Appendix to "The Cost of Recovering Uranium from Seawater by a Braided Polymer Adsorbent System"

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This appendix contains the process flow diagrams and details of the cost estimation methodology and calculations for recovering uranium from seawater using amidoxime adsorbents, as proposed by the Japan Atomic Energy Agency (JAEA). It accompanies the article at the publisher's web-site and is also posted at http://scienceandglobalsecurity.org/archive/2013/06/the_cost_of_recovering_uranium.html

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Appendix A. Process Flow Diagrams

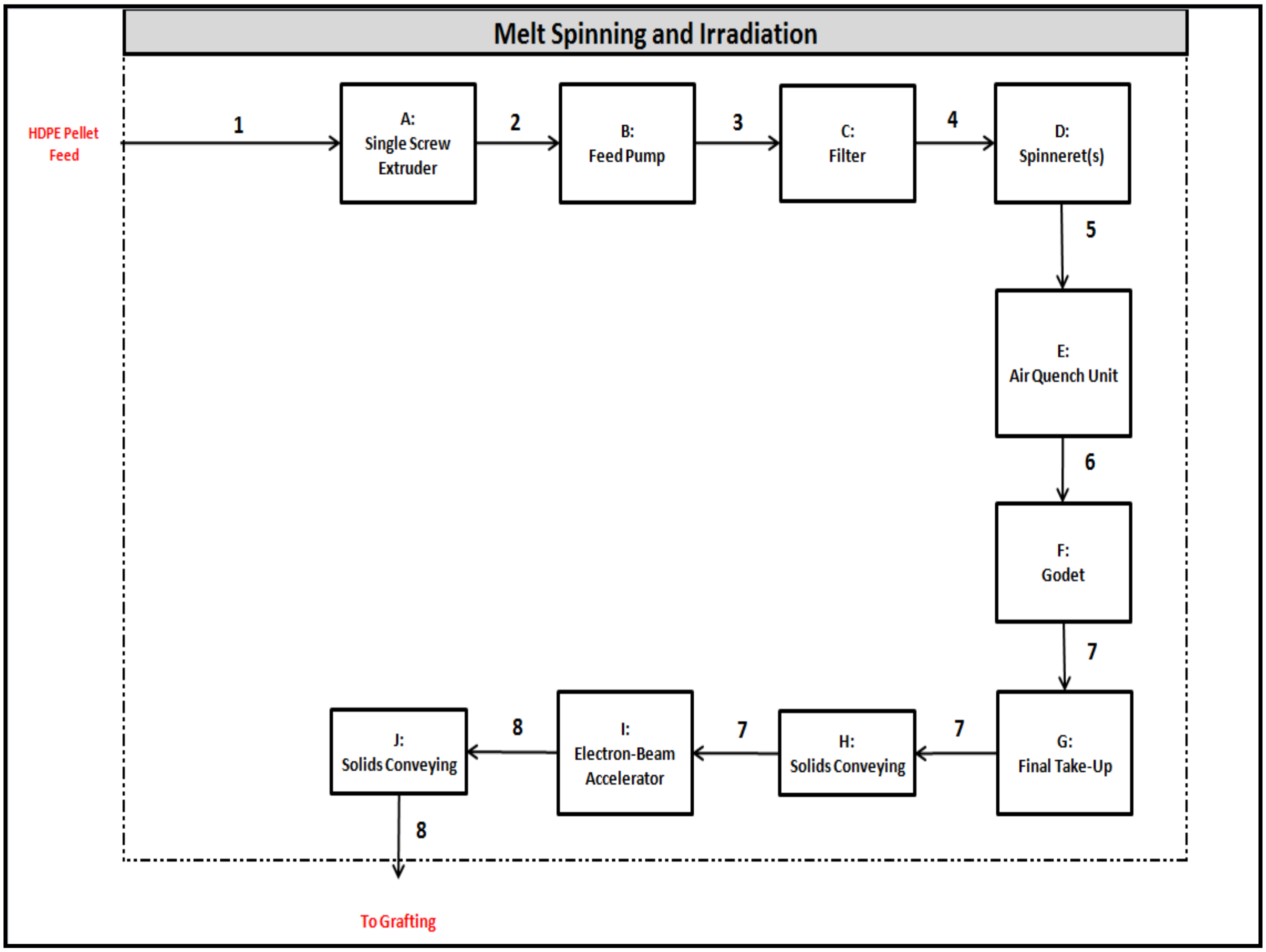

Figure A.1. Process Flow Diagram – Melt Spinning and Irradiation

Table A.1. Equipment and Stream Table for Melt Spinning and Irradiation Process Flow Diagram

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)		

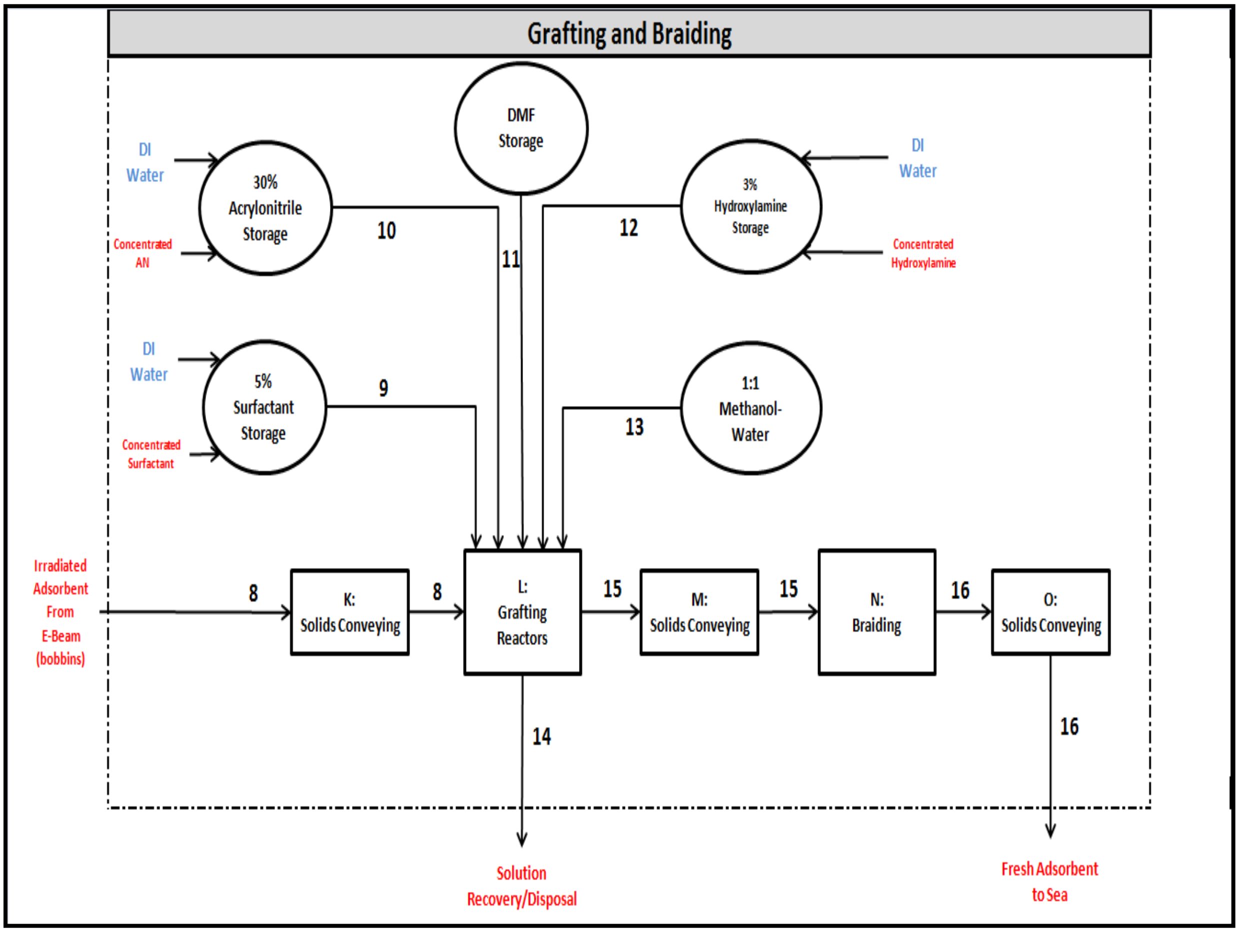

Figure A.2. Process Flow Diagram – Grafting and Braiding

Table A.2. Equipment and Stream Table for Grafting and Braiding Process Flow Diagram

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)		

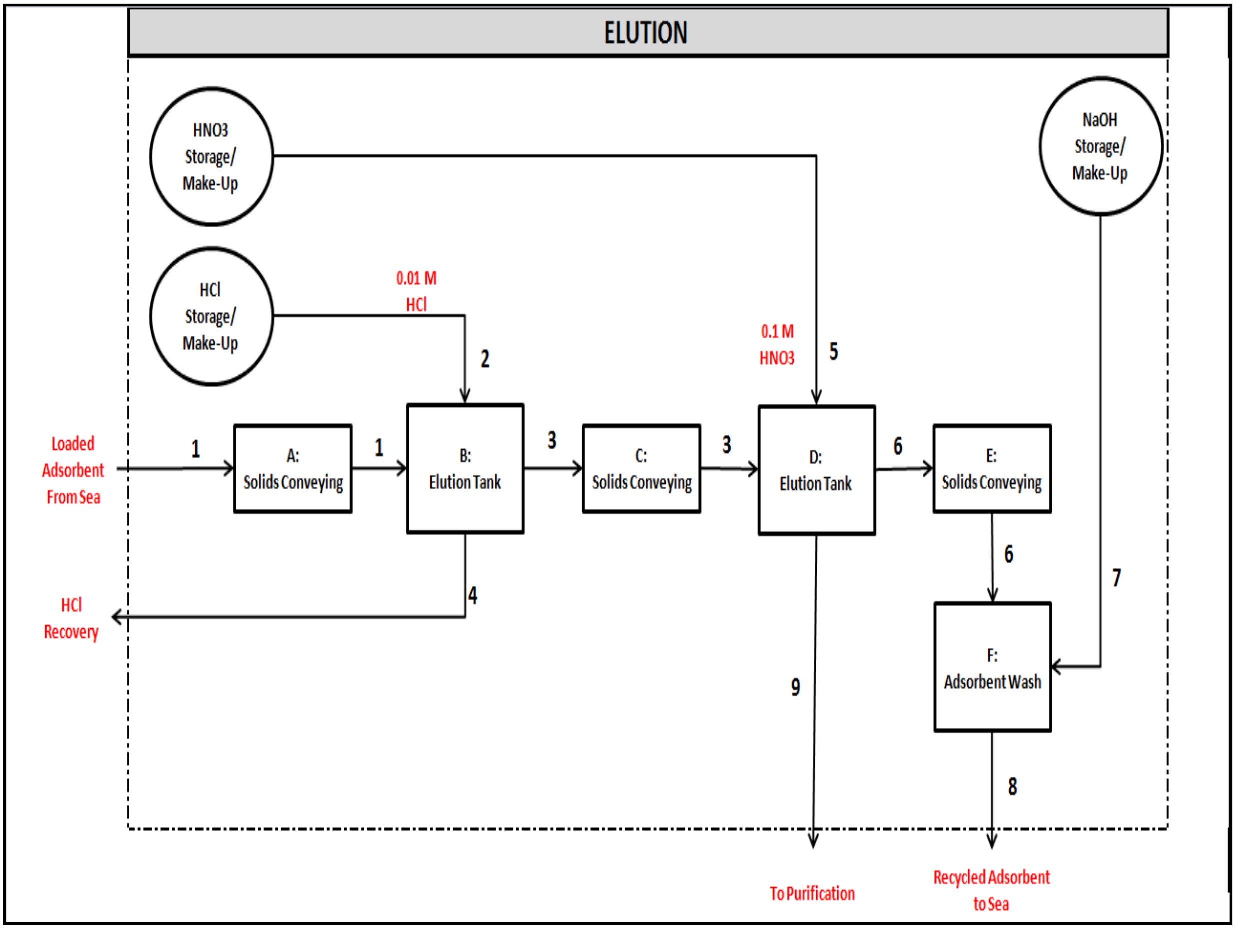

Figure A.3. Process Flow Diagram – Elution

Table A.3. Equipment and Stream Table for Elution Process Flow Diagram

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)		

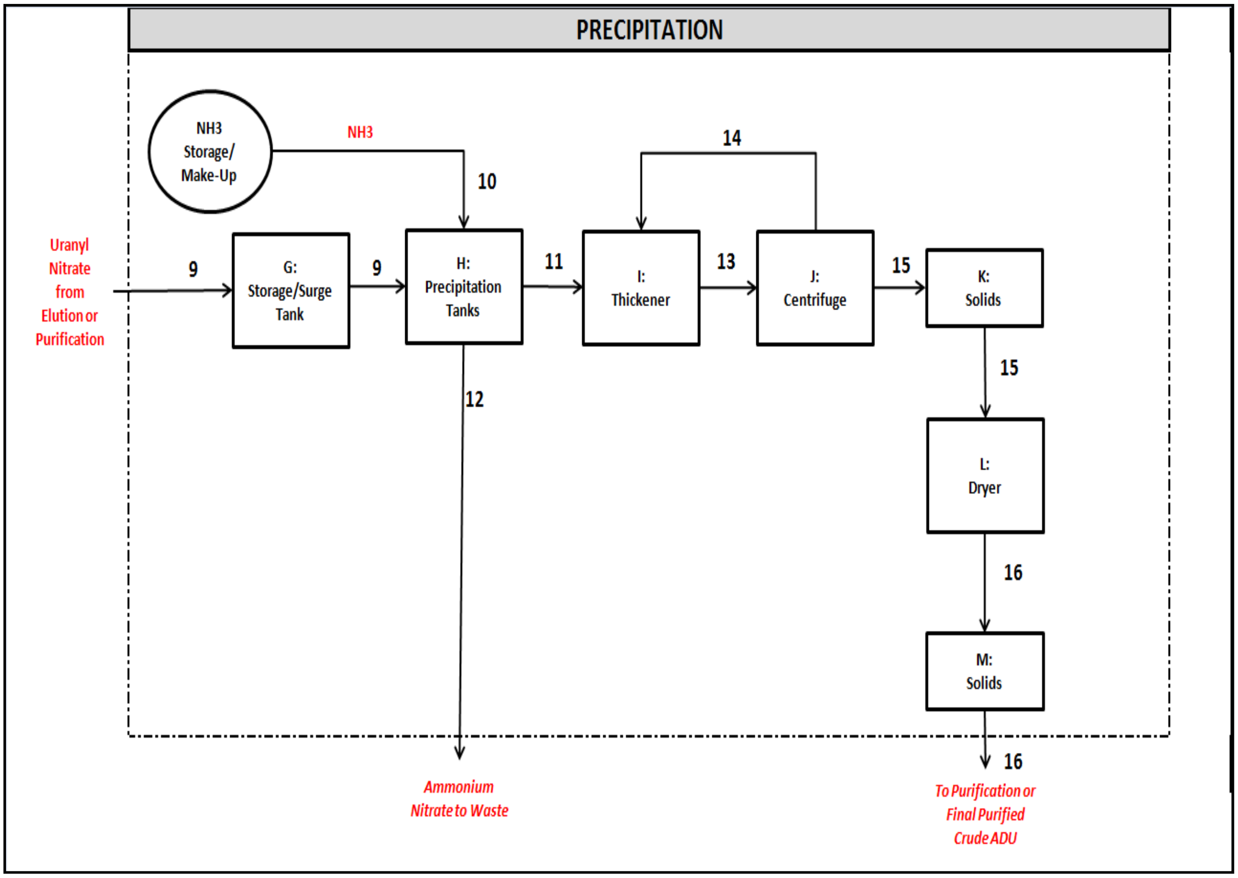

Figure A.4. Process Flow Diagram – Precipitation

Table A.4. Equipment and Stream Table for Precipitation Process Flow Diagram

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		

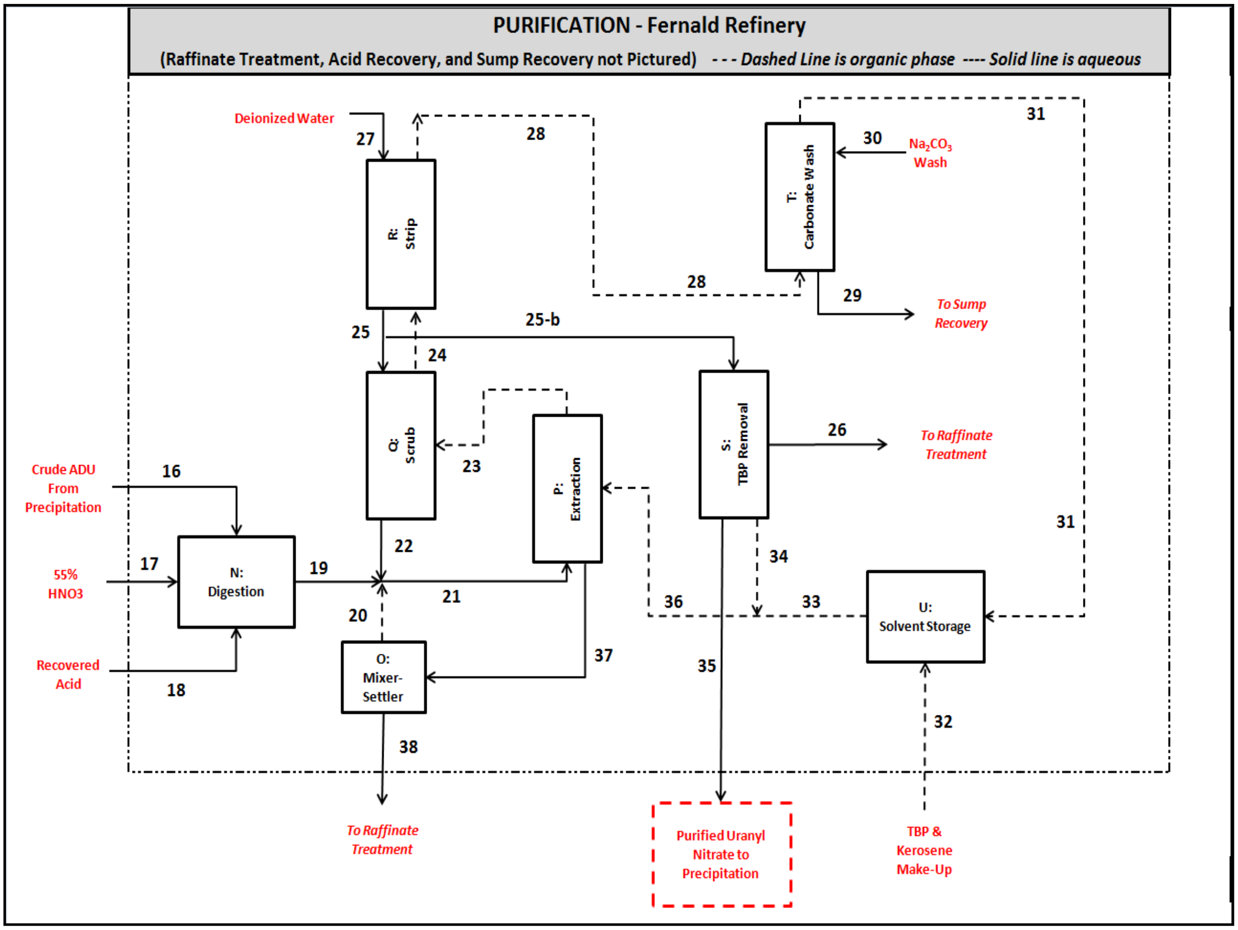

Figure A.5. Process Flow Diagram – Purification (Fernald Refinery)[1]

Table A.5. 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		

Appendix B. Detailed Cost Estimation Methodology and Calculations

B.1. CODE OF ACCOUNTS AND IMPLEMENTATION

Table B.1 is a generic code of accounts (COA) adapted from the EMWG framework that will be used for capital cost estimation for this analysis. Table B.2 reflects the COA for annualized operating and maintenance costs (O&M) and financial costs.

Table B.1. Modified COA for Capital Cost Estimation[2]

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.
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
23	Process Equipment	All process equipment and systems associated with plant output
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
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 (rentals, temp facil, etc)	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
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

46	Other Owners' capital investment costs	
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
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.
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 B.2. Modified COA for Annualized O&M and Financial Cost Estimation[2]

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
99	Contingency on Financial Costs	

The categories in the tables 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). The COA provides the hierarchical structure for the component costs used to develop the figure of merit for this project. One goal of this assessment was to ensure the one-digit categories of the COA (at minimum) were estimated.

Several cost estimation techniques were used in tandem with specific data provided in the Japanese assessment to populate the COA tables. The techniques are covered generically in this section and were adapted to specific process areas as needed. Table B.3 provides an overview of the techniques that were used to populate each of the single-digit accounts in the COA.

Table B.3. Overview of Cost Estimation Techniques used to Populate Code of Accounts

<table>
<tr><th>Account</th><th>Category</th><th>Estimation Technique</th></tr>
<tr><td>1</td><td>Capitalized Pre-Construction Cost</td><td rowspan="3">Fixed Capital Investment Technique</td></tr>
<tr><td>2</td><td>Capitalized Direct Cost</td></tr>
<tr><td>3</td><td>Capitalized Indirect Services Cost</td></tr>
<tr><td>4</td><td>Capitalized Owner's Cost</td><td>Labor Estimation Technique</td></tr>
<tr><td>5</td><td>Capitalized Supplementary Cost</td><td>Fixed Capital Investment Technique
Decommissioning Not Covered</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Capitalized Financial Cost</td><td>62: Fixed Capital Investment</td></tr>
<tr><td>63: IDC Estimation</td></tr>
<tr><td>7</td><td>Annualized O&M Cost</td><td>Labor Estimation Technique
Utility and Chemicals Estimation
Fixed Capital Investment Technique</td></tr>
<tr><td>9</td><td>Annualized Financial Cost</td><td>N/A</td></tr>
</table>

B.1.1 Capital Cost Estimation: Fixed Capital Investment (COA 1 to 6)

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. Table B.4 summarizes the techniques and data requirements.

Table B.4. Capital Cost Estimation Techniques[3,4]

	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

The capital cost estimation in this work is largely a combination of order of magnitude and study level estimation based data available at the time of this analysis.

This analysis relies on cost-scaling estimates based on the equipment lists and required capacity from the JAEA estimates; where possible, vendor quotes were obtained to provide specific equipment cost points. Sizing and costing assume the JAEA base case, 100,000 tonnes of annual adsorbent production and 1200 tonnes of uranium produced.5 In cases where reference capacity for an equipment or process differed from that required for the current design or when the overall uranium production capacity was varied, the following general cost scaling law was used:

$$\boldsymbol{C_2} = \boldsymbol{C_1} * \left(\frac{\boldsymbol{I_2}}{\boldsymbol{I_1}}\right) * \left(\frac{\boldsymbol{S_2}}{\boldsymbol{S_1}}\right)^{\boldsymbol{x}} \quad \text{(B.1)}$$

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)

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

x = Scaling exponent

For each piece of equipment, a cost scaling exponent, x, was identified from literature when possible. In cases where detailed references were not available or sizing was not possible at the equipment level, the scaling relationship in equation A.1 was applied to the entire process area. In the absence of scaling exponents and relationships in the literature, the "two-thirds" scaling rule was applied (x=0.67 in equation A.1); this value represents an average across all types of chemical plants[6].

Two engineering cost indices were 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.

The purchased equipment cost derived from equation A.1 is a component of the fixed capital investment (FCI) categories in the COA (Accounts 1 to 5). The method used for FCI estimation3 was based on delivered equipment cost. 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 was added as delivery costs. All other components of the total FCI are estimated as a percentage of the delivered equipment cost. The components of FCI are summarized in Table B.5; the percentage of delivered equipment costs are based on industry-wide average values for chemical plants.[3]

Table B.5. Factors for estimating fixed capital investment from delivered equipment cost3 and grass roots adjustment[4]

	% 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%	JAEA 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 is 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%	

In sum, the FCI is 4.78 times the total delivered purchased equipment cost.

B.1.2 ANNUALIZED O&M COST ESTIMATION

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

Labor cost calculations include 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. 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[7]. The correlation, which remains in wide use today, yielded the following empirical relationship:

$$\boldsymbol{O_{WH}} = \boldsymbol{t} * \left[\frac{\boldsymbol{N_P}}{\boldsymbol{C_D}^{0.76}}\right] \quad \text{(B.2 a)}$$

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:

$$\boldsymbol{N_{OL}} = \frac{\boldsymbol{O_{WH}}}{\boldsymbol{H_W}} * \boldsymbol{C_Y} \quad \text{(B.2 b)}$$

where

N_{OL}= Number of operators required

H_W = Hours worked by single operator (1960 hours per year)

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) used the labor-intensive t-value of 23. All other processes implemented a t-value of 17, which corresponds to average labor intensity. Major process steps were defined as those that include unit operation such as separations equipment or a reactor; storage tanks, pumps, and material handling equipment were 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 was obtained from the United States Bureau of Labor Statistics (BLS). The rates used in this analysis are summarized in Table B.6.

Table B.6. National average wage rates[8] for selected occupations, 2010 US$

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 include benefits to reflect the true cost to employers. The last two rows in Table B.6 apply to the mooring and deployment operations; all other staff were treated as chemical plant operators. The final labor cost estimate from this method is estimated as follows:

$$\boldsymbol{C_{OL}} = \boldsymbol{N_{OL}} * \boldsymbol{W} \qquad \text{(B.3)}$$

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%4. For this analysis, supervisory and clerical labor was estimated as 18% of the operating labor costs. The cost of management staff for a process can be summarized as:

$$\boldsymbol{C_{ML}} = \boldsymbol{f_{labor}} * \boldsymbol{C_{OL}} \qquad \text{(B.4)}$$

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 is aggregated with supplies and materials for maintenance in account 76.

Raw Materials (COA 74)

Raw materials or process chemicals costs are derived from the mass balance of chemicals used in each process and the unit price of each chemical. Chemical unit prices and associated variation in the historical data are summarized in Table B.7.

Table B.7. Chemical Prices and Standard Deviation from Historical Data[9,10,11,12]

Chemical	Description	Price, 2010 US$ average	Std. Dev.	Unit	Source(s)
Nitric Acid	42° Nitric Acid (67 wt%)	$284	$47	metric ton	CMR/ICIS Historical[9,10]
Ammonia	Spot Price, 100% Ammonia	$341	$148	metric ton	CMR/ICIS Historical[9,10]
Hydrochloric Acid	22° Nitric Acid (36 wt%),	$148	$58	metric ton	CMR/ICIS Historical[9,10]
Sulfuric Acid	66° Sulfuric Acid (93 wt%), Commercial Grade	$63	$20	metric ton	CMR/ICIS Historical[9,10]
Tributyl Phosphate (TBP)	100% TBP	$6,420	$1,850	metric ton	CMR/ICIS Historical[9,10] Vendor Quote
Kerosene	Kerosene from refiner to end users	$1.70	$0.69	gallon	EIA[12]
Filter Aid (Diatomite)		$325	$59	metric tons	USGS Historical[11]
Magnesium Oxide	deadburned bgs., c.l., t.l., works	$598	$121	metric ton	CMR/ICIS Historical[9,10]
Calcium Oxide (Lime)	chemical pebble (quicklime), hydrated bulk, c.l., f.o.b. works	$107	$15	metric ton	USGS Historical[11]

Chemical	Description	Price, 2010 US$ average	Std. Dev.	Unit	Source(s)
Polyethylene (HDPE)	US Gulf, bagged, export, HDPE blmldg	$1,470	$280	metric ton	CMR/ICIS Historical[9,10]
Acrylonitrile	US Gulf, contract dom. del., 100% Acrylonitrile	$1,331	$587	metric ton	CMR/ICIS Historical[9,10]
Dimethylformamide (DMF)	BASF, isocontainers, duty paid in Houston	$1,245	$591	metric ton	CMR/ICIS Historical[9,10] Vendor Quote
Hydroxylamine	Includes data for hydroxylamine salts.	$3,077	$411	metric ton	CMR/ICIS Historical[9,10] Vendor Quote
Methanol	US Gulf, contract barge, 100% Methanol	$284	$127	metric ton	CMR/ICIS Historical[9,10]
Surfactant (Sodium Dodecyl Sulfate)		$2,101	$642	metric ton	CMR/ICIS Historical[9,10] Vendor Quote
Sodium Carbonate (Soda Ash)	dense, US Gulf, FOB bulk	$149	$43	metric ton	USGS Historical
Vendor Identities are anonymous per vendor requests.					

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 provided most utility requirements (including the type of utility required); the mass balance provided any process water requirements for each section. The unit cost for each type of utility in this analysis is given in Table B.8. All values are inflation adjusted using the Consumer Price Index[13].

Table B.8. Utility Unit Costs 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	Endnote 14		
Cooling Water ($/1000 m^3)	16.01	Endnote 4	14.8	2006
High Purity Water ($/1000 kg):				
Process Water	0.072	Endnote 4	0.067	2006
Boiler Water (@ 115 °C)	2.65	Endnote 4	2.45	2006
Potable Water	0.28	Endnote 4	0.26	2006
Deionized Water	1.08	Endnote 4	1	2006
Steam ($/1000 kg):				
Low Pressure - 5 barg, 160°C	31.68	Endnote 4	29.29	2006
Medium Pressure - 10 barg, 184°C	32.01	Endnote 4	29.59	2006
High Pressure - 41 barg, 254°C	32.42	Endnote 4	29.97	2006
Wastewater Treatment ($/1000 m^3):				
Primary (filtration)	44.35	Endnote 4	41	2006
Secondary (filtration + activated sludge)	57.33	Endnote 4	53	2006
Tertiary (filtration, activated sludge, chemical treatment)	60.57	Endnote 4	56	2006
#2 Fuel Oil: ($/gallon)				
New York Harbor #2 Heating Oil, Spot Price[b]	2.12	Endnote 12	N/A	N/A

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 were estimated from the fixed capital investment as calculated via Table B.5. The two primary components remaining in this cost category (maintenance costs and supplies) were estimated as follows[4]:

$$C_{OS} = f_{supplies} * C_n \qquad \text{(B.5)}$$

where

$f_{supplies}$ = Fraction of fixed capital investment, 0.011 (range 0.002 to 0.02)[17]

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

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

And

$$C_M = f_{maint} * C_n \qquad \text{(B.6)}$$

where

f_{maint} = Fraction of fixed capital investment, 0.06 (range 0.02 to 0.1) 4

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

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

Finally, the total costs associated with account 76 are summarized as:

$$C_{76} = C_U + C_{OS} + C_M \qquad \text{(B.7)}$$

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 were also estimated as a portion of the fixed capital investment:

$$C_{TI} = f_{taxes} * C_n \qquad \text{(B.8)}$$

where

f_{taxes}= Fraction of fixed capital investment, 0.032 (range 0.014 to 0.05)4

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

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

SUMMARY

Table B.9 provides a summary of the operating cost estimation techniques for each COA item.

Table B.9. 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 A.2 and A.3)*
72	Management Staff	0.18 * Cost of Operating Staff *(See equation A.4)*
73	Salary-Related Costs	Included in 71 and 72 above
74	Raw Materials	Quantity consumed * Unit cost of chemical (Table B.7*)*
75	Spare Parts	N/A
76	Utilities, Supplies and Consumables	Utilities consumed * Unit Cost of Utility + 0.011*FCI + 0.06*FCI *(See equations B.5 - B.7 and* Table B.8*)*
77	Capital Plant Upgrades	N/A
78	Taxes and Insurance	0.032 * FCI (See equation B.8)
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
99	Contingency on Financial Costs	

B.1.3 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)2. 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 given a capital expenditure profile described by equation B.9[15]:

$$f_k = \frac{\Gamma(n) * \Gamma(\alpha + k - 1) * \Gamma(n + \beta - k) * \Gamma(\alpha + \beta)}{\Gamma(k) * \Gamma(n - k + 1) * \Gamma(\alpha + \beta + n - 1) * \Gamma(\alpha) * \Gamma(\beta)} \quad \text{(B.9)}$$

Where

f_k = 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[15] for the distribution = $1 + e^{-0.432*(n-11.5)}$

β = Shape parameter[15] 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)[15]

If α and β are restricted to integer values (as in this analysis), the gamma function can be solved by factorial expansion:

$$\Gamma(n) = (n - 1)!$$

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.

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 capital expenditure profile described in A.9 and a 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.

B.1.4 Uncertainty Associated with Cost Inputs

As discussed in section 3.2, estimates of uncertainty were developed for all cost inputs and two performance inputs (adsorption capacity and degradation rate). Table B.10 summarizes the input uncertainties.

Table B.10. Variables included in Monte Carlo Analysis with mean and standard deviation

Item	Mean	Standard Deviation	Data Provided As:	Category
Cost of Electricity ($/kWh)	$0.069	$0.002	Data Set	Utilities
Cooling Water ($/1000 m³)	$16.00	$2.40	Point Estimate	
Process Water ($/1000 kg)	$0.073	$0.011	Point Estimate	
Boiler Water (@ 115 °C) ($/1000 kg)	$2.65	$0.40	Point Estimate	
Potable Water ($/1000 kg)	$0.28	$0.04	Point Estimate	
Deionized Water ($/1000 kg)	$1.08	$0.16	Point Estimate	
Low Pressure - 5 barg, 160°C ($/1000 kg)	$31.70	$4.75	Point Estimate	
Medium Pressure - 10 barg, 184°C ($/1000 kg)	$32.00	$4.80	Point Estimate	
High Pressure - 41 barg, 254°C ($/1000 kg)	$32.40	$4.86	Point Estimate	
Wastewater Treatment: Primary ($/1000 m3)	$44.30	$6.65	Point Estimate	
Wastewater Treatment: Secondary ($/1000 m3)	$57.30	$8.60	Point Estimate	

Item	Mean	Standard Deviation	Data Provided As:	Category
Wastewater Treatment: Tertiary ($/1000 m3)	$60.60	$9.09	Point Estimate	
#2 Heating Oil ($/gal)	$2.12	$0.28	Data Set	
Nitric Acid ($/tonne)	$284	$47	Data Set	Chemicals
Ammonia ($/tonne)	$341	$148	Data Set	
Hydrochloric Acid ($/tonne)	$148	$58	Data Set	
Sulfuric Acid ($/tonne)	$63	$20	Data Set	
Tributyl Phosphate ($/tonne)	$6,420	$1,850	Data Set	
Kerosene ($/gallon)	$1.70	$0.69	Data Set	
Filter Aid (Diatomite) ($/tonne)	$325	$59	Data Set	
Magnesium Oxide ($/tonne)	$598	$121	Data Set	
Calcium Oxide (Lime) ($/tonne)	$107	$15	Data Set	

Item	Mean	Standard Deviation	Data Provided As:	Category
Polyethylene (HDPE) ($/tonne)	$1,470	$280	Data Set	
Acrylonitrile ($/tonne)	$1,330	$587	Data Set	
Dimethylformamide ($/tonne)	$1,250	$591	Data Set	
Hydroxylamine ($/tonne)	$3,080	$411	Data Set	
Methanol ($/tonne)	$284	$127	Data Set	
Surfactant (Sodium Dodecyl Sulfate) ($/tonne)	$2,100	$642	Data Set	
Sodium Carbonate ($/tonne)	$149	$43	Data Set	
Sodium Hydroxide ($/tonne)	$483	$113	Data Set	
Dimethyl Sulfoxide** ($/tonne)	$1,660	$624	Data Set	
Methacrylic Acid** ($/tonne)	$3,444	$518	Data Set	
Land (% of FCI)	0.015	0.0025	Range	Cost Estimation Factors

Item	Mean	Standard Deviation	Data Provided As:	Category
Plant Licensing (% of FCI)	0.03	0.015	Range	
Chemical Plant - Cost Scaling Exponent	0.67	0.13	Data Set	
Solvent Extraction Cost Scaling Exponent	0.73	0.1095	Point Estimate	
Purchased Equipment Delivered - (Basis for FCI Estimate)	100%	15%	Point Estimate	
Purchased Equipment Cost Uncertainty Factor	1	0.15	Point Estimate	
Melt Spinning Cost Scaling Exponent	0.46	0.09	Data Set	
E-Beam Cost Scaling Exponent	0.258	0.111	Data Set	
Labor Estimation Factor - Maximum labor requirements	23	3.5	Point Estimate	
Labor Estimation Factor - Average labor requirements	17	2.6	Point Estimate	
Labor Estimation Factor - Minimum labor requirements	10	1.5	Point Estimate	
Chemical Plant and System Operators: Annual Salary with Benefits	$82,900	$492	Data Set	

Item	Mean	Standard Deviation	Data Provided As:	Category
Sailors and Marine Oilers: Annual Salary with Benefits	$58,500	$456	Data Set	
Captains, Mates, Pilots of Water Vessels: Annual Salary with Benefits	$108,000	$1,128	Data Set	
Direct supervisory and clerical labor Estimation Factor (% of OL Cost)	0.175	0.038	Range	
Maintenance Estimation Factor (% of FCI)	0.06	0.02	Range	
Operating Supplies Estimation Factor (% of FCI)	0.011	0.005	Range	
Local Taxes and Insurance Estimation Factor (% of FCI)	0.032	0.009	Range	
Mooring and Deployment: Other Operating Cost Factor (% of FCI)	0.04	0.005	Range	
Disposal Cost Uncertainty Factor	1	0.15	Point Estimate	
Adsorbent Degradation (% per recycle)	0.05	0.025	Point Estimate	Performance Parameters
Adsorbent Capacity (kg U/t adsorbent)*	2	0.5	Data Set	

* Standard deviation derived from an empirical model. See Appendix D.

B.2. SUPPORTING CALCULATIONS BY PROCESS AREA

In addition to the general costing techniques discussed in the preceding section, each area required of process area required specific sizing and scaling assumptions to develop capital and operating costs. Key assumptions and calculations are summarized by process area.

B.2.1 Adsorbent Production Supporting Calculations

The adsorbent production area consists of melt spinning, fiber irradiation, and polymer grafting processes depicted in Figure A.1 and Figure A.2 in Appendix A. The spinning equipment costs were developed via reference plant costs and vendor quotes for a variety of melt spinning facilities. Table B.11 lists the reference plant sources used to develop a cost estimate for the melt spinning process; the data in the table represent the total capital investment for the plant, including major equipment items.

Table B.11. Melt Spinning Line Cost and Capacity Reference Data

Year	Annual Capacity (metric tons)	Investment 2010 US$	Material	Location	Source
2011	65	$1,930,000	PAN	U.S.A	ORNL Carbon Fiber Pilot Facility[16]
2010	500,000	$295,000,000	N/A	China	Jiangsu Challen Fiber S&T Co.,Ltd[17]
2008	160,000	$38,300,000	Polyester	China	Zhejiang Huatesi Polymer Technical Co.,Ltd., Phase 1[18]
2010	180,000	$32,500,000	Polyester	China	Zhejiang Huatesi Polymer Technical Co.,Ltd., Phase 2[18]
2003	200,000	$74,500,000	Polyester	China	Tongxiang Zhongxin Chemical Fiber Co., Ltd.[19]
2007	200,000	$68,900,000	Polyester	China	Tongxiang Zhongchi Chemical Fiber Co., Ltd.[19]

Regression analysis was implemented to derive a cost scaling exponent (0.464) that was applied in the following scaling relationship:

$$\boldsymbol{C_2} = \boldsymbol{C_1} * \left({\boldsymbol{S_2}}/{\boldsymbol{S_1}}\right)^{\mathbf{0.464}} \qquad \text{(B.10)}$$

where

C_2 = Capital Investment, 2010 US$

C_1 = Capital Investment, **Reference Plant**, 2010 US$

S_2 = Melt spinning plant capacity, metric tonnes/year

S_1 = Melt spinning plant capacity, **Reference Plant**, metric tonnes/year

The ORNL facility (first entry) in Table B.11 was used as the reference design.

The irradiation step includes the electron beam accelerator and associated equipment. Electron beam accelerators are classified by the energy of electrons in 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, the dose (in grays or kilograys, Gy or kGy) is an important factor in polymer grafting. JAEA cited an average dose of 50 kGy in the radiation grafting process[20]; other sources cite a range from 20 kGy to 100 kGy for similar processes[21]. The current system will assume a dose of 50 kGy.

Depth-dose distribution curves allow energy and thickness specification to ensure dose uniformity; however, they do not consider throughput requirements. The accelerator must maintain the required dose to generate reactive sites through the entire depth of the polymer product while maximizing throughput. Equation 2.3 illustrates the relationship between throughput and the beam characteristics[21]:

$$\boldsymbol{I} = \left(\frac{\boldsymbol{D_0}}{\boldsymbol{F_i K_0}}\right) * \frac{\boldsymbol{A_p}}{\boldsymbol{T}} \qquad \text{(B.11)}$$

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 mentioned, beam energy and current ultimately determine the power of the accelerator as given by equation 2.4:

$$\boldsymbol{P} = \left(\frac{\boldsymbol{E}}{\boldsymbol{q}}\right) * \boldsymbol{I} \qquad \text{(B.12)}$$

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.

The power of the accelerator is used to scale the cost from the reference design. The reference design cost and specifications were obtained via a vendor quote based on a similar fiber irradiation process. Table B.12 summarizes the design data for the braid adsorbent irradiation process as well as the equipment specifications and cost provided by the vendor[22].

Table B.12. Electron Beam Design Specifications and Vendor Reference Design

	Parameter	Value	Unit
Design Specifications	Capacity	50,000	tonnes/year
	Dose	50	kGy
	Individual Fiber Diameter	23	mm
	Fiber Bundle Thickness	1	mm
	Operating Hours (@95% availability)	8300	Hours
Vendor Reference	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	$2,250,000	2010 US$

Figure B.1 includes cost data collected by Sandia National Laboratories over a range of accelerator power and the vendor estimate from Table B.12.

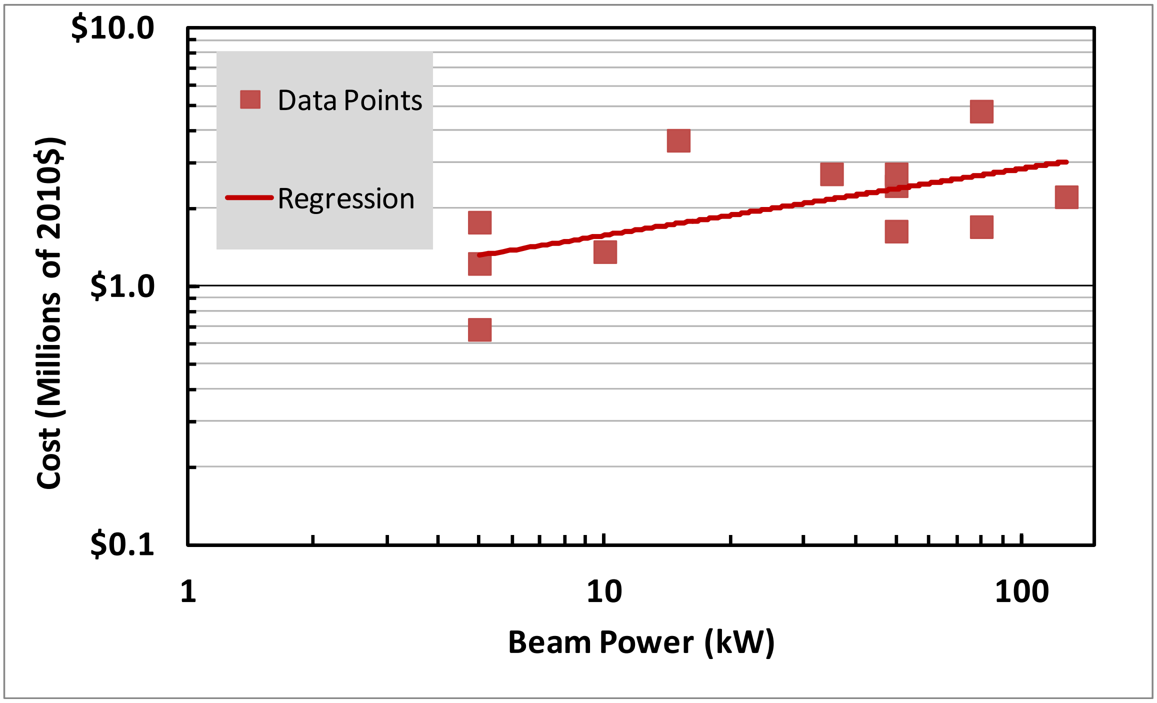

Figure B.1. Electron Beam Cost as Function of Beam Power[23], with vendor data[22]

The data in Figure B.1 was used to derive the scaling exponent in the following cost estimate for electron beam accelerators:

$$C_2 = C_1 * \left({P_2}/{P_1}\right)^{0.258} \qquad \text{(B.13)}$$

where

C_2 = Capital Investment, 2010 US$

C_1 = Capital Investment, **Reference Design**, 2010 US$

P_2 = Accelerator Power, kW

P_1 = Accelerator Power, **Reference Design**, kW

Equations 2.3 and 2.4 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 the reference for cost scaling in equation 2.5.

Figure A.2 (Appendix A) is the process flow diagram for the grafting and braiding process. There are 4 primary types of equipment in this area: solids conveying, grafting reactors, storage tanks, and braiders.

The solids conveying equipment is used to transport the irradiated fibers 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.

Table B.13. Belt Conveyor System Specifications – Grafting Area

Adsorbent Produced Annually	100,000	tonnes adsorbent/yr
Plant Uptime	0.9	Uptime
Operating Hours	7,800	Operating Hours/year
Mass Flow Rate	13	tons/hr
	3.5	kg/s
Belt Width	0.4	meters
Transport Distance*	1,500	meters
Belt Speed	0.75	m/s

*Transport Distance estimated as distance around perimeter of entire adsorbent production facility specified in JAEA analysis (143,215 m^2 facility)[20]

Table B.13 shows the design parameters for the solids conveying system. With the belt width and the transport distance, the cost estimate for the belt conveyor was developed from a standard cost scaling relationship3:

$$\boldsymbol{Cost\ of\ Conveyor} = \mathbf{1050} * \boldsymbol{Distance} + \mathbf{5884} \qquad \text{(B.14)}$$

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 in Table B.14.

Table B.14. Grafting Reactor Sizing Data

Parameter	Value	Units	Comments
HDPE Grafted Annually	50,000	tonnes/yr	yields 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
Bobbins per Reactor	250	bobbins	JAEA Assumption
Weight per Bobbin	1	Kg	JAEA Assumption
Reactor Volume	4	m^3	JAEA Assumption

The grafting reactors were treated as jacketed, stirred reactors for cost estimation purposes. The cost was estimated from an empirical relationship[3]:

$$\boldsymbol{Cost\ of\ Tank = 21200 * Volume^{0.53}} \quad \text{(B.15)}$$

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 should be stored in bulk on site considering the large volumes and high throughput rates of the adsorbent production process. Each storage tank was sized to a 30 day capacity for each chemical. The following cost scaling relationship was implemented using the calculated tank volumes[16]:

$$\boldsymbol{Cost\ of\ Tank = 163 * Volume + 63100} \quad \text{(B.16)}$$

where

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

Volume = Size of Tank, m^3.

After the grafting process is complete, the multifilament bundles are braided around a central backbone that serves as a float for the adsorbents; the braiding is the final step of adsorbent production. The price and quantity of the custom braiders was taken directly from the JAEA analysis[20].

B.2.2 Mooring and Deployment Supporting Calculations

The mooring and deployment area required sizing of anchor chains to moor the braid adsorbent as well as ships to recover and transport the adsorbent.

Chain sizing is limited by the forces experienced by the chain during recovery by the anchor windlass. Stud-link anchor chain size is designated by the diameter of each link and each size has an associated working-load limit which should not be exceeded during operation.[24] The minimum size requirement for the chains in this analysis were determined by approximating loads maximum loads experienced during recovery and choosing the minimum chain size that exceeds the working-load limit.

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

$$\boldsymbol{F_D = \frac{1}{2} * \rho_{sea} * u^2 * C_D * A} \quad \text{(B.17)}$$

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:

$$\boldsymbol{F_{TL} = W_C + n_B W_B + F_{DW} + F_{DC} - (n_B B_B + B_C)} \quad \text{(B.18)}$$

where

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

W_C = Weight of Chain, N

n_B = Number of braids per chain (240)

B_B = Buoyant force on braids = ρ_{sea}*g*V_B

ρ_{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 = ρ_B*g*V_B

ρ_B = Density of Braids, kg/m^3 (953 kg/m^3, density of HDPE)

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 from literature[25] used 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 resulted in a total load of 543 kN. The working load (safety limit) for a 44 mm, Grade 3 chain is 539 kN[24]. The working load limit on a chain one size smaller (42 mm) is 490 kN while the calculated load is 535 kN, exceeding the limit by nearly 10%. These preliminary calculations support the JAEA specification of a 44 mm chain.[3]

Work boat requirements are dictated by the adsorbent field size required to meet annual U production requirements and the speed with which adsorbent braids can be recovered by ships. Thus, ship sizing calculations couple adsorbent field design with chain recovery speed by the anchor windlass on each ship. Given that the entire braid adsorbent field must be recovered over the course of a campaign, the following set of equations derive the speed and number of the anchor windlasses from the reference adsorbent field size. Values in parentheses following variable definitions indicate the base case value for the variable.

$$\boldsymbol{N_C} = \boldsymbol{N_{Braids}} \Big/ \left[\frac{(\boldsymbol{L_C} - 2 * \boldsymbol{End\ Spacing})}{\boldsymbol{Braid\ Spacing}}\right] \qquad \text{(B.19)}$$

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)

$$\boldsymbol{R_{CR}} = \frac{\boldsymbol{N_C}}{\boldsymbol{Campaign\ Length}} \qquad \text{(B.20)}$$

where

R_{CR} = required daily chain recovery rate, chains per day

Campaign Length = Days in each production campaign (60 days)

$$N_{Windlass} = \frac{R_{CR}}{OH_{Daily} * 60 * R_{Windlass}} \quad \text{(B.21)}$$

where

$N_{Windlass}$ = number of windlasses required

OH_{Daily} = Operating hours of mooring system per day (9 hours)

$R_{Windlass}$ = 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 previous section.

The ships required for adsorbent deployment and recovery are directly related to the number of windlasses:

$$N_{Ships} = \frac{N_{Windlass}}{N_{Windlass-Ship}} \quad \text{(B.22)}$$

where

$N_{Windlass\text{-}Ship}$ = number of windlasses per ship (1 per ship)

The size of each 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 is calculated as follows:

$$DW_{Ship} = \frac{M_{Adsorbent}}{N_{Ships}} \quad \text{(B.23)}$$

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 capital cost in past analyses for a wide range of cargo and transport vessels. Work by Cullinane and Khanna provided the highest degree of correlation ($R^2 = 0.93$) to a large dataset of ships (n=153)[26]:

$$\mathbf{ln}(\boldsymbol{ship\ price}) = \mathbf{4.81 + 0.759 * ln}(\boldsymbol{NTEU}) \qquad \text{(B.24)}$$

where

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

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

The regression analysis dataset used to develop equation 2.14 covered ships from roughly 2800 DWT to 84,000 DWT[26]. Table 8 (main paper) summarizes all of the required mooring equipment and associated costs for the base case conditions.

Work by Cullinane and Khanna[26] related fuel consumption to the installed brake horsepower of the ship and in turn correlated brake horsepower to ship size. Therefore, for a given ship size, fuel consumption can be estimated as follows:

$$\mathbf{FO} = \frac{\mathbf{BHP * SFOC * U * OH_{Daily}}}{\mathbf{1,000,000}} \qquad \text{(B.25a)}$$

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

$$\mathbf{ln}(\boldsymbol{BHP}) = \mathbf{2.63 + 0.967 * ln}(\boldsymbol{NTEU}) \qquad \boldsymbol{R^2} = \mathbf{0.94}$$

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[27]. 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 (Table B.8), annual fuel costs are given in Table 9 (main paper).

Crew requirements are not well correlated to ship size, and thus an empirical estimate cannot be used to determine crew size. Instead, heuristics developed by Cullinane and Khanna[26] were used to estimate labor requirements (Table B.15).

Table B.15. 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 was assumed to be a captain while the remainder are sailors/workers.

B.2.3 Elution and Purification Supporting Calculations

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 section B.2.1. Annual adsorbent processing capacity in the elution area includes repeated processing of the entire adsorbent field as it is recycled and the metals loaded in the adsorbents. [3, 28] Table B.16 summarizes the specifications of the solids conveying system in the elution area.

Table B.16. Belt Conveyor System Specifications – Elution Area

Adsorbent Processed (Field Size x Campaigns)	600,000	tonnes adsorbent/yr
Mass of Known Adsorbed Metals	22,394	t adsorbent/yr
Loaded Adsorbent Mass (with safety margin – see footnote 28)	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 Speed	1.30	m/s

The storage and elution tanks are field erected tanks as in the grafting area; Equation 3.15 provides the cost scaling relationship for the tanks. The solvent storage tanks are sized for 30 day supply. 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[3]:

$$\boldsymbol{Cost\ of\ Agitator} = \mathbf{3370} * \boldsymbol{Power}^{\mathbf{0.173}} \qquad \text{(B.26)}$$

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 area1.

The basis for the purification process used in this analysis is the Fernald refinery, which converted and processed uranium ore to purified uranium products. An equipment list was obtained for the Fernald refinery from a design report developed during refinery start-up1. Modern cost scaling data was used to develop equipment costs for the Fernald equipment list[3]. The total refinery cost was scaled to 1200 tonnes of uranium capacity for the current evaluation using a cost scaling exponent from literature of 0.73 for solvent extraction facilities6.

An equipment list for the precipitation area (Table A.4 in Appendix A) was obtained from a study of uranium extraction in Canada[29]. Equipment costs were developed using equipment sizing data from the Canadian report and cost scaling data[3] or, where equipment sizing was insufficient for the estimation methods, costs were taken directly from the report. The total precipitation plant cost derived from the component equipment costs was adjusted from the reference capacity of 278 tonnes of uranium per year to the 1200 tonne/year basis in this analysis.

B.2.3 Polymer Disposal Supporting Calculations

Under the Atomic Energy Act and its amendments, the 11.e(2) classification was established by the US Nuclear Regulatory Commission to encompass materials or wastes produced as byproducts of the extraction or concentration of uranium from ore[30]. Guidance specific to the disposal of large quantities of 11.e (2) polymer material does not exist; therefore, large-scale disposal operations involving an analogous polymer material will be used as a precedent for costing the disposal of used adsorbent braids. The material selected is ion exchange resins employed for water purification at nuclear fuel cycle facilities and nuclear power plants.

Slightly-contaminated materials requiring disposal as low-level radioactive waste (LLW) or mixed low-level waste (MLLW), including polymers, arise from research, industrial or medical applications at 35 DOE and some 20,000 commercial sites[31]. A 1990 DOE study of twenty-nine treatment and disposal options for LLW- or MLLW-classified spent ion exchange resins[32] will provide the basis for the cost estimate used here. The study addressed an anticipated annual waste stream of 15,000 ft^3 (4,572 m^3) of LLW-classified resin arising from wastewater treatment operations at the Hanford site. Using the life cycle cost and ease of permitting as bases, the study recommended four strategies: joule-heated vitrification, incineration followed by cementation, acid digestion followed by cementation, high-temperature steam destruction followed by cementation. The incineration/cementation option is applied here. The incineration approach is widely-used for all types of polymers[33], and has been industrially achieved for polymer LLW. Studsvik RadWaste, for instance, operated an incineration/pyrolisis facility for uranium-contaminated polymer waste at Erwin, TN[34,35].

To treat 15,000 ft^3 (4,572 m^3) of polymer wastes annually for 30 years, 137,160 m^3 of polymer in total, DOE estimated the undiscounted unit cost of the incineration/cementation strategy as \$343/m^3 of polymer in 2010 dollars. This cost will be assumed valid for the HDPE-derived polymer used in the adsorbent system. The density of the adsorbent is 950 kg/m^3, so the unit cost associated with incineration and disposal becomes \$0.360/kg ads. Since (DOE 1990) provided insufficient data to disaggregate the cost into the COA items used elsewhere in this study, this disposal unit cost will be treated as a fixed, fee-for-service cost component not subject to economies of scale.

Appendix C. Populated Code of Accounts

Table C.1. 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)	$2,510,000	$0.22
10 series			
11	Land and land rights	$2,510,000	$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	
19	Contingency on Pre-Construction Costs (aggregated below)	$0	
2	Capitalized Direct Costs (Subtotal)	$134,000,000	$13.87
20 series			
21	Structures and Improvements	$36,400,000	$3.22
23	Process Equipment	$74,400,000	$8.15
24	Electrical equipment	$3,800,000	$0.42
25	Heat Rejection System	$0	$0.00
26	Miscellaneous plant equipment	$19,000,000	$2.08
27	Special materials	$0	
29	Contingency on Direct Costs (aggregated below)	$0	
Sum 1-2	Total Direct Cost		
3	Capitalized Indirect Services (Subtotal)	$32,300,000	$3.54
30 series			
31	Field indirect costs (rentals, temp facil., etc)	$20,100,000	$2.20
32	Construction supervision	$12,100,000	$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)	$1,520,000	$0.17
40 series			
41	Staff recruitment and training	$0	
42	Staff housing facilities	$0	
43	Staff salary-related costs	$0	
46	Other Owners' capital investment costs	$1,520,000	$0.17
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	
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	$17,000,000	$1.86
OVNT	Overnight cost	$187,000,000	$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	
69	Contingency on financial costs	$0	
Sum 1-6	Total Capital Investment Cost		
	Total Capitalized Cost (TCIC)	$187,000,000	$19.65
Annualized Costs			
7	Annualized O&M Cost (subtotal)	$512,000,000	$426.79
70 series			
71	Operations Staff	$6,630,000	$5.53
72	Management Staff	$1,160,000	$0.97
73	Salary-Related Costs	$0	$0.00
74	Raw Materials	$397,000,000	$330.93
75	Spare Parts	$0	$0.00
76	Utilities, Supplies and Consumables	$55,300,000	$46.10
77	Capital Plant Upgrades	$0	$0.00
78	Taxes and Insurance	$5,360,000	$4.46
79	Contingency on O&M Cost	$46,600,000	$38.80
9	Annualized Financial Costs (subtotal)	$0	0
90 series			
91	Escalation	$0	
92	Fees	$0	
93	Cost of Money	$0	
99	Contingency on Financial Costs	$0	

Table C.2. 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)	$2,130,000,000	$233.85
20 series			
21	Structures and Improvements	$0	$0.00
23	Process Equipment	$2,130,000,000	$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	
29	Contingency on Direct Costs	$0	
Sum 1-2	Total Direct Cost		
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	
46	Other Owners' capital investment costs	$0	$0.00
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	
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	$213,000,000	$23.38
OVNT	Overnight cost	$2,350,000,000	$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	
69	Contingency on financial costs	$0	
Sum 1-6	Total Capital Investment Cost		
	Total Capitalized Cost (TCIC)	$2,350,000,000	$257.23
Annualized Costs			
7	Annualized O&M Cost (subtotal)	$257,000,000	$214.40
70 series			
71	Operations Staff	$109,000,000	$90.49
72	Management Staff	$12,600,000	$10.48

73	Salary-Related Costs	$0	$0.00
74	Raw Materials	$1,910,000	$1.59
75	Spare Parts	$0	$0.00
76	Utilities, Supplies and Consumables	$111,000,000	$92.34
77	Capital Plant Upgrades	$0	$0.00
78	Taxes and Insurance	$0	$0.00
79	Contingency on O&M Cost	$23,400,000	$19.49
9	Annualized Financial Costs (subtotal)	$0	0
90 series			
91	Escalation	$0	
92	Fees	$0	
93	Cost of Money	$0	
99	Contingency on Financial Costs	$0	

Table C.3. 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)	$1,630,000	$0.14
10 series			
11	Land and land rights	$1,630,000	$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)	$86,900,000	$9.02
20 series			
21	Structures and Improvements	$23,700,000	$2.10
23	Process Equipment	$48,400,000	$5.30
24	Electrical equipment	$2,470,000	$0.27

25	Heat Rejection System	$0	$0.00
26	Miscellaneous plant equipment	$12,300,000	$1.35
27	Special materials	$0	
29	Contingency on Direct Costs	$0	
Sum 1-2	Total Direct Cost		
3	Capitalized Indirect Services (Subtotal)	$21,000,000	$2.30
30 series			
31	Field indirect costs (rentals, temp facil, etc)	$13,100,000	$1.43
32	Construction supervision	$7,900,000	$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)	$988,000	$0.11
40 series			
41	Staff recruitment and training	$0	
42	Staff housing facilities	$0	
43	Staff salary-related costs	$0	
46	Other Owners' capital investment costs	$988,000	$0.11
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	
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	$11,100,000	$1.21
OVNT	Overnight cost	$122,000,000	$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	
69	Contingency on financial costs	$0	
Sum 1-6	Total Capital Investment Cost		
	Total Capitalized Cost (TCIC)	$122,000,000	$12.79
Annualized Costs			
7	Annualized O&M Cost (subtotal)	$25,700,000	$21.38
70 series			
71	Operations Staff	$8,370,000	$6.98
72	Management Staff	$1,460,000	$1.22
73	Salary-Related Costs	$0	$0.00
74	Raw Materials	$1,610,000	$1.34
75	Spare Parts	$0	$0.00
76	Utilities, Supplies and Consumables	$8,400,000	$7.00
77	Capital Plant Upgrades	$0	$0.00
78	Taxes and Insurance	$3,490,000	$2.90
79	Contingency on O&M Cost	$2,330,000	$1.94
9	Annualized Financial Costs (subtotal)	$0	0
90 series			
91	Escalation	$0	
92	Fees	$0	
93	Cost of Money	$0	
99	Contingency on Financial Costs	$0	

Appendix D. Additional Calculations

D.1 CORRELATION OF IMMERSION TIME, TEMPERATURE AND CAPACITY

Data from JAEA field tests enabled the correlation of immersion time and water temperature to adsorption capacity. The raw data is reported in Table D.1.

Table D.1. Field Data on Uranium Adsorption[36]

Trial	Submersion Time (Days)	Number of Stacks	Seawater Temperature (°C)		Amount of U Adsorbed (g)	Apparent Adsorbent Rate (g/(day*stack))
			Min	Max		
1	20	144	19	21	66	0.023
2	20	144	12	13	47	0.016
3	40	144	13	22	66	0.011
4	30	144	22	24	101	0.023
5	20	144	22	24	76	0.026
6	20	144	18	22	77	0.027
7	30	216	13	18	95	0.015
8	60	72	13	20	48	0.011
9	90	72	13	19	120	0.019
10	30	216	18	20	119	0.018
11	60	144	18	19	150	0.017
12	30	216	19	20	118	0.018

The data was used to regress a relationship between the uranium adsorbed and the duration and temperature conditions at the mooring site. Per a suggestion from M. Tamada (personal communication), the amount adsorbed was fit to a function of form

$$A = \mathrm{K}\, t^{1/2}\, \mathrm{T}^{\alpha} \qquad \text{(D.1)}$$

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 results of the regression are shown in Figure D.1 and the regression parameters are given in Table D.2. In this figure, $A/t^{1/2}$ is normalized against its value at T = 25 C and plotted against the temperature.

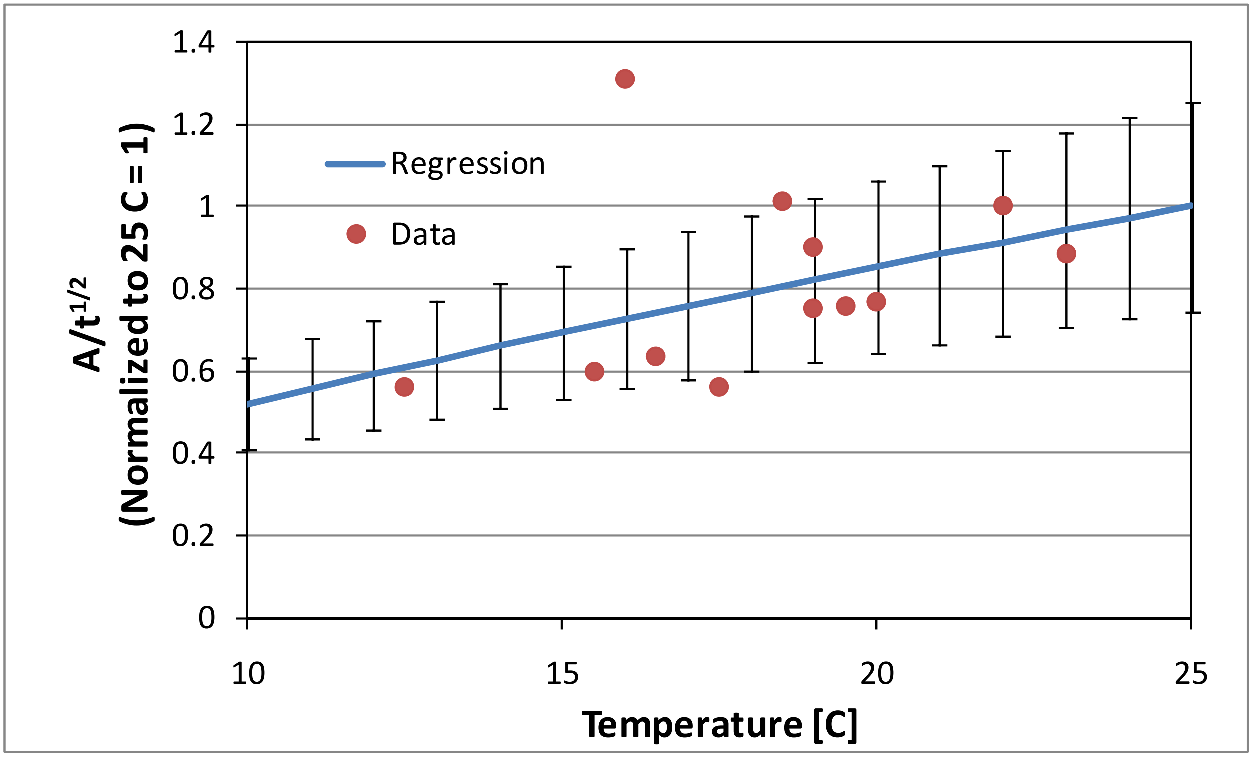

Figure D.1. Time and Temperature Dependence of Adsorption

Table D.2. Regression parameters for time-temperature-adsorption model

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

The regression results are used as 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 component is strictly empirical.

In the analyses, the above relationship was scaled to yield adsorption capacity of 2.0 kg U/t ads at 25 C and 60 days' soaking. At these conditions, the empirical relationship yields a standard deviation of +/- 0.50 kg U/t ads. This relationship was used in the uncertainty analysis to describe the range of variation of the adsorbent performance about its expected value.

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