** | | |
| | **Total Capitalized Cost (TCIC)** | **$2,347,846,357** | **$257.23** |
| | **Annualized Costs** | | |
| **7** | **Annualized O&M Cost (subtotal)** | **$257,274,706** | **$214.40** |
| **70 series** | | | |
| **71** | **Operations Staff** | $108,590,277 | $90.49 |
| **72** | **Management Staff** | $12,581,538 | $10.48 |
| **73** | **Salary-Related Costs** | $0 | $0.00 |
| **74** | **Raw Materials** | $1,911,706 | $1.59 |
| **75** | **Spare Parts** | $0 | $0.00 |
| **76** | **Utilities, Supplies and Consumables** | $110,802,575 | $92.34 |
| **77** | **Capital Plant Upgrades** | $0 | $0.00 |
| **78** | **Taxes and Insurance** | $0 | $0.00 |
| **79** | **Contingency on O&M Cost** | $23,388,610 | $19.49 |
| **9** | **Annualized Financial Costs (subtotal)** | **$0** | 0 |
| **90** | | | |

| | | | |
|---|---|---|---|
| **series** | | | |
| **91** | **Escalation** | $0 | |
| **92** | **Fees** | $0 | |
| **93** | **Cost of Money** | $0 | |
| **94** | | $0 | |
| **95** | | $0 | |
| **96** | | $0 | |
| **97** | | $0 | |
| **98** | | $0 | |
| **99** | **Contingency on Financial Costs** | $0 | |

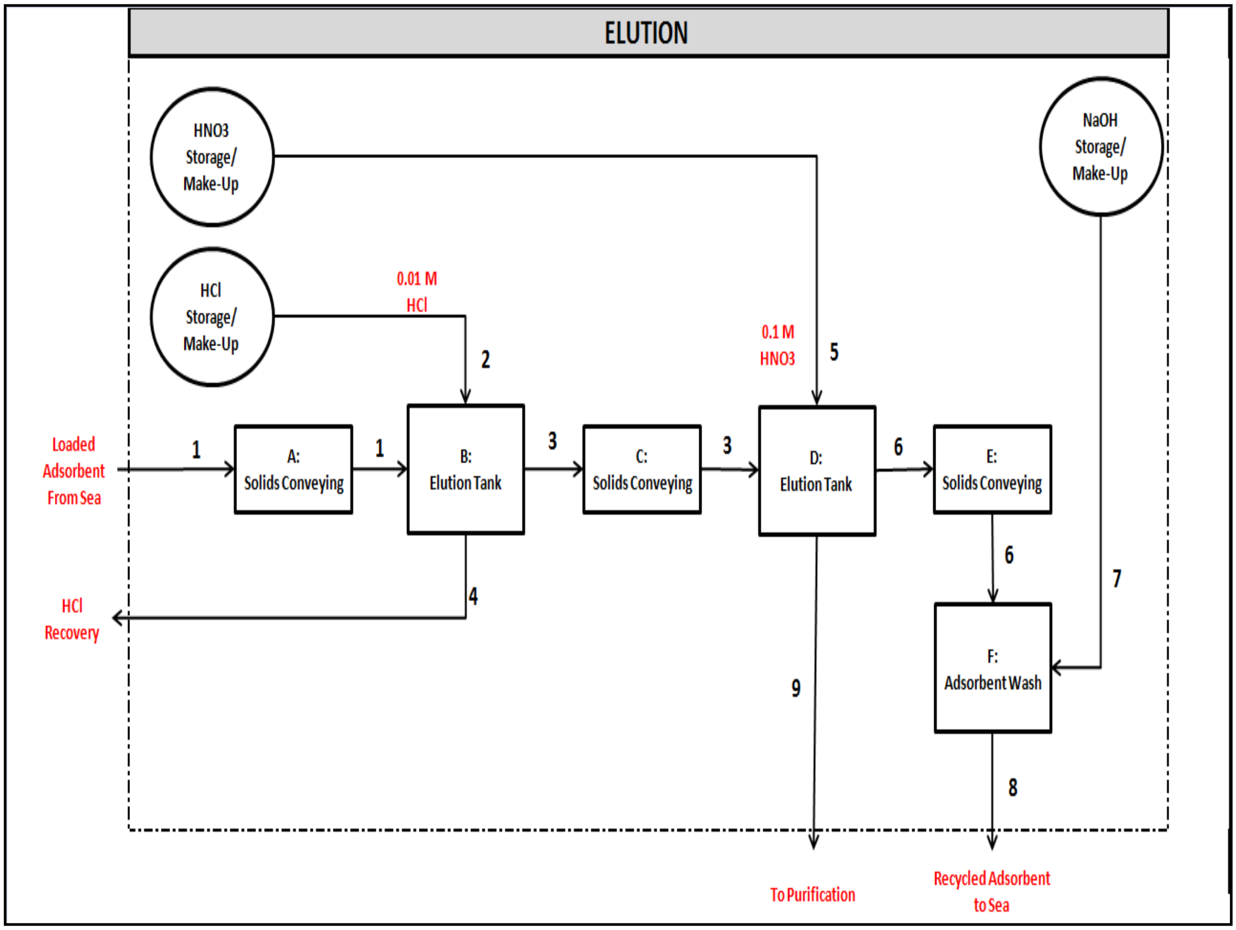


Figure A.4.3: Process Flow Diagram – Elution

Table A.4.5: Equipment and Stream Table for Elution Process Flow Diagram

| **PFD Table** | | |
|---|---|---|
| **Equipment** | | |
| **ID** | **Equipment Type** | **Description** |
| A | Belt Conveyor | Carry loaded adsorbent to refining processes |
| B | Agitated Tank | HCl Elution to remove Alkali/Alkali Earth Metals |
| C | Belt Conveyor | Move adsorbent to second elution step |
| D | Agitated Tank | HNO3 Elution to selectively remove Uranium |
| E | Belt Conveyor | Move adsorbent to wash step |
| F | Agitated Tank | Regenerate adsorbent with alkali solution (Unclear if needed) |
| ETC. | Storage Tanks | HCl, HNO3, and NaOH |
| **Streams** | | |
| **ID** | **Components** | **Description** |
| 1 | Adsorbent, uranium, other metals | 600,000 t/yr adsorbent + 1200 t/yr of recovered U + other metals |
| 2 | 0.01 M HCl | Removes Alkali/Alkali Earth Metals |
| 3 | Eluted Adsorbent | |
| 4 | Alkali/Alkali Earth Metals in HCl | |
| 5 | 0.1 M Nitric Acid | Selectively elute uranium to form uranyl nitrate solution |
| 6 | Regenerated Adsorbent | |
| 7 | Sodium Hydroxide | Regenerate adsorbent with alkali solution |
| 8 | Regenerated Adsorbent | Return adsorbent for deployment |
| 9 | Crude uranyl nitrate | Uranyl nitrate with impurities |
| **Total Major Process Steps** | | **3** |
| ***Major Process Steps are Elution (B), Elution (D) and Adsorbent Wash (F)** | | |

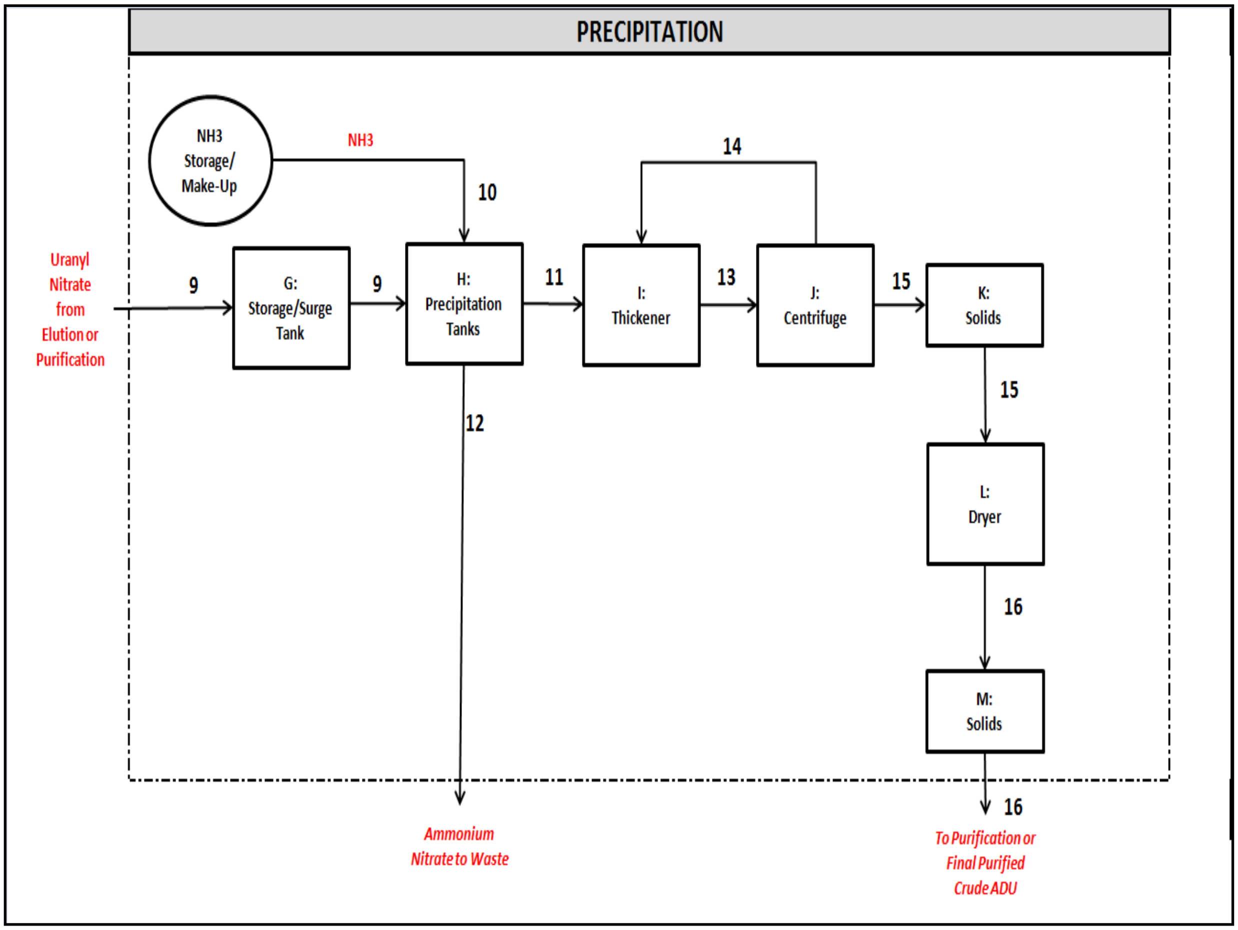


Figure A.4.4: Process Flow Diagram – Precipitation

Table A.4.6: Equipment and Stream Table for Precipitation Process Flow Diagram

| **PFD Table** | | |
|---|---|---|
| **Equipment** | | |
| **ID** | **Equipment Type** | **Description** |
| G | Storage Tanks | Inventory/Control of eluted uranyl nitrate |
| H | Agitated Tank | Precipitate Crude ADU in stirred tank with Ammonia |
| I | Thickener | Remove excess liquid |
| J | Centrifuge | Concentrate solid ADU |
| K | Belt Conveyor | Make-Up/Feed Chemicals (HCl, HNO3, NH3) |
| L | Dryer | Dry ADU for final storage/transport |
| M | Belt Conveyor | Move crude ADU to purification or pure ADU to final storage |
| **Streams** | | |
| **ID** | **Components** | **Description** |
| 9 | Uranyl Nitrate | Uranyl Nitrate from elution or purification |
| 10 | Ammonia | Ammonia to precipitate ADU |
| 11 | Ammonium Diuranate (ADU) | Crude or purified ADU |
| 12 | Ammonium Nitrate | Waste from precipitation; to raffinate treatment area |
| 13 | ADU | Thickened ADU |
| 14 | Recycled Solution | Low mass phase from centrifuge |
| 15 | ADU | |
| 16 | ADU | Dried ADU |
| **Total Major Process Steps** | | **8** |
| **Major Process Steps are Precipitation (H), Thickening (I), Centrifuge (J) and Drying (L) * Two precipitation areas** | | |

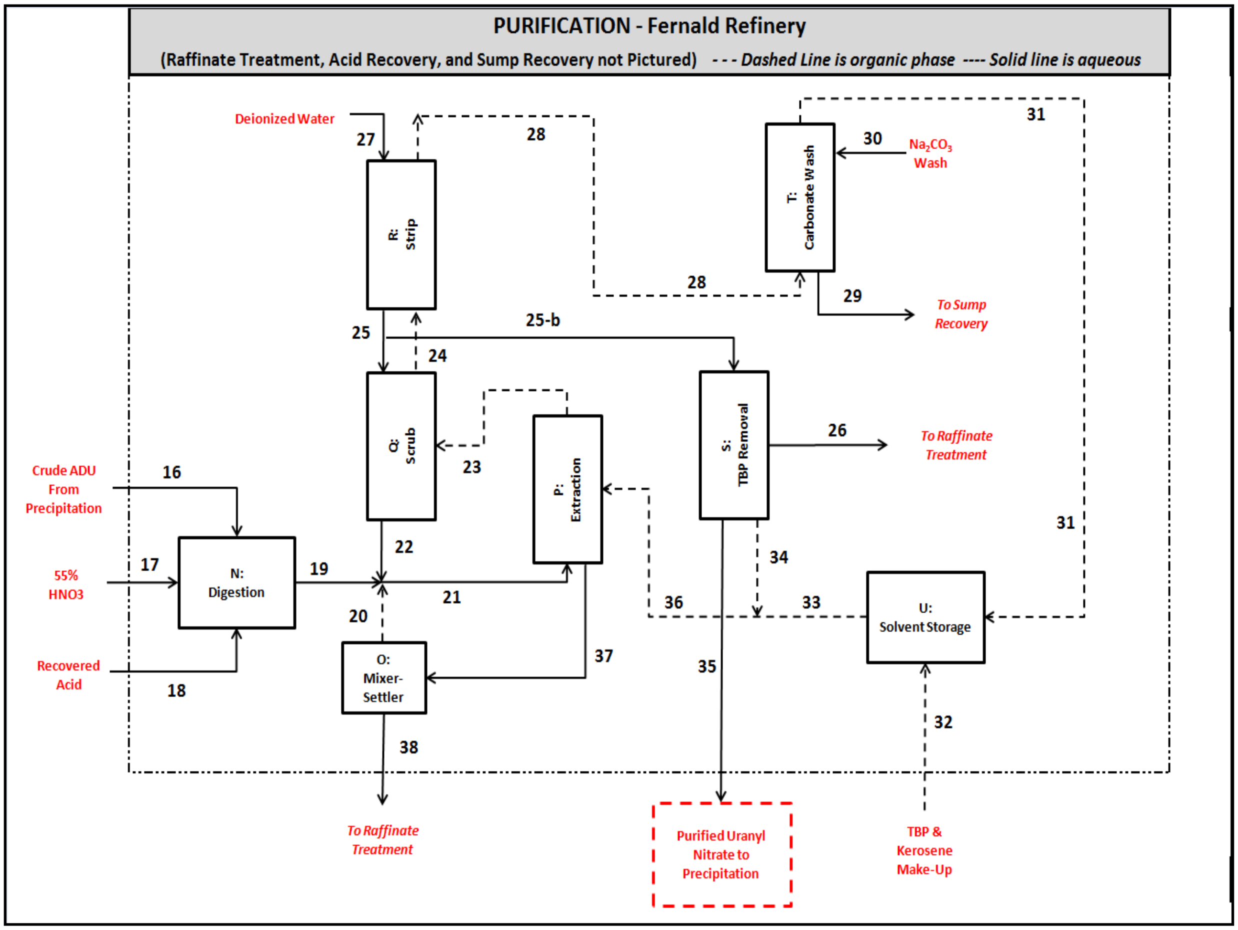


Figure A.4.5: Process Flow Diagram – Purification (Fernald Refinery)

Table A.4.7: Equipment and Stream Table for Purification Process Flow Diagram

| **PFD Table** | | |
|---|---|---|
| **Equipment** | | |
| **ID** | **Equipment Type** | **Description** |
| N | Agitated Tank | Dissolve ADU in nitric acid for purification |
| O | Mixer-Settler | Separate raffinate from recoverable organic solvent |
| P | Pulsed Column | Primary extraction column |
| Q | Pulsed Column | Scrubs impurities from organic phase |
| R | Pulsed Column | Strip uranium into aqueous phase for final processing |

| | | |
|---|---|---|
| S | Multiple | Area to remove entrained TBP and remove waste streams |
| T | Multiple | Wash Solvent |
| U | Filter | Storage/Inventory for organic solvent |
| Etc | Storage Tanks | DI Water, Sodium Carbonate, and TBP/Kerosene |
| **Streams** | | |
| **ID** | **Components** | **Description** |
| 16 | Crude Ammonium Diuranate | Precipitated ADU after elution |
| 17 | Aqueous (HNO3) | 55 wt% Nitric Acid |
| 18 | Recovered HNO3 | From Acid Recovery Area |
| 19 | Uranyl Nitrate Solution | Crude Uranyl Nitrate |
| 20 | Organic (TBP/Kerosene) | |
| 21 | Aqueous with Uranium | |
| 22 | Stripped Aqueous | |
| 23 | Organic with Uranium | |
| 24 | Organic with Uranium | Impurities scrubbed by Aqueous Stream |
| 25 | Aqueous with Uranium | |
| 25-b | Aqueous with Uranium | Main Product Recovery Stream |
| 26 | Aqueous Raffinate | To Raffinate area for treatment |
| 27 | Deionized Water | Stripping Agent |
| 28 | Stripped Organic | Contains impurities such as dibutyl phosphate |
| 29 | Waste Stream | Waste to Sump for recovery/disposal |
| 30 | Sodium Carbonate | Solution to clean solvent |
| 31 | Organic (TBP/Kerosene) | |
| 32 | Organic (TBP/Kerosene) | Fresh TBP/Kerosene to make-up for losses |
| 33 | Organic (TBP/Kerosene) | |
| 34 | Organic (TBP/Kerosene) | Recovered organic solvent from product/waste streams |
| 35 | Purified Uranyl Nitrate | Product of solvent extraction area - to precipitation for final processing |
| 36 | Organic (TBP/Kerosene) | Main Organic feed for extraction |
| 37 | Aqueous/Organic Mix | Residual from primary extraction |
| 38 | Aqueous Raffinate | To Raffinate area for treatment |
| **Total Equipment Count/Major Process Steps*** | | **13** |
| ***Includes Raffinate Treatment, Sump Recovery, and Nitric Acid Recovery not included in PFD** | | |

Table A.4.8: Code of Accounts – Elution-Purification Area

| EMWG Acct # | Account Title | Total Cost (2010 US$) | Specific Annual Cost ($/kg U) |
|---|---|---|---|
| **1** | **Capitalized Pre-construction Costs (Subtotal)** | **$1,633,817** | **$0.14** |
| **10 series** | | | |
| **11** | **Land and land rights** | $1,633,817 | $0.14 |
| **12** | **Site permits** | $0 | |
| **13** | **Plant licensing** | $0 | |
| **14** | **Plant permits** | $0 | |
| **15** | **Plant studies** | $0 | |
| **16** | **Plant reports** | $0 | |
| **17** | **Other Pre-Construction Costs** | $0 | |
| **18** | **Reserved for other activity as needed** | $0 | |
| **19** | **Contingency on Pre-Construction Costs** | $0 | |
| **2** | **Capitalized Direct Costs (Subtotal)** | **$86,939,316** | **$9.02** |
| **20 series** | | | |
| **21** | **Structures and Improvements** | $23,710,723 | $2.10 |
| **22** | **N/A** | $0 | 0 |
| **23** | **Process Equipment** | $48,409,392 | $5.30 |
| **24** | **Electrical equipment** | $2,469,867 | $0.27 |
| **25** | **Heat Rejection System** | $0 | $0.00 |
| **26** | **Miscellaneous plant equipment** | $12,349,335 | $1.35 |
| **27** | **Special materials** | $0 | |
| **28** | **N/A** | $0 | |
| **29** | **Contingency on Direct Costs** | $0 | |
| **Sum 1-2** | **TOTAL DIRECT COST** | | |
| | | | |
| **3** | **Capitalized Indirect Services (Subtotal)** | **$20,993,869** | **$2.30** |
| **30 series** | | | |
| **31** | **Field indirect costs (rentals, temp facil, etc)** | $13,090,295 | $1.43 |
| **32** | **Construction supervision** | $7,903,574 | $0.87 |
| **33** | **Commissioning and Start-Up Costs** | $0 | $0.00 |

| | | | |
|---|---|---|---|
| **34** | **Demonstration Test Run** | $0 | $0.00 |
| **Sum 1 - 34** | **TOTAL FIELD COST** | | |
| **35** | **Design Services Offsite** | $0 | |
| **36** | **PM/CM Services Offsite** | $0 | |
| **37** | **Design Services Onsite** | $0 | |
| **38** | **PM/CM Services Onsite** | $0 | |
| **39** | **Contingency on  Indirect Services** | $0 | |
| **Sum 1-3** | **BASE CONSTRUCTION COST** | | |
| **4** | **Capitalized Owner's costs (Subtotal)** | **$987,947** | **$0.11** |
| **40 series** | | | |
| **41** | **Staff recruitment and training** | $0 | |
| **42** | **Staff housing facilities** | $0 | |
| **43** | **Staff salary-related costs** | $0 | |
| **44** | **Reserved** | $0 | |
| **45** | **Reserved** | $0 | |
| **46** | **Other Owners' capital investment costs** | $987,947 | $0.11 |
| **47** | **Reserved** | $0 | |
| **48** | **Reserved** | $0 | |
| **49** | **Contingency on Owner's Costs** | $0 | - |
| **5** | **Capitalized Supplementary Costs (subtotal)** | **$0** | 0 |
| **50 series** | | | |
| **51** | **Shipping & transportation costs** | $0 | |
| **52** | **Spare parts and supplies** | $0 | |
| **53** | **Taxes** | $0 | |
| **54** | **Insurance** | $0 | |
| **55** | **N/A** | $0 | |
| **56** | **Reserved** | $0 | |
| **57** | **Reserved** | $0 | |
| **58** | **Decommissioning Costs** | $0 | |
| **59** | **Contingency on supplementary costs** | $0 | |
| **Sum 1-5** | **OVERNIGHT CONSTRUCTION COST** | | |
| **CONT** | **Total contingency:accts 19+29+39+49+59** | **$11,055,495** | **$1.21** |
| **OVNT** | **Overnight cost** | **$121,610,444** | **$12.79** |
| | | | |

| | | | |
|---|---|---|---|
| **6** | **Capitalized Financial Costs (subtotal)** | **$0** | **$0.00** |
| **60 series** | | | |
| **61** | **Escalation** | $0 | |
| **62** | **Fees/Royalties** | $0 | 0 |
| **63** | **Interest during construction** | $0 | |
| **64** | | $0 | |
| **65** | | $0 | |
| **66** | | $0 | |
| **67** | | $0 | |
| **68** | | $0 | |
| **69** | **Contingency on financial costs** | $0 | |
| **Sum 1-6** | **TOTAL CAPITAL INVESTMENT COST** | | |
| | **Total Capitalized Cost (TCIC)** | **$121,610,444** | **$12.79** |
| | **Annualized Costs** | | |
| **7** | **Annualized O&M Cost (subtotal)** | **$25,661,896** | **$21.38** |
| **70 series** | | | |
| **71** | **Operations Staff** | $8,370,758 | $6.98 |
| **72** | **Management Staff** | $1,464,883 | $1.22 |
| **73** | **Salary-Related Costs** | $0 | $0.00 |
| **74** | **Raw Materials** | $1,605,673 | $1.34 |
| **75** | **Spare Parts** | $0 | $0.00 |
| **76** | **Utilities, Supplies and Consumables** | $8,402,208 | $7.00 |
| **77** | **Capital Plant Upgrades** | $0 | $0.00 |
| **78** | **Taxes and Insurance** | $3,485,476 | $2.90 |
| **79** | **Contingency on O&M Cost** | $2,332,900 | $1.94 |
| **9** | **Annualized Financial Costs (subtotal)** | **$0** | 0 |
| **90 series** | | | |
| **91** | **Escalation** | $0 | |
| **92** | **Fees** | $0 | |
| **93** | **Cost of Money** | $0 | |
| **94** | | $0 | |
| **95** | | $0 | |
| **96** | | $0 | |
| **97** | | $0 | |

| | | | |
|---|---|---|---|
| **98** | | $0 | |
| **99** | **Contingency on Financial Costs** | $0 | |

# Appendix B: Other Tables and Figures

Table B.4.1: Engineering Cost Indices (Chemical Engineering 2011), (Peters, Timmerhaus and West 2003), (Turton, et al. 2009)

| | Marshall and Swift | Chemical Engineering |
|---|---|---|
| **1953** | 182.5 | 84.7 |
| **1954** | 184.6 | 86.1 |
| **1955** | 190.6 | 88.3 |
| **1956** | 208.8 | 93.9 |
| **1957** | 225.1 | 98.5 |
| **1958** | 229.2 | 99.7 |
| **1959** | 234.5 | 101.8 |
| **1960** | 237.7 | 102 |
| **1961** | 237.2 | 101.5 |
| **1962** | 238.5 | 102 |
| **1963** | 239.2 | 102.4 |
| **1964** | 241.8 | 103.3 |
| **1965** | 244.9 | 104.2 |
| **1966** | 252.5 | 107.2 |
| **1967** | 262.9 | 109.7 |
| **1968** | 273.1 | 113.6 |
| **1969** | 285 | 119 |
| **1970** | 303.3 | 125.7 |
| **1971** | 321.3 | 132.2 |
| **1972** | 332 | 137.2 |
| **1973** | 344.1 | 144.1 |
| **1974** | 398.4 | 165.4 |
| **1975** | 444.3 | 182.4 |
| **1976** | 472.1 | 192.1 |
| **1977** | 505.4 | 204.1 |
| **1978** | 545.3 | 218.8 |
| **1979** | 599.4 | 238.7 |
| **1980** | 659.6 | 261.2 |
| **1981** | 721.3 | 297 |
| **1982** | 745.6 | 314 |
| **1983** | 760.8 | 316.9 |

| | | |
|---|---|---|
| **1984** | 780.4 | 322.7 |
| **1985** | 789.6 | 325.3 |
| **1986** | 797.6 | 318.5 |
| **1987** | 814.0 | 324.0 |
| **1988** | 852.0 | 343.0 |
| **1989** | 895.0 | 355.0 |
| **1990** | 915.1 | 357.6 |
| **1991** | 930.6 | 361.3 |
| **1992** | 943.1 | 358.2 |
| **1993** | 964.2 | 359.2 |
| **1994** | 993.4 | 368.1 |
| **1995** | 1027.5 | 381.1 |
| **1996** | 1039.1 | 381.7 |
| **1997** | 1056.8 | 386.5 |
| **1998** | 1061.9 | 389.5 |
| **1999** | 1068.3 | 390.6 |
| **2000** | 1089.0 | 394.1 |
| **2001** | 1093.9 | 394.3 |
| **2002** | 1104.2 | 395.6 |
| **2003** | 1123.6 | 402.0 |
| **2004** | 1178.5 | 444.2 |
| **2005** | 1244.5 | 468.2 |
| **2006** | 1302.3 | 499.6 |
| **2007** | 1373.3 | 525.4 |
| **2008** | 1449.3 | 575.4 |
| **2009** | 1468.6 | 521.9 |
| **2010** | 1457.4 | 550.8 |

Table B.4.2: Consumer Price Index (Bureau of Labor Statistics 2011)

| Year | Jan | Feb | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. | Avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1913** | 9.8 | 9.8 | 9.8 | 9.8 | 9.7 | 9.8 | 9.9 | 9.9 | 10.0 | 10.0 | 10.1 | 10.0 | **9.9** |
| **1914** | 10.0 | 9.9 | 9.9 | 9.8 | 9.9 | 9.9 | 10.0 | 10.2 | 10.2 | 10.1 | 10.2 | 10.1 | **10.0** |
| **1915** | 10.1 | 10.0 | 9.9 | 10.0 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.2 | 10.3 | 10.3 | **10.1** |
| | | | | | | | | | | | | | |
| **1916** | 10.4 | 10.4 | 10.5 | 10.6 | 10.7 | 10.8 | 10.8 | 10.9 | 11.1 | 11.3 | 11.5 | 11.6 | **10.9** |
| **1917** | 11.7 | 12.0 | 12.0 | 12.6 | 12.8 | 13.0 | 12.8 | 13.0 | 13.3 | 13.5 | 13.5 | 13.7 | **12.8** |
| **1918** | 14.0 | 14.1 | 14.0 | 14.2 | 14.5 | 14.7 | 15.1 | 15.4 | 15.7 | 16.0 | 16.3 | 16.5 | **15.1** |
| **1919** | 16.5 | 16.2 | 16.4 | 16.7 | 16.9 | 16.9 | 17.4 | 17.7 | 17.8 | 18.1 | 18.5 | 18.9 | **17.3** |
| **1920** | 19.3 | 19.5 | 19.7 | 20.3 | 20.6 | 20.9 | 20.8 | 20.3 | 20.0 | 19.9 | 19.8 | 19.4 | **20.0** |
| | | | | | | | | | | | | | |
| **1921** | 19.0 | 18.4 | 18.3 | 18.1 | 17.7 | 17.6 | 17.7 | 17.7 | 17.5 | 17.5 | 17.4 | 17.3 | **17.9** |
| **1922** | 16.9 | 16.9 | 16.7 | 16.7 | 16.7 | 16.7 | 16.8 | 16.6 | 16.6 | 16.7 | 16.8 | 16.9 | **16.8** |
| **1923** | 16.8 | 16.8 | 16.8 | 16.9 | 16.9 | 17.0 | 17.2 | 17.1 | 17.2 | 17.3 | 17.3 | 17.3 | **17.1** |
| **1924** | 17.3 | 17.2 | 17.1 | 17.0 | 17.0 | 17.0 | 17.1 | 17.0 | 17.1 | 17.2 | 17.2 | 17.3 | **17.1** |
| **1925** | 17.3 | 17.2 | 17.3 | 17.2 | 17.3 | 17.5 | 17.7 | 17.7 | 17.7 | 17.7 | 18.0 | 17.9 | **17.5** |
| | | | | | | | | | | | | | |
| **1926** | 17.9 | 17.9 | 17.8 | 17.9 | 17.8 | 17.7 | 17.5 | 17.4 | 17.5 | 17.6 | 17.7 | 17.7 | **17.7** |
| **1927** | 17.5 | 17.4 | 17.3 | 17.3 | 17.4 | 17.6 | 17.3 | 17.2 | 17.3 | 17.4 | 17.3 | 17.3 | **17.4** |
| **1928** | 17.3 | 17.1 | 17.1 | 17.1 | 17.2 | 17.1 | 17.1 | 17.1 | 17.3 | 17.2 | 17.2 | 17.1 | **17.1** |
| **1929** | 17.1 | 17.1 | 17.0 | 16.9 | 17.0 | 17.1 | 17.3 | 17.3 | 17.3 | 17.3 | 17.3 | 17.2 | **17.1** |
| **1930** | 17.1 | 17.0 | 16.9 | 17.0 | 16.9 | 16.8 | 16.6 | 16.5 | 16.6 | 16.5 | 16.4 | 16.1 | **16.7** |
| | | | | | | | | | | | | | |
| **1931** | 15.9 | 15.7 | 15.6 | 15.5 | 15.3 | 15.1 | 15.1 | 15.1 | 15.0 | 14.9 | 14.7 | 14.6 | **15.2** |
| **1932** | 14.3 | 14.1 | 14.0 | 13.9 | 13.7 | 13.6 | 13.6 | 13.5 | 13.4 | 13.3 | 13.2 | 13.1 | **13.7** |
| **1933** | 12.9 | 12.7 | 12.6 | 12.6 | 12.6 | 12.7 | 13.1 | 13.2 | 13.2 | 13.2 | 13.2 | 13.2 | **13.0** |
| **1934** | 13.2 | 13.3 | 13.3 | 13.3 | 13.3 | 13.4 | 13.4 | 13.4 | 13.6 | 13.5 | 13.5 | 13.4 | **13.4** |
| **1935** | 13.6 | 13.7 | 13.7 | 13.8 | 13.8 | 13.7 | 13.7 | 13.7 | 13.7 | 13.7 | 13.8 | 13.8 | **13.7** |
| | | | | | | | | | | | | | |
| **1936** | 13.8 | 13.8 | 13.7 | 13.7 | 13.7 | 13.8 | 13.9 | 14.0 | 14.0 | 14.0 | 14.0 | 14.0 | **13.9** |
| **1937** | 14.1 | 14.1 | 14.2 | 14.3 | 14.4 | 14.4 | 14.5 | 14.5 | 14.6 | 14.6 | 14.5 | 14.4 | **14.4** |
| **1938** | 14.2 | 14.1 | 14.1 | 14.2 | 14.1 | 14.1 | 14.1 | 14.1 | 14.1 | 14.0 | 14.0 | 14.0 | **14.1** |
| **1939** | 14.0 | 13.9 | 13.9 | 13.8 | 13.8 | 13.8 | 13.8 | 13.8 | 14.1 | 14.0 | 14.0 | 14.0 | **13.9** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1940** | 13.9 | 14.0 | 14.0 | 14.0 | 14.0 | 14.1 | 14.0 | 14.0 | 14.0 | 14.0 | 14.0 | 14.1 | **14.0** |
| | | | | | | | | | | | | | |
| **1941** | 14.1 | 14.1 | 14.2 | 14.3 | 14.4 | 14.7 | 14.7 | 14.9 | 15.1 | 15.3 | 15.4 | 15.5 | **14.7** |
| **1942** | 15.7 | 15.8 | 16.0 | 16.1 | 16.3 | 16.3 | 16.4 | 16.5 | 16.5 | 16.7 | 16.8 | 16.9 | **16.3** |
| **1943** | 16.9 | 16.9 | 17.2 | 17.4 | 17.5 | 17.5 | 17.4 | 17.3 | 17.4 | 17.4 | 17.4 | 17.4 | **17.3** |
| **1944** | 17.4 | 17.4 | 17.4 | 17.5 | 17.5 | 17.6 | 17.7 | 17.7 | 17.7 | 17.7 | 17.7 | 17.8 | **17.6** |
| **1945** | 17.8 | 17.8 | 17.8 | 17.8 | 17.9 | 18.1 | 18.1 | 18.1 | 18.1 | 18.1 | 18.1 | 18.2 | **18.0** |
| | | | | | | | | | | | | | |
| **1946** | 18.2 | 18.1 | 18.3 | 18.4 | 18.5 | 18.7 | 19.8 | 20.2 | 20.4 | 20.8 | 21.3 | 21.5 | **19.5** |
| **1947** | 21.5 | 21.5 | 21.9 | 21.9 | 21.9 | 22.0 | 22.2 | 22.5 | 23.0 | 23.0 | 23.1 | 23.4 | **22.3** |
| **1948** | 23.7 | 23.5 | 23.4 | 23.8 | 23.9 | 24.1 | 24.4 | 24.5 | 24.5 | 24.4 | 24.2 | 24.1 | **24.1** |
| **1949** | 24.0 | 23.8 | 23.8 | 23.9 | 23.8 | 23.9 | 23.7 | 23.8 | 23.9 | 23.7 | 23.8 | 23.6 | **23.8** |
| **1950** | 23.5 | 23.5 | 23.6 | 23.6 | 23.7 | 23.8 | 24.1 | 24.3 | 24.4 | 24.6 | 24.7 | 25.0 | **24.1** |
| | | | | | | | | | | | | | |
| **1951** | 25.4 | 25.7 | 25.8 | 25.8 | 25.9 | 25.9 | 25.9 | 25.9 | 26.1 | 26.2 | 26.4 | 26.5 | **26.0** |
| **1952** | 26.5 | 26.3 | 26.3 | 26.4 | 26.4 | 26.5 | 26.7 | 26.7 | 26.7 | 26.7 | 26.7 | 26.7 | **26.5** |
| **1953** | 26.6 | 26.5 | 26.6 | 26.6 | 26.7 | 26.8 | 26.8 | 26.9 | 26.9 | 27.0 | 26.9 | 26.9 | **26.7** |
| **1954** | 26.9 | 26.9 | 26.9 | 26.8 | 26.9 | 26.9 | 26.9 | 26.9 | 26.8 | 26.8 | 26.8 | 26.7 | **26.9** |
| **1955** | 26.7 | 26.7 | 26.7 | 26.7 | 26.7 | 26.7 | 26.8 | 26.8 | 26.9 | 26.9 | 26.9 | 26.8 | **26.8** |
| | | | | | | | | | | | | | |
| **1956** | 26.8 | 26.8 | 26.8 | 26.9 | 27.0 | 27.2 | 27.4 | 27.3 | 27.4 | 27.5 | 27.5 | 27.6 | **27.2** |
| **1957** | 27.6 | 27.7 | 27.8 | 27.9 | 28.0 | 28.1 | 28.3 | 28.3 | 28.3 | 28.3 | 28.4 | 28.4 | **28.1** |
| **1958** | 28.6 | 28.6 | 28.8 | 28.9 | 28.9 | 28.9 | 29.0 | 28.9 | 28.9 | 28.9 | 29.0 | 28.9 | **28.9** |
| **1959** | 29.0 | 28.9 | 28.9 | 29.0 | 29.0 | 29.1 | 29.2 | 29.2 | 29.3 | 29.4 | 29.4 | 29.4 | **29.1** |
| **1960** | 29.3 | 29.4 | 29.4 | 29.5 | 29.5 | 29.6 | 29.6 | 29.6 | 29.6 | 29.8 | 29.8 | 29.8 | **29.6** |
| | | | | | | | | | | | | | |
| **1961** | 29.8 | 29.8 | 29.8 | 29.8 | 29.8 | 29.8 | 30.0 | 29.9 | 30.0 | 30.0 | 30.0 | 30.0 | **29.9** |
| **1962** | 30.0 | 30.1 | 30.1 | 30.2 | 30.2 | 30.2 | 30.3 | 30.3 | 30.4 | 30.4 | 30.4 | 30.4 | **30.2** |
| **1963** | 30.4 | 30.4 | 30.5 | 30.5 | 30.5 | 30.6 | 30.7 | 30.7 | 30.7 | 30.8 | 30.8 | 30.9 | **30.6** |
| **1964** | 30.9 | 30.9 | 30.9 | 30.9 | 30.9 | 31.0 | 31.1 | 31.0 | 31.1 | 31.1 | 31.2 | 31.2 | **31.0** |
| **1965** | 31.2 | 31.2 | 31.3 | 31.4 | 31.4 | 31.6 | 31.6 | 31.6 | 31.6 | 31.7 | 31.7 | 31.8 | **31.5** |
| | | | | | | | | | | | | | |
| **1966** | 31.8 | 32.0 | 32.1 | 32.3 | 32.3 | 32.4 | 32.5 | 32.7 | 32.7 | 32.9 | 32.9 | 32.9 | **32.4** |
| **1967** | 32.9 | 32.9 | 33.0 | 33.1 | 33.2 | 33.3 | 33.4 | 33.5 | 33.6 | 33.7 | 33.8 | 33.9 | **33.4** |
| **1968** | 34.1 | 34.2 | 34.3 | 34.4 | 34.5 | 34.7 | 34.9 | 35.0 | 35.1 | 35.3 | 35.4 | 35.5 | **34.8** |
| **1969** | 35.6 | 35.8 | 36.1 | 36.3 | 36.4 | 36.6 | 36.8 | 37.0 | 37.1 | 37.3 | 37.5 | 37.7 | **36.7** |
| **1970** | 37.8 | 38.0 | 38.2 | 38.5 | 38.6 | 38.8 | 39.0 | 39.0 | 39.2 | 39.4 | 39.6 | 39.8 | **38.8** |
| | | | | | | | | | | | | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1971** | 39.8 | 39.9 | 40.0 | 40.1 | 40.3 | 40.6 | 40.7 | 40.8 | 40.8 | 40.9 | 40.9 | 41.1 | **40.5** |
| **1972** | 41.1 | 41.3 | 41.4 | 41.5 | 41.6 | 41.7 | 41.9 | 42.0 | 42.1 | 42.3 | 42.4 | 42.5 | **41.8** |
| **1973** | 42.6 | 42.9 | 43.3 | 43.6 | 43.9 | 44.2 | 44.3 | 45.1 | 45.2 | 45.6 | 45.9 | 46.2 | **44.4** |
| **1974** | 46.6 | 47.2 | 47.8 | 48.0 | 48.6 | 49.0 | 49.4 | 50.0 | 50.6 | 51.1 | 51.5 | 51.9 | **49.3** |
| **1975** | 52.1 | 52.5 | 52.7 | 52.9 | 53.2 | 53.6 | 54.2 | 54.3 | 54.6 | 54.9 | 55.3 | 55.5 | **53.8** |
| | | | | | | | | | | | | | |
| **1976** | 55.6 | 55.8 | 55.9 | 56.1 | 56.5 | 56.8 | 57.1 | 57.4 | 57.6 | 57.9 | 58.0 | 58.2 | **56.9** |
| **1977** | 58.5 | 59.1 | 59.5 | 60.0 | 60.3 | 60.7 | 61.0 | 61.2 | 61.4 | 61.6 | 61.9 | 62.1 | **60.6** |
| **1978** | 62.5 | 62.9 | 63.4 | 63.9 | 64.5 | 65.2 | 65.7 | 66.0 | 66.5 | 67.1 | 67.4 | 67.7 | **65.2** |
| **1979** | 68.3 | 69.1 | 69.8 | 70.6 | 71.5 | 72.3 | 73.1 | 73.8 | 74.6 | 75.2 | 75.9 | 76.7 | **72.6** |
| **1980** | 77.8 | 78.9 | 80.1 | 81.0 | 81.8 | 82.7 | 82.7 | 83.3 | 84.0 | 84.8 | 85.5 | 86.3 | **82.4** |
| | | | | | | | | | | | | | |
| **1981** | 87.0 | 87.9 | 88.5 | 89.1 | 89.8 | 90.6 | 91.6 | 92.3 | 93.2 | 93.4 | 93.7 | 94.0 | **90.9** |
| **1982** | 94.3 | 94.6 | 94.5 | 94.9 | 95.8 | 97.0 | 97.5 | 97.7 | 97.9 | 98.2 | 98.0 | 97.6 | **96.5** |
| **1983** | 97.8 | 97.9 | 97.9 | 98.6 | 99.2 | 99.5 | 99.9 | 100.2 | 100.7 | 101.0 | 101.2 | 101.3 | **99.6** |
| **1984** | 101.9 | 102.4 | 102.6 | 103.1 | 103.4 | 103.7 | 104.1 | 104.5 | 105.0 | 105.3 | 105.3 | 105.3 | **103.9** |
| **1985** | 105.5 | 106.0 | 106.4 | 106.9 | 107.3 | 107.6 | 107.8 | 108.0 | 108.3 | 108.7 | 109.0 | 109.3 | **107.6** |
| | | | | | | | | | | | | | |
| **1986** | 109.6 | 109.3 | 108.8 | 108.6 | 108.9 | 109.5 | 109.5 | 109.7 | 110.2 | 110.3 | 110.4 | 110.5 | **109.6** |
| **1987** | 111.2 | 111.6 | 112.1 | 112.7 | 113.1 | 113.5 | 113.8 | 114.4 | 115.0 | 115.3 | 115.4 | 115.4 | **113.6** |
| **1988** | 115.7 | 116.0 | 116.5 | 117.1 | 117.5 | 118.0 | 118.5 | 119.0 | 119.8 | 120.2 | 120.3 | 120.5 | **118.3** |
| **1989** | 121.1 | 121.6 | 122.3 | 123.1 | 123.8 | 124.1 | 124.4 | 124.6 | 125.0 | 125.6 | 125.9 | 126.1 | **124.0** |
| **1990** | 127.4 | 128.0 | 128.7 | 128.9 | 129.2 | 129.9 | 130.4 | 131.6 | 132.7 | 133.5 | 133.8 | 133.8 | **130.7** |
| | | | | | | | | | | | | | |
| **1991** | 134.6 | 134.8 | 135.0 | 135.2 | 135.6 | 136.0 | 136.2 | 136.6 | 137.2 | 137.4 | 137.8 | 137.9 | **136.2** |
| **1992** | 138.1 | 138.6 | 139.3 | 139.5 | 139.7 | 140.2 | 140.5 | 140.9 | 141.3 | 141.8 | 142.0 | 141.9 | **140.3** |
| **1993** | 142.6 | 143.1 | 143.6 | 144.0 | 144.2 | 144.4 | 144.4 | 144.8 | 145.1 | 145.7 | 145.8 | 145.8 | **144.5** |
| **1994** | 146.2 | 146.7 | 147.2 | 147.4 | 147.5 | 148.0 | 148.4 | 149.0 | 149.4 | 149.5 | 149.7 | 149.7 | **148.2** |
| **1995** | 150.3 | 150.9 | 151.4 | 151.9 | 152.2 | 152.5 | 152.5 | 152.9 | 153.2 | 153.7 | 153.6 | 153.5 | **152.4** |
| | | | | | | | | | | | | | |
| **1996** | 154.4 | 154.9 | 155.7 | 156.3 | 156.6 | 156.7 | 157.0 | 157.3 | 157.8 | 158.3 | 158.6 | 158.6 | **156.9** |
| **1997** | 159.1 | 159.6 | 160.0 | 160.2 | 160.1 | 160.3 | 160.5 | 160.8 | 161.2 | 161.6 | 161.5 | 161.3 | **160.5** |
| **1998** | 161.6 | 161.9 | 162.2 | 162.5 | 162.8 | 163.0 | 163.2 | 163.4 | 163.6 | 164.0 | 164.0 | 163.9 | **163.0** |
| **1999** | 164.3 | 164.5 | 165.0 | 166.2 | 166.2 | 166.2 | 166.7 | 167.1 | 167.9 | 168.2 | 168.3 | 168.3 | **166.6** |
| **2000** | 168.8 | 169.8 | 171.2 | 171.3 | 171.5 | 172.4 | 172.8 | 172.8 | 173.7 | 174.0 | 174.1 | 174.0 | **172.2** |
| | | | | | | | | | | | | | |
| **2001** | 175.1 | 175.8 | 176.2 | 176.9 | 177.7 | 178.0 | 177.5 | 177.5 | 178.3 | 177.7 | 177.4 | 176.7 | **177.1** |
| **2002** | 177.1 | 177.8 | 178.8 | 179.8 | 179.8 | 179.9 | 180.1 | 180.7 | 181.0 | 181.3 | 181.3 | 180.9 | **179.9** |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2003** | 181.7 | 183.1 | 184.2 | 183.8 | 183.5 | 183.7 | 183.9 | 184.6 | 185.2 | 185.0 | 184.5 | 184.3 | **184.0** |
| **2004** | 185.2 | 186.2 | 187.4 | 188.0 | 189.1 | 189.7 | 189.4 | 189.5 | 189.9 | 190.9 | 191.0 | 190.3 | **188.9** |
| **2005** | 190.7 | 191.8 | 193.3 | 194.6 | 194.4 | 194.5 | 195.4 | 196.4 | 198.8 | 199.2 | 197.6 | 196.8 | **195.3** |
| | | | | | | | | | | | | | |
| **2006** | 198.3 | 198.7 | 199.8 | 201.5 | 202.5 | 202.9 | 203.5 | 203.9 | 202.9 | 201.8 | 201.5 | 201.8 | **201.6** |
| **2007** | 202.4 | 203.5 | 205.4 | 206.7 | 207.9 | 208.4 | 208.3 | 207.9 | 208.5 | 208.9 | 210.2 | 210.0 | **207.3** |
| **2008** | 211.1 | 211.7 | 213.5 | 214.8 | 216.6 | 218.8 | 220.0 | 219.1 | 218.8 | 216.6 | 212.4 | 210.2 | **215.3** |
| **2009** | 211.1 | 212.2 | 212.7 | 213.2 | 213.9 | 215.7 | 215.4 | 215.8 | 216.0 | 216.2 | 216.3 | 215.9 | **214.5** |
| **2010** | 216.7 | 216.7 | 217.6 | 218.0 | 218.2 | 218.0 | 218.0 | 218.3 | 218.4 | 218.7 | 218.8 | 219.2 | **218.1** |
| | | | | | | | | | | | | | |
| **2011** | 220.2 | 221.3 | 223.5 | 224.9 | 226.0 | | | | | | | | |

Table B.4.3: Specialized Consumer Price Index, Electricity and Fuel Oil

| **Annual Average CPI** | | | |
|---|---|---|---|
| **Year** | **All Goods** | **Electricity** | **Fuel Oil #2** |
| 1998 | 163 | 0.087 | 0.880 |
| 1999 | 166.6 | 0.086 | 0.900 |
| 2000 | 172.2 | 0.087 | 1.360 |
| 2001 | 177.1 | 0.092 | 1.310 |
| 2002 | 179.9 | 0.091 | 1.162 |
| 2003 | 184 | 0.093 | 1.400 |
| 2004 | 188.9 | 0.094 | 1.645 |
| 2005 | 195.3 | 0.100 | 2.221 |
| 2006 | 201.6 | 0.112 | 2.495 |
| 2007 | 207.342 | 0.117 | 2.681 |
| 2008 | 215.303 | 0.123 | 3.752 |
| 2009 | 214.537 | 0.127 | 2.514 |
| 2010 | 218.056 | 0.128 | 2.925 |
| Source: Bureau of Labor Statistics 2011 | | | |

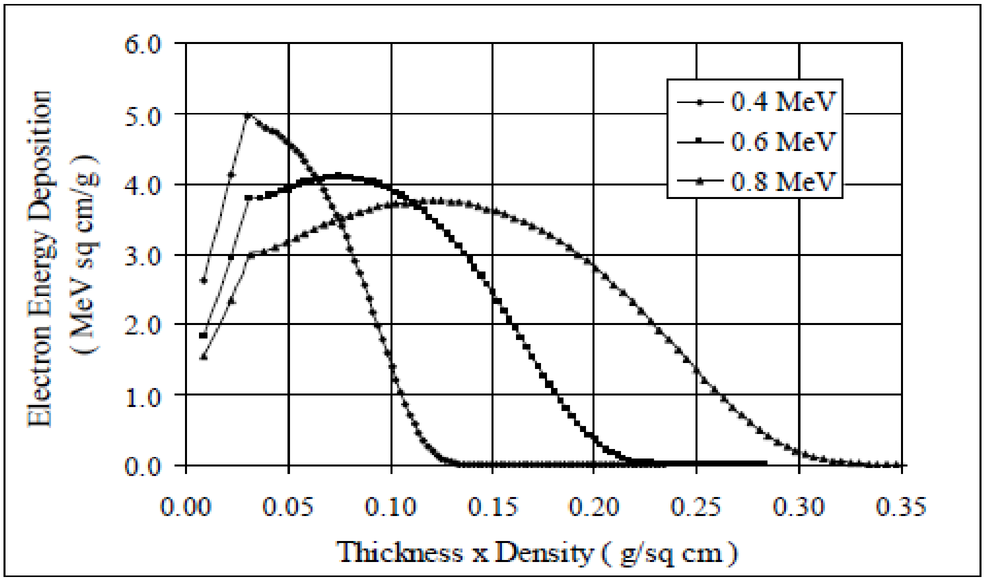


Figure B.4.1: Electron Energy Deposition in Polyethylene, 0.4 to 0.8 MeV. 40µm titanium beam window thickness, 15 cm air gap at 0.0012 g/cm3 (Cleland 2005)

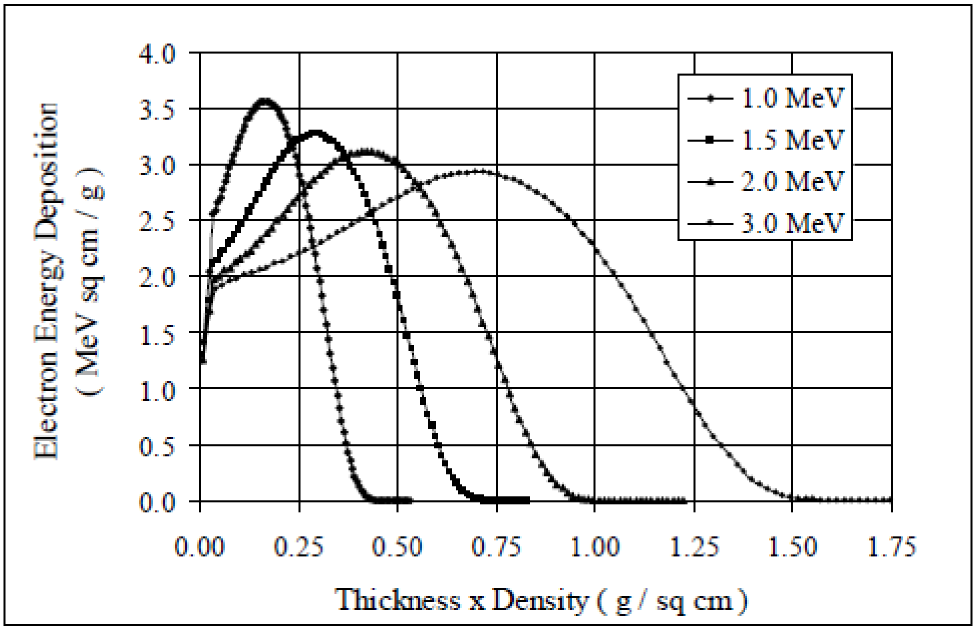


Figure B.4.2: Electron Energy Deposition in Polyethylene, 1 to 3 MeV. 40µm titanium beam window thickness, 15 cm air gap at 0.0012 g/cm$^3$ (Cleland 2005)

Table B.4.4: Chemical Prices and Standard Deviation from Historical Data

| Chemical | Description | Price, 2010 US$ average | Std. Dev. | Unit | Source |
|---|---|---|---|---|---|
| Nitric Acid | 42° Nitric Acid (67 wt%) | $284.09 | $47.35 | metric ton | CMR/ICIS Historical |
| Ammonia | Spot Price, 100% Ammonia | $340.88 | $148.47 | metric ton | CMR/ICIS Historical |
| Hydrochloric Acid | 22° Nitric Acid (36 wt%), | $148.08 | $58.15 | metric ton | CMR/ICIS Historical |
| Sulfuric Acid | 66° Sulfuric Acid (93 wt%), Commercial Grade | $63.08 | $20.17 | metric ton | CMR/ICIS Historical |
| Tributyl Phosphate (TBP) | 100% TBP | $6,419 | $1,848 | metric ton | CMR/ICIS Historical Vendor Quote |
| Kerosene | Kerosene from refiner to end users | $1.70 | $0.69 | gallon | EIA |
| Filter Aid (Diatomite) |  | $324.81 | $59.25 | metric tons | USGS Historical |
| Magnesium Oxide | deadburned bgs., c.l., t.l., works | $598.41 | $121.38 | metric ton | CMR/ICIS Historical |
| Calcium Oxide (Lime) | chemical pebble (quicklime), hydrated bulk, c.l., f.o.b. works | $106.91 | $15.45 | metric ton | USGS Historical |
| Polyethylene (HDPE) | US Gulf, bagged, export, HDPE blmldg | $1,467.24 | $280.45 | metric ton | CMR/ICIS Historical |

| | | | | | |
|---|---|---|---|---|---|
| Acrylonitrile | US Gulf, contract dom. del., 100% Acrylonitrile | $1,331.00 | $586.69 | metric ton | CMR/ICIS Historical |
| Dimethylformamide (DMF) | BASF, isocontainers, duty paid in Houston | $1,245.18 | $591.04 | metric ton | CMR/ICIS Historical Vendor Quote |
| Hydroxylamine | Includes data for hydroxylamine salts. | $3,077.27 | $410.68 | metric ton | CMR/ICIS Historical Vendor Quote |
| Methanol | US Gulf, contract barge, 100% Methanol | $283.55 | $126.83 | metric ton | CMR/ICIS Historical |
| Surfactant (Sodium Dodecyl Sulfate) | | $2,100.51 | $641.62 | metric ton | CMR/ICIS Historical Vendor Quote |
| Sodium Carbonate (Soda Ash) | dense, US Gulf, f.o.b. bulk | $148.59 | $42.55 | metric ton | USGS Historical |
| **Dimethyl Sulfoxide*** | | $1,607.28 | $682.64 | metric ton | Vendor Quotes |
| **Methacrylic Acid*** | US Gulf, contract, fd railcar | $3,443.97 | $518.31 | metric ton | CMR/ICIS Historical Vendor Quote |

Sources: (ICIS 2008), (Chemical Market Reporter 1998-2005), (Kelly and Matos 2010) - USGS, (U.S. EIA 2011)Vendor Identities are anonymous per vendor requests.
***These chemicals are not part of the baseline JAERI process. They reflect an alternative process developed in Japan and under investigation at ORNL.**

Table B.4.5: Stud Link Anchor Chain Specifications and Cost (American Bureau of Shipping 2010)

| | Normal Strength Grade 1 | | | High Strength Grade 2 | | | Extra High Strength Grade 3 | | | | Cost Per Meter Vendor Data** (Grade 3 Chain) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chain Diameter | Working Load Limit* | Proof Load | Breaking Load | Working Load Limit* | Proof Load | Breaking Load | Working Load Limit* | Proof Load | Breaking Load | Mass per 27.5 meters | |
| mm | kN | kN | kN | kN | kN | kN | kN | kN | kN | kg | 2010 US$ |
| 12.5 | 23.1 | 46.1 | 65.7 | 32.9 | 65.7 | 92.2 | 46.1 | 92.2 | 132.4 | 110 | $9.33 |
| 14 | 29.0 | 57.9 | 82.4 | 41.2 | 82.4 | 115.7 | 57.9 | 115.7 | 164.8 | 130 | $13.63 |
| 16 | 37.8 | 75.5 | 106.9 | 53.5 | 106.9 | 150 | 75.0 | 150 | 215.7 | 170 | $19.38 |
| 17.5 | 44.7 | 89.3 | 127.5 | 63.8 | 127.5 | 179.5 | 89.8 | 179.5 | 260.8 | 180 | $23.69 |
| 19 | 52.5 | 104.9 | 150 | 75.5 | 150.9 | 210.8 | 105.4 | 210.8 | 301.1 | 220 | $28.00 |
| 20.5 | 61.3 | 122.6 | 174.6 | 87.3 | 174.6 | 244.2 | 122.1 | 244.2 | 349.1 | 260 | $32.31 |
| 22 | 70.1 | 140.2 | 200.1 | 100.1 | 200.1 | 280.5 | 140.3 | 280.5 | 401.1 | 300 | $36.62 |
| 24 | 83.4 | 166.7 | 237.3 | 118.7 | 237.3 | 332.4 | 166.2 | 332.4 | 475.6 | 340 | $42.37 |
| 26 | 97.1 | 194.2 | 277.5 | 138.8 | 277.5 | 389.3 | 194.7 | 389.3 | 556 | 420 | $48.11 |
| 28 | 112.3 | 224.6 | 320.7 | 160.4 | 320.7 | 449.1 | 224.6 | 449.1 | 642.3 | 480 | $53.86 |
| 30 | 128.5 | 256.9 | 367.7 | 183.9 | 367.7 | 513.9 | 257.0 | 513.9 | 734.5 | 550 | $59.60 |
| 32 | 145.7 | 291.3 | 416.8 | 208.4 | 416.8 | 582.5 | 291.3 | 582.5 | 832.6 | 610 | $65.35 |
| 34 | 163.8 | 327.5 | 467.8 | 233.9 | 467.8 | 655.1 | 327.6 | 655.1 | 936.5 | 700 | $71.10 |
| 36 | 182.9 | 365.8 | 522.7 | 261.4 | 522.7 | 731.6 | 365.8 | 731.6 | 1049.3 | 790 | $76.84 |
| 38 | 203.0 | 406 | 580.6 | 290.3 | 580.6 | 812 | 406.0 | 812 | 1157.2 | 880 | $84.25 |
| 40 | 224.1 | 448.2 | 640.4 | 320.2 | 640.4 | 896.3 | 448.2 | 896.3 | 1284.7 | 970 | $88.34 |
| 42 | 246.2 | 492.3 | 703.1 | 351.6 | 703.1 | 980.7 | 490.4 | 980.7 | 1402.3 | 1070 | $94.08 |
| 44 | 269.2 | 538.4 | 768.8 | 384.4 | 768.8 | 1078.7 | 539.4 | 1078.7 | 1539.6 | 1170 | $96.74 |
| 46 | 292.8 | 585.5 | 836.5 | 418.3 | 836.5 | 1167 | 583.5 | 1167 | 1676.9 | 1270 | $105.57 |
| 48 | 317.8 | 635.5 | 908.1 | 454.1 | 908.1 | 1274.9 | 637.5 | 1274.9 | 1814.2 | 1380 | $111.32 |
| 50 | 343.3 | 686.5 | 980.7 | 490.4 | 980.7 | 1372.9 | 686.5 | 1372.9 | 1961.3 | 1480 | $117.07 |
| 52 | 369.7 | 739.4 | 1059.1 | 529.6 | 1059.1 | 1480.8 | 740.4 | 1480.8 | 2108.4 | 1600 | $122.81 |
| 54 | 397.2 | 794.3 | 1137.6 | 568.8 | 1137.6 | 1588.7 | 794.4 | 1588.7 | 2265.3 | 1720 | $128.56 |
| 56 | 425.6 | 851.2 | 1216 | 608.0 | 1216 | 1706.4 | 853.2 | 1706.4 | 2432 | 1850 | $134.31 |
| 58 | 454.6 | 909.1 | 1294.5 | 647.3 | 1294.5 | 1814.2 | 907.1 | 1814.2 | 2598.8 | 1990 | $140.05 |
| 60 | 484.5 | 968.9 | 1382.7 | 691.4 | 1382.7 | 1941.7 | 970.9 | 1941.7 | 2765.5 | 2120 | $145.80 |
| 62 | 514.9 | 1029.7 | 1471 | 735.5 | 1471 | 2059.4 | 1029.7 | 2059.4 | 2942 | 2250 | $151.54 |
| 64 | 549.2 | 1098.3 | 1559.3 | 779.7 | 1559.3 | 2186.9 | 1093.5 | 2186.9 | 3128.3 | 2440 | $157.29 |
| 66 | 578.6 | 1157.2 | 1657.3 | 828.7 | 1657.3 | 2314.4 | 1157.2 | 2314.4 | 3304.8 | 2590 | $163.04 |
| 68 | 612.9 | 1225.8 | 1745.6 | 872.8 | 1745.6 | 2451.7 | 1225.9 | 2451.7 | 3501 | 2750 | $168.78 |
| 70 | 647.3 | 1294.5 | 1843.7 | 921.9 | 1843.7 | 2579.1 | 1289.6 | 2579.1 | 3687.3 | 2910 | $174.53 |
| 73 | 696.3 | 1392.5 | 1990.7 | 995.4 | 1990.7 | 2794.9 | 1397.5 | 2794.9 | 3991.3 | 3180 | $183.15 |
| 76 | 750.2 | 1500.4 | 2147.6 | 1073.8 | 2147.6 | 3010.6 | 1505.3 | 3010.6 | 4295.3 | 3470 | $191.77 |
| 78 | 789.5 | 1578.9 | 2255.5 | 1127.8 | 2255.5 | 3157.7 | 1578.9 | 3157.7 | 4501.3 | 3650 | $197.51 |

*Working Load Limit Estimated as 50% of Proof Load.

**Vendor data only provided between 38 and 51 mm; all other costs are extrpolated.

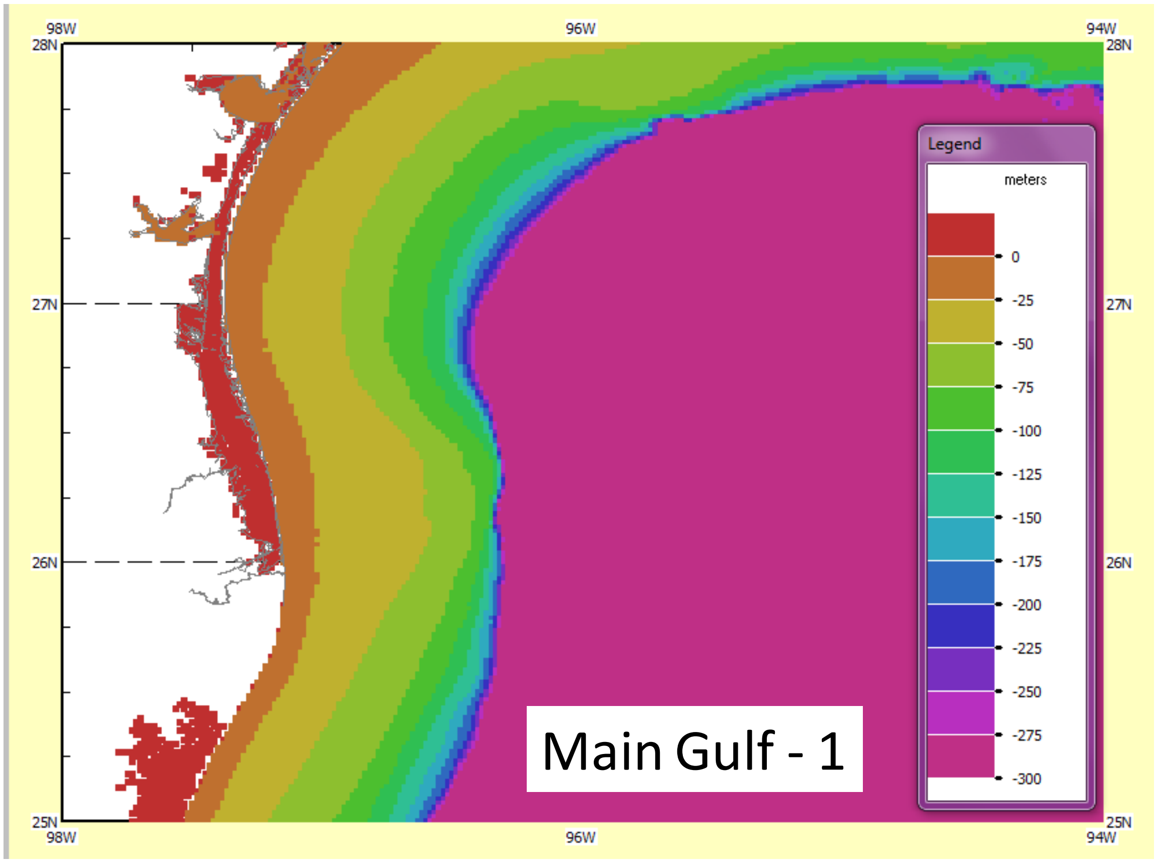


Figure B.4.3: Coastal Relief Map, Mooring Region 1, Part 1 created from (NOAA National Geophysical Data Center 2011)

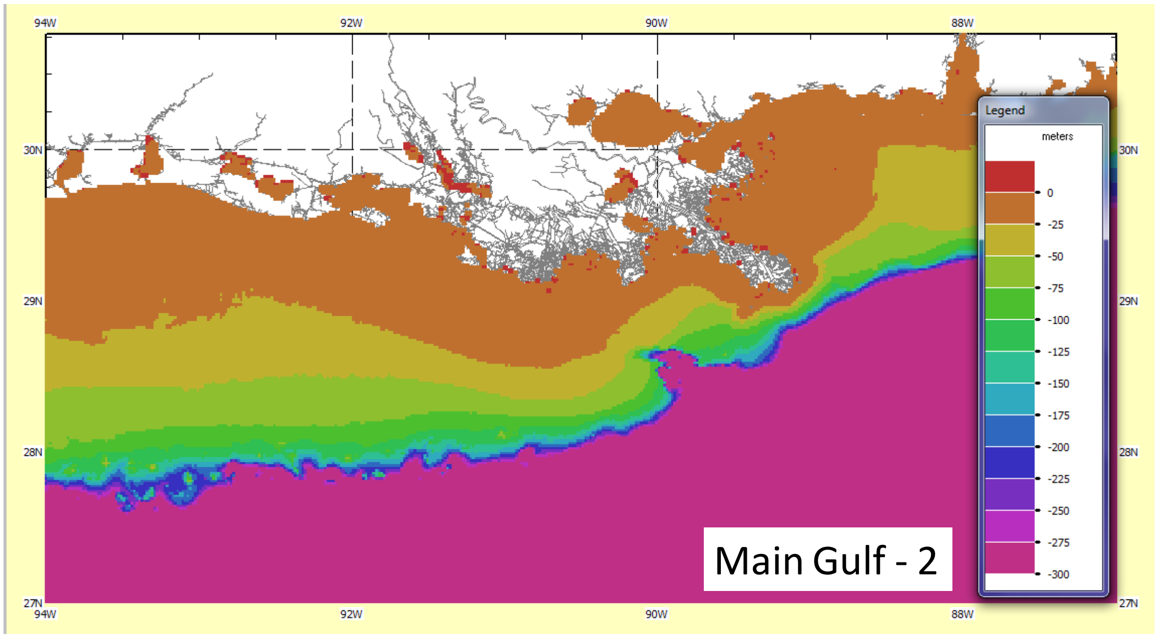


Figure B.4.4: Coastal Relief Map, Mooring Region 1, Part 2 created from (NOAA National Geophysical Data Center 2011)

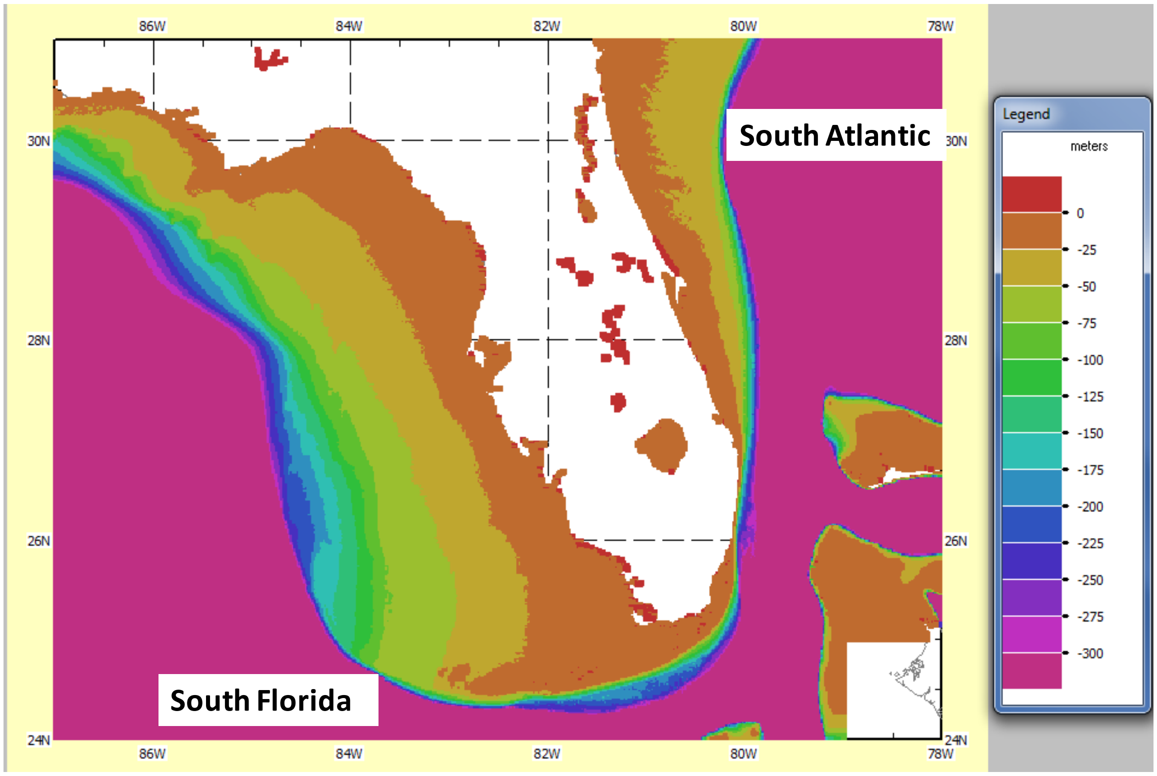


Figure B.4.5: Coastal Relief Map, Mooring Regions 2 and 3 created from (NOAA National Geophysical Data Center 2011)

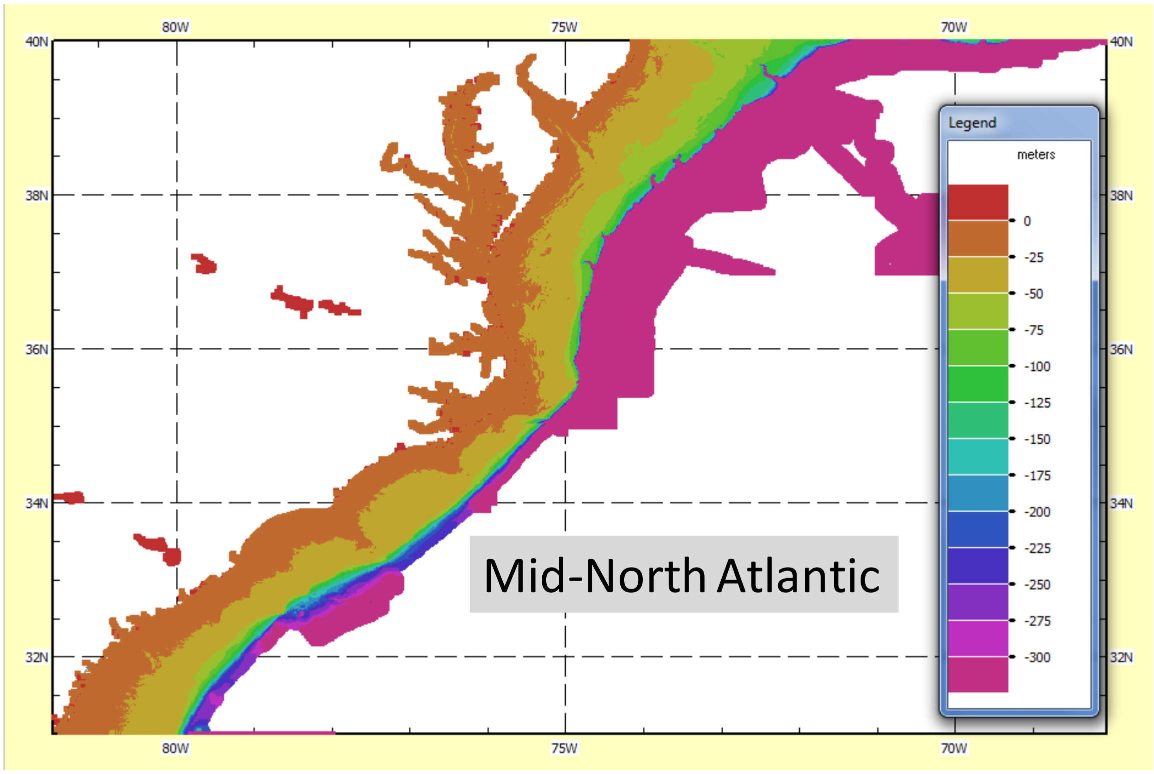


Figure B.4.6: Coastal Relief Map, Mooring Regions 4 and 5 created from (NOAA National Geophysical Data Center 2011)

Table B.4.6: Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, 1998 through 2009 (U.S. EIA 2010)

| **Period** | **Residential** | **Commercial** | **Industrial** | **All Sectors** | **Industrial in 2010$** | **Average Industrial (1998-2009) 2010$** |
|---|---|---|---|---|---|---|
| 1998 | 8.26 | 7.41 | **4.48** | 6.74 | **6.59** | **6.92** |
| 1999 | 8.16 | 7.26 | **4.43** | 6.64 | **6.55** | |
| 2000 | 8.24 | 7.43 | **4.64** | 6.81 | **6.79** | |
| 2001 | 8.58 | 7.92 | **5.05** | 7.29 | **6.98** | |
| 2002 | 8.44 | 7.89 | **4.88** | 7.2 | **6.84** | |
| 2003 | 8.72 | 8.03 | **5.11** | 7.44 | **7.03** | |
| 2004 | 8.95 | 8.17 | **5.25** | 7.61 | **7.11** | |
| 2005 | 9.45 | 8.67 | **5.73** | 8.14 | **7.32** | |
| 2006 | 10.4 | 9.46 | **6.16** | 8.9 | **7.00** | |
| 2007 | 10.65 | 9.65 | **6.39** | 9.13 | **6.99** | |
| 2008 | 11.26 | 10.36 | **6.83** | 9.74 | **7.07** | |
| 2009 | 11.51 | 10.26 | **6.7** | 9.83 | **6.73** | |

# Appendix C: Supporting Calculations and Discussion

## ELECTRON-BEAM SELECTION AND OPTIMIZATION

The e-beam sizing and costing in section 4.2 provided the theoretical framework for sizing electron beam accelerators to meet given throughput and dose requirements for the braid adsorbent product. Several governing equations were provided to highlight key parameters in sizing an accelerator; specifically, the beam energy and current maintain throughput and dose uniformity in the product (see equations 4.18 through 4.20). However, the discussion in chapter 4 does not consider optimal sizing of an accelerator; many conceivable accelerator designs could meet throughput and dose uniformity requirements. An optimal design will find the energy and current (power) that meets the throughput and uniformity constraints at the lowest possible cost.

To define an optimal design, the physical model provided in chapter 4 will be merged with an economic model to formulate a cost objective function:

$$\boldsymbol{TAC = N_A * (CC * AF + AOC)} \tag{C.1}$$

where

TAC = Total Annualized Costs, \$

$N_A$ = Number of Accelerators required

CC = Capital Cost of Electron Beam Accelerator, \$

AF = Amortization Factor = $\dfrac{1}{\frac{1-(1+r)^{-n}}{r}}$ (0.13 when r = 10%, n = 15 years)

r = Annual interest rate of capital, %

n = Total number of payments or period of amortization, years

AOC = Annualized Operating Costs, \$ (electricity consumption for design optimization)

Note that the annual operating cost for the optimization consists of only electricity consumption; while the irradiation facility and equipment will have incur operating costs and utilities, the only operating cost tied directly to the power of the accelerator is the electricity consumption.

Equation C.1 is the basic form of the objective function that will be minimized by the optimization process. The first step in defining the cost function in terms of process parameters discussed in Chapter 4 is to relate the beam power to the capital and operating cost as follows:

$$\boldsymbol{CC = 869,096 * P^{0.2578}} \tag{C.2}$$

where

P = Power of beam, kW

and

$$\boldsymbol{AOC = \frac{P}{\eta} * C_e * OH} \tag{C.3}$$

where

η = Wall-Plug Efficiency (varies as a function of energy – see discussion below)

$C_e$ = Cost of electricity, annual industrial average, \$/kWh (See Table B.4.6)

OH = Operating Hours per Year (8322 hours = 95% uptime)

Equation C.2 was derived from Figure 4.5 in Chapter 4 (see Chpater 4 for details). Equations C.1 and C.2 can be further modified by expressing the power in terms of energy and current using equation C.4:

$$P = \left(\frac{E}{q}\right) * I \qquad \text{(C.4)}$$

where

E = Beam Energy in MeV/electron

q = Integer value of the elementary particle charge (q = -1 for electrons)

I = Beam Current in mA.

Equations C.2, C.3, and C.4 can be substituted into the objective function, C.1 to produce the following:

$$TAC = N_A * 869{,}096 * (E * I)^{0.2578} * AF + \frac{E * I}{\eta} * Price * OH \qquad \text{(C.5)}$$

The cost is now related to two primary process parameters for an electron beam accelerator. Next, dose, throughput and dose uniformity constraints are formulated. The following relationships from chapter 4 can be used to modify C.5:

$$I = \left(\frac{D_0}{F_i K_0}\right) * \frac{A_p}{T} \qquad \text{(C.6)}$$

where

$D_o$ = Surface Dose in kGy (50 kGy for this process)

$F_i$ = Beam Current Utilization Efficiency (0.8 to 0.9)

$K_o$ = Area Processing Coefficient in kGy*m$^2$/mA*min

$A_P/T$ = Area Throughput in $m^2$/min

Also,

$$K_0 = 50.3 * e^{-2.5*E} + 11.3 \tag{C.7}$$

where

E = Beam energy, MeV (from 0.4 to 10 MeV)

Equation C.6 and C.7 create a constraint on the energy and area throughout of the accelerator; as the energy of the accelerator increases, Ko decreases according to equation C.7; the current of the system increases for a fixed dose and area throughput. The power of the system increases via the relationship in equation C.4; an upper limit on power is one of the constraints of the optimization model, as discussed later in this section. Increasing area throughput for a given dose and energy has the same effect of reaching a power limit constraint via the increasing current.

Equation C.7 was imputed from the data in Table 4.11 in Chapter 4 by fitting an exponential curve to the data to allow interpolation between the points provided in the table; linear interpolation would not have been appropriate given the non-linear nature of the trend in the dataset. Further, the number of accelerators (NA) in equation C.5 is also a function of throughput:

$$N_A = \frac{TP_{Total}}{\frac{A_p}{T} * R_{opt}} \tag{C.8}$$

where

$TP_{Total}$ = Total Throughput required for accelerator fleet, kg/hr (6,008 kg/hr in base case)

$R_{opt}$ = Optimum Product Thickness in g/cm$^2$

and

$$R_{opt} = 0.404 * E - 0.161 \tag{C.9}$$

Finally, equations C.6 through C.9 can be substituted into C.5 to give the final cost function:

$$\text{TAC}= \frac{\text{TP}_{\text{Total}}}{\frac{\text{A}_\text{p}}{\text{T}}*(0.404*\text{E}-0.161)}*869{,}096*\left(\text{E}*\frac{\text{D}_0}{\text{F}_\text{i}(50.3*\text{e}^{-2.5*\text{E}}+11.3)}*\frac{\text{A}_\text{p}}{\text{T}}\right)^{0.2578}$$

$$*\text{AF}+\frac{\text{E}*\frac{\text{D}_0}{\text{F}_\text{i}(50.3*\text{e}^{-2.5*\text{E}}+11.3)}*\frac{\text{A}_\text{p}}{\text{T}}}{\eta}*\text{Price}*\text{OH} \tag{C.10}$$

In this final form, the total annual cost is a function of energy and area throughput; all other parameters are fixed for a given dose target and material. Therefore, the final optimization problem can be described as follows:

$$\min_{E,\frac{A_p}{T}} TAC \tag{C.11}$$

st

$$0.4\, MeV \leq E \leq 10\, MeV; \tag{a}$$

$$\frac{A_p}{T} > 0; \tag{b}$$

$$P \leq 100\ kW. \tag{c}$$

The first constraint encompasses the common range of industrial electron beam accelerators from low to high energy; above this range, activation or degradation of the product becomes a concern. The range also corresponds to the dataset derived from the depth-dose distributions for polyethylene (Cleland 2005). The final constraint for the power of the system arises because the cost scaling relationship represented by equation C.2 (and Figure 4.5) is limited to 160 kW; lack of data precludes empirical correlations above 160 kW. It should be noted that the cost scaling data only has one data point beyond 80 kW, so the predictive power of the regression model is limited for high power systems.

### Wall-Plug Efficiency

The cost function in C.5 includes conversion efficiency for electricity to electron energy in the accelerator. This "wall-plug" efficiency varies by type of electron beam system. In general, it is expected to drop with increasing accelerator voltage (and increasing beam energy) with typical direct current accelerators ranging from 65% to 95% based on energy and the specific piece of equipment (Berejka 1995). Literature review did not yield a physical or empirical model relating efficiency to beam energy, however. To incorporate the change in efficiency with beam energy into the optimization model, the efficiency was assumed to vary linearly over the range of beam energies used in this analysis:

$$\eta = -0.03 * E + 0.96 \tag{C.12}$$

This approximation is not sufficient for detailed modeling of energy use in electron beam accelerators, but provides a means to incorporate the impact of efficiency on annual operating cost and is a more realistic representation than a constant efficiency across a range of beam energies. As the project design advances to a detailed level, vendors can be consulted for real efficiency values or power consumption values to refine the cost estimate.

## Optimization Procedure and Verification

The objective function and constraints represented by equations C.10 and C.11 were entered into a spreadsheet model in Microsoft Excel©. The optimization was attempted with the Excel Solver Add-In which is based on a generalized reduced gradient method (GRG)[13] for nonlinear functions such as the cost function used in this analysis. However, the GRG method is intended to find local minima and does not include a multi-start or comparable global optimum search method (Fylstra, et al. 1998). Therefore, the user-provided starting points for the optimization (energy and area throughout) can bias the optimization and does not ensure the true low-cost configuration for the electron beam accelerator. To verify the calculation of a global optimum, a manual multi-start method was developed. The method generates a series of possible starting points (combination of energy and area throughput values) and calculates the total annual cost for each set of possible starting points. The combinations of beam energy and area throughput can be represented as a matrix. Each row of the matrix corresponds to a different value of the area throughput while each column corresponds to a different value

---

[13] The detailed optimization technique is beyond the scope of this work. For details on optimization in Solver with the GRG approach see (Fylstra, et al. 1998)

of the energy; the values within the matrix are the total annualized cost for the corresponding energy and area throughput. A matrix of possible beam costs is defined as follows:

$$TAC_{ij} \sim f\left(\frac{A}{T}_i, E_j\right) \tag{C.13}$$

where

$\mathrm{i} = 0 \text{ to } \frac{Upper\ Bound\ (\frac{A}{T})}{S_A}$

$\mathrm{j} = 0 \text{ to } \frac{Upper\ Bound\ (E)}{S_E}$

Upper Bound $\left(\frac{\mathrm{A}}{\mathrm{T}}\right)$=Upper Limit on area throughput (limited by Power)

Upper Bound $(E)$=Upper Limit on beam energy (10 MeV)

$S_A$ = Interval between consecutive area throughput values (varied by user)

$S_E$ = Interval between consecutive beam energy values (varied by user)

The size of the matrix (the number of possible solutions calculated) is determined by the upper bounds on beam energy and area throughput as well as the spacing between guesses. Beam energy is already constrained by the equipment available at 10 MeV. Area throughput is constrained by the power constraint described in equation C.11c and equations C.6 and C.4; as the area throughput increases, so does the current of the system and, in turn, the power of the system. Ultimately, for a given energy, the step-wise increase of the area throughput will reach the power constraint.

The spacing between guesses determines the accuracy of the solution developed by this matrix method, though a correlation of optimization output and variable step-size has not been performed. Repeated trials with varying step sizes can provide initial verification of the solution. The algorithm developed in C.13 can also be compared to multiple start points in Solver as another method of verification of results.

## INTEREST DURING CONSTRUCTION

Account 63 in the COA represents interest costs accrued during the construction phase of a project. The interest during construction (IDC) is calculated based on the overnight construction of the plant (sum of accounts 1 through 5) (EMWG-GIF 2007). Loans must be taken out in the construction period to cover all capital assets of the project prior to production. Subsequently, the accumulated interest cost can be capitalized or amortized with the capital assets.

In this analysis, the interest during construction was modeled as a beta binomial distribution mirroring previous work; the distribution can be described by equation C.14 (Bunn, et al. 2003):

$$\boldsymbol{f_k = \frac{\Gamma(n)*\Gamma(\alpha+k-1)*\Gamma(n+\beta-k)*\Gamma(\alpha+\beta)}{\Gamma(k)*\Gamma(n-k+1)*\Gamma(\alpha+\beta+n-1)*\Gamma(\alpha)*\Gamma(\beta)}} \tag{C.14}$$

Where

fk = Fraction of capital funds used in year k of the construction period n

n = Years of construction (6 years)

Γ is the gamma function

α = Shape parameter for the distribution = $1 + e^{-0.432*(n-11.5)}$

β = Shape parameters for the distribution = $\frac{\alpha*(1-p)}{p}$

p = Fraction of construction period where half of the total overnight capital cost has been spent (0.65)

If α and β are restricted to integer values (as in this analysis), the gamma function can be solved by factorial expansion:

$$\boldsymbol{\Gamma(n) = (n-1)!}$$

The parameters used for the equation C.14 are taken from the reference case in Bunn et. al. The 6 year construction period is a conservative estimate that corresponds to nuclear power plants; in this analysis, established manufacturing processes such as melt spinning or uranium purification are unlikely to require a 6 year construction period. However, the full seawater extraction process has never been demonstrated or constructed at the scale assessed in this work, and is subject to a great deal of regulatory and technical uncertainty at the current stage of development. The analogy to a nuclear facility may be warranted until more information regarding project implementation is developed.

In addition, an interest rate of 6.5% was used during the construction period; the rate is lower than private investment rates (the 10% interest rate of capital in this analysis is representative of a private rate). Many factors influence the rate of construction loans, including potential access to equity financing. For simplification, the project in this analysis was assumed to be 100% debt financed; the use of a lower interest rate offsets some of the benefits lost from the 100% debt assumption.

Overnight construction costs of all process areas in the seawater extraction project totaled \$2.7 billion (2010 US\$) in the base case conditions; using the parameters for the beta binomial distribution described in C.14 and the 6.5% construction loan interest rate, total interest accrued during construction was approximately \$470 million. This cost was amortized at 30 years and 10% from the project commencement date.

# References

Department of Atomic Energy, Government of India. *Shaping the Third Stage of Indian Nuclear Power Programme.* Government report, New Delhi: DAE, 2005.

Adelman, M.A., John C. Houghton, Gordon Kaufman, and Martin B. Zimmerman. *Energy Resources in an Uncertain Future.* Cambridge: Ballinger Publishing Company, 1983.

American Bureau of Shipping. *ABS Rule for Testing and Certification of Materials.* Houston, TX: American Bureau of Shipping, 2010.

Becker, R.C., J.H. Bly, M.R. Cleland, and J.P. Farrell. "Accelerator Requirements for Electron Beam Processing." *Radiation Physics and Chemistry*, 1979: 353-375.

Berejka, Anthony J. "Irradiation Processing in the 90's: Energy Savings and Environmental Benefits." *Radiation Physics and Chemistry*, 1995: 429-437.

Best, F.J., and M.J. Driscoll. *Propects for the Recovery of Uranium from Seawater.* Boston: MIT Energy Labratory, 1980.

Bunn, Matthew, Steve Fetter, John P. Holdren, and Bob van der Zwaan. *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel.* DOE Report, Cambridge, MA: Harvard University, 2003.

Bureau of Labor Statistics. *Consumer Price Index.* 2011. http://www.bls.gov/cpi/ (accessed 6 10, 2011).

Bureau of Ocean Energy Management, Regulation and Enforcement. *Outer Continental Shelf.* 10 29, 2010. http://www.boemre.gov/aboutboemre/ocsdef.htm (accessed 7 18, 2011).

Campbell, M.C., F.J. Kelly, and W.J.S. Craigen. "Uranium Extraction Costing in Canada." *Economics of Uranium Ore Processing Operations.* Paris: OECD, 1983. 131-151.

Catalytic Construction Company . *Integrated Proces Design Report on Feed Materials Production Center, Fernald, Ohio : Refinery and Green Salt Plant.* Oak Ridge, TN: United States Atomic Energy Comission, 1952.

Chemical Engineering. "Economic Indicators." *Chemical Engineering*, 2011: 56.

Chemical Market Reporter. "Chemical Prices." *Chemical Market Reporter*, 1998-2005.

Cleland, M.R. "Industrial Applications of Electron Accelerators." *CAS - CERN Accelerator School and KVI: Specialised CAS Course on Small Accelerators*, 2005: 383-416.

Cullinane, Kevin, and Mahim Khanna. "Economies of Scale in Container Ships." *Journal of Transport Economics and Policy*, 1999: 185-207.

Dasgupta, P.S., and G.M. Heal. *Economic Theory and Exhaustible Resources.* Cambridge: Cambridge University Press, 1979.

Driscoll, Alan H. ed. *Handbook of Oceanographic Winch, Wire and Cable Technology.* Narragansett, RI: Office of Naval Research, 1982.

EMWG-GIF. *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems.* The Economic Modeling Working Group of the Generation IV International Forum, OECD, 2007.

Environ International Corporation. *Commercial Marine Emission Inventory Development.* Ann Arbor, MI: U.S. Environmental Protection Agency, 2002.

Fourne, Franz. *Synthetic Fibers.* Munich: Carl Hanser Verlag, 1999.

Frey, H. Christopher. *Quantitative Analysis of Uncertainty and Variability in Environmental Policy Making.* Washington D.C.: Directorate for Science and Policy Programs, American Association for the Advancement of Science, 1992.

Fylstra, Daniel, Leon Lasdon, John Watson, and Allen Warren. "Design and Use of the Microsoft Excel Solver." *Interfaces*, 1998: 29-55.

Giles, Jr, H.F., Jr., J.R. Wagner, and E.M. Mount. *Extrusion: The Definitive Processing Guiide and Handbook.* Norwich, NY: William Andrew, Inc., 2005.

Golberg, M.A., and H.A. Cho. *Introduction to Regression Analysis.* Southhampton, UK: WIT Press, 2004.

Heal, Geoffrey. "The Relationship btween Price and Extraction Cost for a Resource with a Backstop." *The Bell Journal of Economics*, 1976: 371-378.

Hensen, Freidhelm (editor). *Plastics Extrusion Technology.* Munich: Carl Hanser Verlag, 1997.

Hirotsu, T., S. Katoh, K. Sugasaka, N. Takai, M. Seno, and T. Itagaki. "Selective Elution of Uranium from Amidoxime Polymer. I." *Separation Science and Technology*, 1987: 1725-1736.

ICIS. *Indicative Chemical Prices.* 2008. http://www.icis.com/StaticPages/a-e.htm (accessed April 22, 2011).

International Atomic Energy Agency. *Factsheets & FAQs : Adavanced Reactors.* http://www.iaea.org/Publications/Factsheets/English/advrea.html (accessed August 8, 2011).

International Energy Agency. *Key World Energy Statistics.* Technical Report, Paris: International Energy Agency, 2010.

Jiangsu Challen Fiber S&T Co.,Ltd. *Company Overview.* 2010. http://www.challen.com.cn/page/company/index.php (accessed 7 5, 2011).

Kawai, Tomomi, et al. "Preparation of hydrophilic amidoxime fibers by co-grafting acrylonitrile and methacrylic acid from an optimized monomer solution." *Radiation Physics and Chemistry*, 2000: 405-411.

Kaye, Ronald J., and Bob N. Turman. *Issues for Bringing Electron Beam Irradiators Online.* Conference Report, Albuquerque, NM: Sandia National Laboratories, 1999, 1-7.

Kelly, Thomas D., and Grecia R. Matos. "Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140." *USGS.* 1 14, 2010. http://minerals.usgs.gov/ds/2005/140/#vanadium (accessed 10 24, 2010).

Kelmers, A.D. *The Recovery of Uranium from Seawater: Status of Technology and Needed Future Research and Development.* Oak Ridge, TN: Oak Ridge National Laboratory, 1980.

Krautkraemer, Jeffrey A. "Optimal Depletion with Resource Amenities and a Backstop Technology." *Resources and Energy*, 1986: 133-149.

Liski, Matti, and Pauli Murto. *Backstop Technology Adoption.* Helsinki: Helsinki Cneter for Economic Research, 2006.

Locarnini, R. A., et al. *World Ocean Atlas 2009, Volume 1: Temperature.* Washington D.C.: NOAA Atlas NESDIS 68, U.S. Government Printing Office, 2010.

Mortimer, Nigel. "Uranium Resource Economics: An Application of Energy Analysis." *Resources Policy*, 1980: 19-32.

Myers, John J., Carl H. Holm, and Raymond F. McAllister. *Handbook of Ocean and Underwater Engineering.* New York: McGraw-Hill, 1969.

NOAA National Geophysical Data Center. *U.S. Coastal Relief Model.* 2011. http://www.ngdc.noaa.gov/mgg/coastal/crm.html (accessed July 18, 2011).

Nordhaus, William D., Hendrik Houthakker, and Robert Solow. "The Alloacation of Energy Resources." *Brookings Papers on Economic Activity*, 1973: 529-576.

Nuclear Energy Agency. *Uranium 2009: Resources, Production and Demand.* Paris: OECD, 2010.

Oak Ridge National Laboratory. *Carbon Fiber Technology Center, Equipment Specification, ORNL-CFTC-2010MSL01.* Equipment Specification, Oak Ridge, TN: Oak Ridge National Laboratory, 2010.

Pacala, S., and R. Socolow. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science*, 2004: 928-972.

Peters, Max S., Klaus D. Timmerhaus, and Ronald E. West. *Plant Design and Economics for Chemical Engineers.* Boston: McGraw Hill, 2003.

Rao, Linfeng. *Recent International R&D Activities in the Extraction of Uranium from Seawater.* Berkeley, California: Lawrence Berkeley National Laboratory, 2009.

Rauwendaal, Chris. "Scale-Up of Single Screw Extruders." *Polymer Engineering and Science*, 1987: 1059-1068.

Remer, D.S., and L.H. Chai. "Process Plants, Costs of Scaled-up Units." In *Encyclopedia of Chemical Processing and Design, vol. 43*, by J.J. (ed.) McKetta, 294-306. New York: Marcel Dekker, Inc., 1993a.

Schneider, Erich. *Systems / Economics: Status and Path Forward.* Austin: N/A, 2010.

Schneider, Erich, and Darshan Sachde. *Cost and Uncertainty Analysis of an Adsorbent Braid System for Uranium Recovery from Seawater.* Technical Report / DOE sub-contract 00114954, Austin: The University of Texas at Austin; United States Department of Energy, 2011.

Seko, N., A. Katakai, M. Tamada, T. Sugo, and F. Yoshii. "Fine Fibrous Amidoxime Adsorbent Synthesized by Grafting and Uranium Adsorption Cyclic Test with Seawater." *Separation Science and Technology*, 2005: 3753-3767.

Sugo, Takanobu, et al. "Recovery System for Uranium from Seawater with Fibrous Adsorbent and Its Preliminary Cost Estimation." *Journal of the Atomic Energy Society of Japan*, 2001: 1010-1016.

Suzuki, Toshihiro, Kyoichi Saito, Takanobu Sugo, Hisako Ogura, and Koichi Oguma. "Fractional Elution and Determination of Uranium and Vanadium Adsorbed on Amidoxime Fiber from Seawater." *Analytical Sciences*, 2000: 429-432.

Tamada, M. *Current Status of Technology for Collection of Uranium from Seawater.* Takasaki: Japan Atomic Energy Agency, 2009.

Tamada, Masao, Noriaki Seko, Noburu Kasai, and Takao Shimizu. "Cost Estimation of Uranium Recovery from Seawater with System of Braid Type Adsorbent." *Transactions of the Atomic Energy Society of Japan*, 2006: 358-363.

The Open University. *Seawater: Its Composition, Properties and Behavior.* Oxford: Pergamon Press, 1989.

Thorburn, Thomas. *Supply and Demand of Water Transport.* Stockholm: The Business Research Institute at the Stockholm School of Economics, 1960.

Turton, Richard, Richard C. Bailie, Wallace B. Whiting, and Joseph A. Shaeiwitz. *Analysis, Synthesis, and Design of Chemical Processes.* Boston: Prentice Hall, 2009.

U.S. Department of the Interior. *Salazar Signs First U.S. Offshore Commercial Wind Energy Lease with Cape Wind Associates, LLC.* 10 6, 2010. http://www.doi.gov/news/pressreleases/Salazar-Signs-First-US-Offshore-

Commercial-Wind-Energy-Lease-with-Cape-Wind-Associates-LLC.cfm (accessed 7 15, 2011).

U.S. Dpeartment of Energy, Nuclear Energy. *Nuclear Energy Research and Development Roadmap: Report to Congress.* Government report, Washington D.C.: U.S. DOE, 2010.

U.S. EIA. *Electric Power Annual 2009.* Washington D.C.: United States Energy Information Administration, 2010.

—. *Petroleum and Other Liquids.* 6 8, 2011. http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=eer_epd2f_pf4_y35ny_dpg&f=a (accessed 6 10, 2011).

United States Department of Labor. *Occupational Employment Statistics.* 4 6, 2011. http://www.bls.gov/oes/current/oes_nat.htm#53-0000 (accessed 6 9, 2011).

USGS. *Mineral Commodity Sumaries, 2010.* Washington D.C.: United States Geological Survey, 2010.

Wessell, W.E. "New graph correlates operating labor data for chemical processes." *Chemical Engineering*, 1952: 209-210.

Wust, Jr., C.J. "Fibers, Olefin." In *Kirk-Othmer Encyclopedia of Chemical Technology*, 224-246. New York: John Wiley and Sons, Inc., 2004.

Xinfengming Group. *Subsidiaries.* 2008. http://www.xfmpes.com/eabout2.htm (accessed 7 5, 2011).

Yaksic Beckdorf, Andres, and John E. Tilton. "Using the Cumulative Availability Curve to Assess the Threat of Mineral Depletion: The Case of Lithium." *Resources Policy*, 2009: 185-194.

Zhejiang Huatesi Polymer Technical Co.,Ltd. *Company Profile.* http://www.zjhuatsi.com/html/en/gsjj.html (accessed 7 5, 2011).