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# Design and Cost Studies on the Extraction of Uranium from Seawater

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# Design and Cost Studies on the Extraction of Uranium from Seawater

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## ABSTRACT

For a country like Japan, which has very limited energy resources, nuclear power generation is an attractive energy option. However, since known domestic resources of uranium are limited, it is desirable to develop less-conventional uranium sources. To investigate the technical and economic feasibility of extracting uranium from seawater, a research program has been carried out since 1975 by the Metal Mining Agency of Japan, under sponsorship of the Ministry of International Trade and Industry. The program includes studies in the following research areas: chemical process selection, adsorbent development, continuous adsorption and elution performance, eluate recovery by steam stripping or electrodialysis, and secondary concentration of uranium in the eluate. Several site selections around the Japanese coast have been examined along with a comparison of various seawater contacting structures. Conceptual designs and tentative cost estimations have been conducted on two types of commercial plants: pumping and fixed bed, and direct sea current utilization. This paper summarizes the conceptual design and cost estimation results.

## I. INTRODUCTION

Interest in the extraction of uranium from seawater has increased in recent years, particularly in a country like Japan which has very limited energy resources including uranium. To ensure a supply of uranium, various policies such as long-term purchase contracts and exploitation of overseas uranium deposits have been adopted, however, the necessity of exploiting domestic uranium resources has been intensified.

Some experimental studies of the extraction of uranium from seawater have been carried out in Japan since the early 1960's. In 1975, a research program was initiated in the Metal Mining Agency of Japan (MMAJ), sponsored by the Ministry of International Trade and Industry, and considerable progress has been achieved. Japan has many favorable conditions: an island surrounded by the sea, a high seawater temperature which is advantageous for uranium adsorption, and the Kuroshio Current which ensures an adequate supply of fresh uranium-bearing seawater and disperses water that has passed through the plant.

Some previous results of the MMAJ programe (1), the development of hydrous titanium oxide adsorbents, other chemical processes, general descriptions of the conceptual designs (2), and some comparisons of different seawater contacting systems (3) have already been reported.

As for the chemical process to extract uranium from seawater, the adsorption process using hydrous titanium oxide was selected from co-precipitation, organic adsorption, flotation, solvent extraction, and biological processes. A large volume of seawater must be contacted with the adsorbent to extract significant quantities of uranium. For this purpose, various engineering possibilities including fixed bed, fluidized bed, slurry, and moving bed systems were considered. In connection with the contacting structures, tidal lagoon, pumping and fixed-bed, on-shore plant, off-shore bottom supported, and off-shore floating systems were investigated. From these investigations, pumping and fixed bed and near-shore bottom supported systems were selected for the design studies. The latter contacting structure will be referred to hereafter as the direct sea current utilization system. Significant results of the conceptual designs and cost estimations will be described.

## II. PUMPING AND FIXED BED SYSTEM A

This system is considered to be the most realistic because many experimentally proven conditions have been established. Some of the basic conditions for this system are shown in Table 1.

The annually required seawater volume, Q, can be calculated as follows:

$$R = \frac{h \times \gamma \times C_{10}}{\alpha \times v \times t} = \frac{0.10 \times 0.9 \times 196}{3 \times 1152 \times 10} \times 10^{5} \ ,$$

$$= 51\ (\%), \quad \text{where } R = \text{recovery.}$$

$$Q = \frac{W_U}{\alpha \times R \times \eta} \times 10^{13} = \frac{1000}{3 \times 51 \times 81} \times 10^{13} \ ,$$

$$= 8.07 \times 10^{11}\ (m^3/yr)\ .$$

The size of the facilities are:

$$n_p = \frac{Q}{24 \times 60 \times 60 \times D \times q} = \frac{8.07 \times 10^{11}}{8.64 \times 10^{4} \times 250 \times 80} \ ,$$

$$= 467 \ ,$$

where, $n_p$ = number of pumps, D = annual operating days = 250,

q = pump capacity = 80 $m^3$/sec, and

$$L = \frac{n_p(B + \epsilon) + 2\epsilon}{1000} = \frac{467 \times 19 + 8}{1000} \ ,$$

$$= 8.88\ (km) \ ,$$

TABLE 1

Basic Conditions of Pumping and Fixed Bed System A

| | | |
|---|---|---|
| 1. | Annual uranium production, $W_u$ | 1000 t-U |
| 2. | Concentration of uranium in seawater, $\alpha$ | 3ppb |
| 3. | Adsorption structure | Multi-layer fixed bed |
| 4. | Adsorption-elution cycle, t | 10 days-2 days |
| 5. | Annual cycle number, N | 25 |
| 6. | Adsorbent | $TiO_2 \cdot nH_2O$ |
| 7. | Adsorption capacity, $C_{10}$ | 196 μg-U/g-ad/10 days |
| 8. | Bulk Density, $\gamma$ | 0.9 g/cm$^3$ |
| 9. | Linear flow rate of seawater, v | 80 cm/min |
| 10. | Adsorbent loss | 0.1 %/cycle |
| 11. | Bed thickness, h | 10 cm |
| 12. | Elution and concentration recovery, $\eta$ | 81% |
| 13. | Elution temperature | Room temperature |
| 14. | Eluting solution | 1 M $(NH_4)_2CO_3$ |
| 15. | Uranium concentration in eluate | 10 ppm |
| 16. | Decarbonation method | Steam stripping |
| 17. | Secondary concentration | Ion exchange |
| 18. | Final concentration of uranium in product solution | 3000 ppm |



where, L = total length of the facilities,

B = pump fitting width = 15 m, $\epsilon$ = space width = 4 m .

The initial charge of adsorbent $W_{ad}$, is:

$$W_{ad} = \frac{W_u}{C_{10} \times \eta \times N} \times 10^8 = \frac{1000}{196 \times 81 \times 25} \times 10^8 \ ,$$

$$= 25.19 \times 10^4 \ (t), \text{ and}$$

$$W_{ac} = \frac{W_{ad}}{n_p} = \frac{25.19 \times 10^4}{467} = 539.4 \ (t) \ ,$$

where, $W_{ac}$ = initial charge of adsorbent per unit.

The width of the facilities, B, is:

TABLE 2

Size Summary of Pumping and Fixed Bed System A

| Item | Approximate Quantity |
|---|---|
| Total length of facility | 8.88 km |
| Width of facility | 130 m |
| Total volume of seawater | $3.74 \times 10^4$ $m^3$/sec |
| Initial adsorbent charge | $25.19 \times 10^4$ t |
| Number of adsorption bed stacks | 15878 |
| Power requirement | $67 \times 10^4$ kW |
| Fresh water requirement | $26 \times 10^4$ $m^3$/day |
| Eluant requirement | $220 \times 10^4$ $m^3$ |



$$B = L_p + \frac{N_s \times L_s}{m} = 66 + \frac{34 \times 3.3}{2} = 122 \text{ (m)} ,$$

where, $L_p$ = length of pumping part = 66 m ,

$N_s$ = number of bed stacks in one adsorption unit = 34 ,

$L_s$ = width of bed stack = 3.3 m, and

m = number of rows of bed stacks = 2.

A summary of the pumping and fixed bed system A facility size is shown in Table 2.

Based on the process design considerations, a conceptual design was proposed which is shown in Fig. 1. The upper part of the figure shows a plan view of the overall facilities and the lower part shows a sectional view of the facilities.

The total capital cost was estimated based on the conceptual design of the pumping and fixed bed system A for a production rate of 1,000 t-U/yr. The results are shown in Table 3.

The operating costs for extracting uranium from seawater are estimated from the economic bases shown in Table 4. The operating cost results are shown in Table 5.

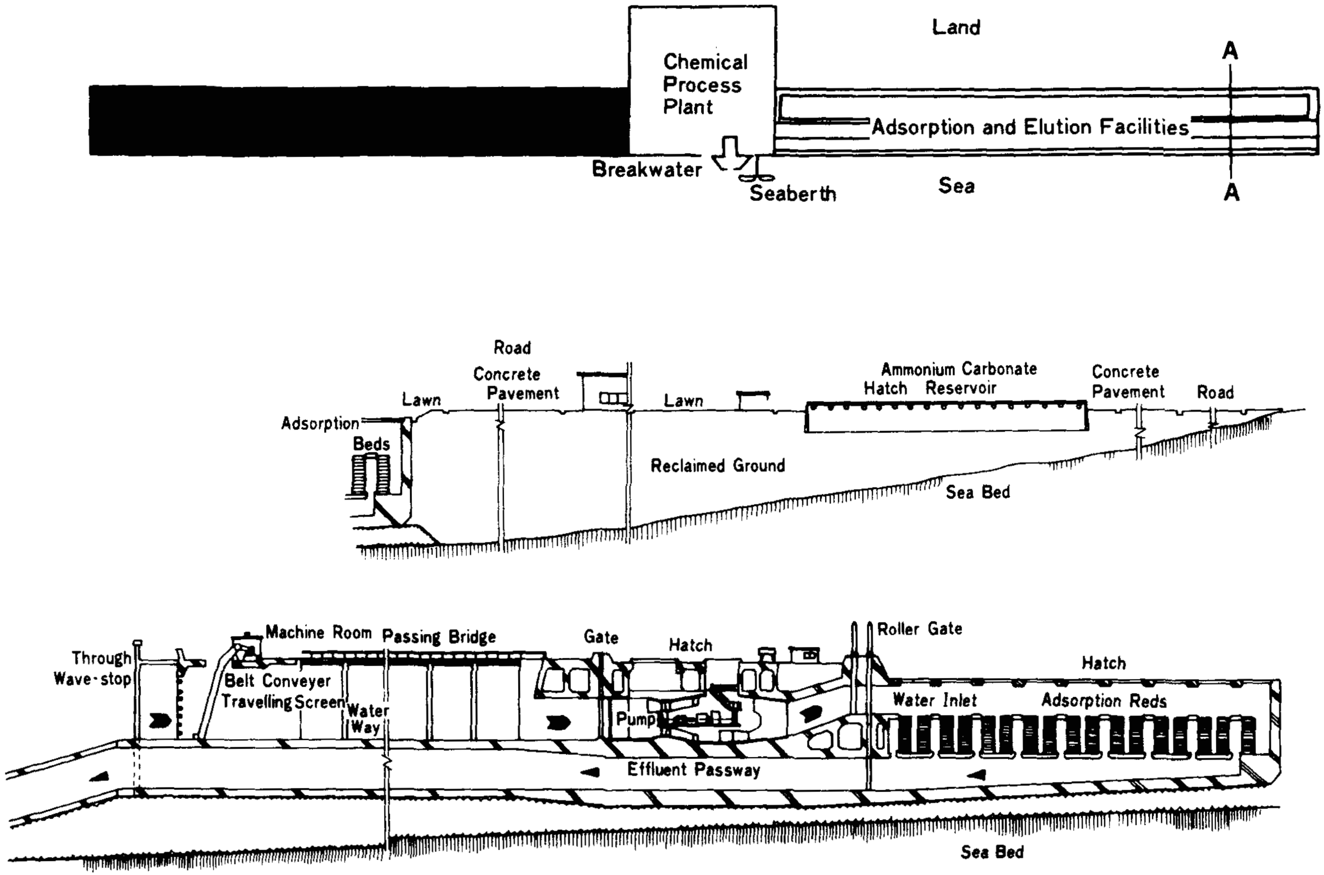



Fig. 1. Conceptual design of pumping and fixed bed system A

TABLE 3

Capital Cost Estimate for Pumping and Fixed Bed System A

| Item | Number | Thousands of Dollars* Unit Cost | Cost | Remarks |
|---|---|---|---|---|
| Adsorption facilities | | | | |
| 1. Concrete structure | 468 | 2,000 | 936,000 | |
| 2. Mound construction | | | 62,400 | |
| 3. Reclamation works | | | 156,000 | |
| 4. Piping | | | 25,000 | |
| 5. Adsorption bed stacks | 468 | 617 | 288,600 | Include adsorbent |
| 6. Wave-stop works | | | 40,667 | |
| 7. Machineries | 468 | 5,000 | 2,340,000 | pump, screen, etc. |
| Subtotal | | | 3,848,667 | |
| Supporting facilities | | | | |
| 1. Seaberth | | | 1,333 | include pipelines |
| 2. Breakwater | | | 16,667 | |
| 3. Bank-revetment | | | 8,333 | |
| 4. Water intake | | | 11,333 | include pumps |
| 5. Drainage | | | 1,333 | |
| 6. Water reservoir | | | 1,667 | |
| 7. Fresh water supply | | | 6,800 | |
| Subtotal | | | 47,466 | |
| Chemical process plant etc. | | | | |
| 1. Process plant etc. | | | 388,667 | |
| 2. Boiler power plant | | | 345,000 | |
| 3. Buildings | | | 35,000 | |
| 4. Roads | | | 3,333 | |
| 5. Chemicals reservoir | | | 9,000 | |
| 6. Chemical tanks | | | 7,000 | |
| 7. Electrical systems | | | 176,333 | |
| 8. Concrete pits | | | 3,000 | |
| Subtotal | | | 967,333 | |
| Total Cost | | | 4,863,466 | |

*All costs were expressed in 1976 dollars.

TABLE 4

Chemical and Energy Unit Cost Summary

| Item | Unit Requirement t/t-U | Unit Cost $/t | Total Cost $/t-U |
|---|---|---|---|
| Fuel | | | |
| Heavy oil | 1,350 | 80 | 108,000 |
| LNG | 15,000 ($Nm^3$/t-U) | 0.0567 ($/$Nm^3$) | 850 |
| Electric power | 1,600 (MWH/t-U) | 33.3 ($/MWH) | 53,333 |
| Adsorbent | 10 | 667 | 6,667 |
| Chemicals for elution | | | |
| 35% HCl | 24 | 70 | 1,680 |
| 98% $H_2SO_4$ | 4 | 50 | 200 |
| 45% NaOH | 28 | 183.3 | 5,133 |
| NaCl | 24 | 43.3 | 1,040 |
| $H_2CO_3$ | 1 | 150 | 150 |
| $NH_4OH$ | 8 | 250 | 2,000 |
| Total | | | 179,053 |

TABLE 5

Operating Costs for Pumping and Fixed Bed System A

| Operating scheme | 1st operation (4th year) | 2nd operation (6th year) | Full operation (8th year) |
|---|---|---|---|
| Uranium production/yr | 200 t | 600 t | 1,000 t |
| | | Thousands of dollars | |
| Adsorption | | | |
| Adsorbent cost | 1,333 | 4,000 | 6,667 |
| Power cost | 10,667 | 32,000 | 53,333 |
| Labor cost | 693 | 2,080 | 3,467 |
| Elution and concentration | | | |
| Eluant and Chemicals | 2,040 | 6,113 | 10,203 |
| Heavy oil and LNG | 21,770 | 65,310 | 108,850 |
| Labor cost | 2,050 | 6,150 | 10,250 |
| Miscellaneous | | | |
| Shipping, etc. | 50 | 150 | 250 |
| Supervision | 1,370 | 4,113 | 6,857 |
| Total | 39,973 | 119,916 | 199,877 |

Based on the preceding estimations and economic data shown in Table 6, a unit production cost of \$334/lb $U_3O_8$ (1976 dollars) was derived.

TABLE 6

Economic Data Summary

| | | |
|---|---|---|
| Capital depreciation period | 25 yr | |
| Remaining factor | 15% | |
| Insurance | 0.7% of remaining capital | |
| Taxes | 1.4% | |
| Interest for long-term debt | 6.5% | |
| Interest for short-term debt | 9.0% | |
| Construction time | 8 years | |
| Labor requirement: | adsorption facilities | 208 |
| | elution and concentration | 615 |
| | total | 823 |
| Average annual salary | \$16,667 | |

## III. PUMPING AND FIXED BED SYSTEM B

A second conceptual design and cost estimation was conducted using larger pumps with a capacity of 500 instead of 80 $m^3$/sec. The pumps were arranged to be of the breakwater type instead of the on-shore parallel type used in system A. The major parameters in Table 1 were fixed except for the following conditions shown in Table 7.

TABLE 7

Basic Conditions of Pumping and Fixed Bed System B

| | |
|---|---|
| 1. Adsorption capacity, $C_{ao}$ | 200 μg-U/g-ad/10 days |
| 2. Adsorption recovery, R | 60% |
| 3. Bulk density, $\gamma$ | 1.0 g/$cm^3$ |
| 4. Linear flow rate of seawater, v | 60 cm/min |
| 5. Elution and concentration recovery, $\eta$ | 90% |

This case resulted in some size reduction of the facilities as shown in Table 8.

TABLE 8

Size Summary of Pumping and Fixed Bed System B

| Item | Approximate Quantity |
|---|---|
| Total length of facility | 3.84 km |
| Width of facility | 254.4 m |
| Total volume of seawater | $2.86 \times 10^4$ $m^3$/sec |
| Initial adsorbent charge | $22.0 \times 10^4$ t |
| Number of pumps | 60 (include 3 spares) |
| Number of adsorption bed stacks | 6,480 |
| Power requirement | $70 \times 10^4$ kw |
| Fresh water requirement | $21.1 \times 10^4$ $m^3$/day |
| Eluant requirement | $31.7 \times 10^4$ $m^3$/day |



Based on the system B parameters, a conceptual design was completed and is shown in Figs. 2 and 3. Figure 2 shows the structure of the adsorption bed stacks, and Fig. 3 shows the plan and sectional views of the facility. Using the second design conditions, capital and operating costs for the pumping and fixed bed system B were estimated and are shown in Tables 9 and 10, respectively.

Using the new capital and operating costs, the economic data for the pumping and fixed bed system A, and a construction time of 10 years, a unit cost of \$223/lb $U_3O_8$ (1976 dollars) was obtained.

## IV. PUMPING AND FIXED BED SYSTEM C

It has been recognized for some time that adsorption recovery and uranium concentration in the eluate have direct influences on the facility size and operating costs which will alter the overall production costs. There has been some experimental evidence to indicate that an adsorbent may be developed with an increased adsorption recovery and a high concentration of uranium in the eluate. Accordingly, a third set of cost estimations was completed with some basic condition changes as shown in Table 11.

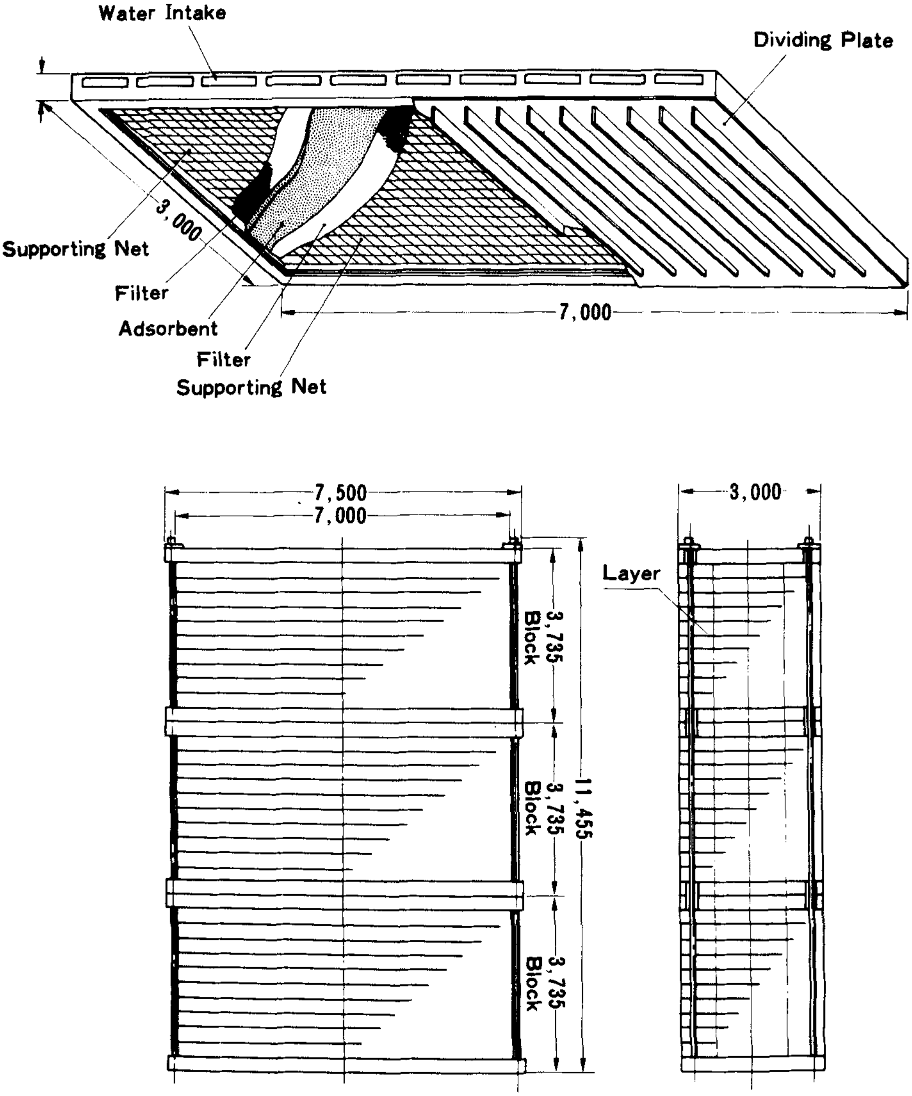
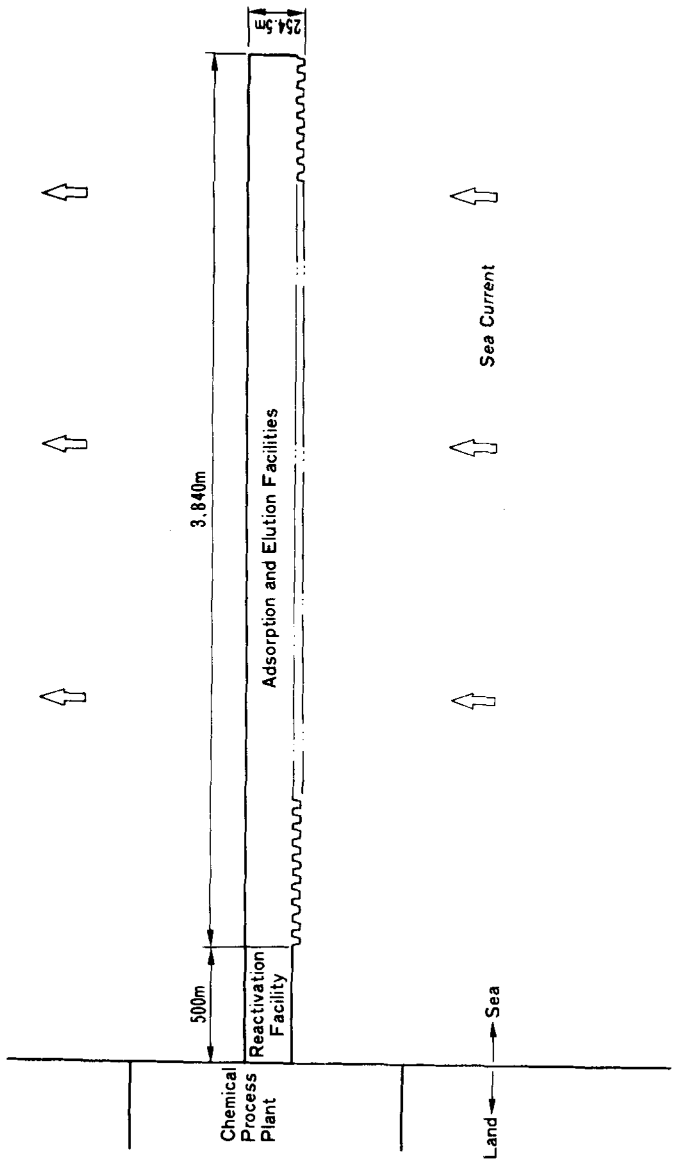



Fig. 2. Structure of adsorption bed stacks


254.5m
3,840m
Adsorption and Elution Facilities
Sea Current
500m
Reactivation Facility
Chemical Process Plant
Sea
Land

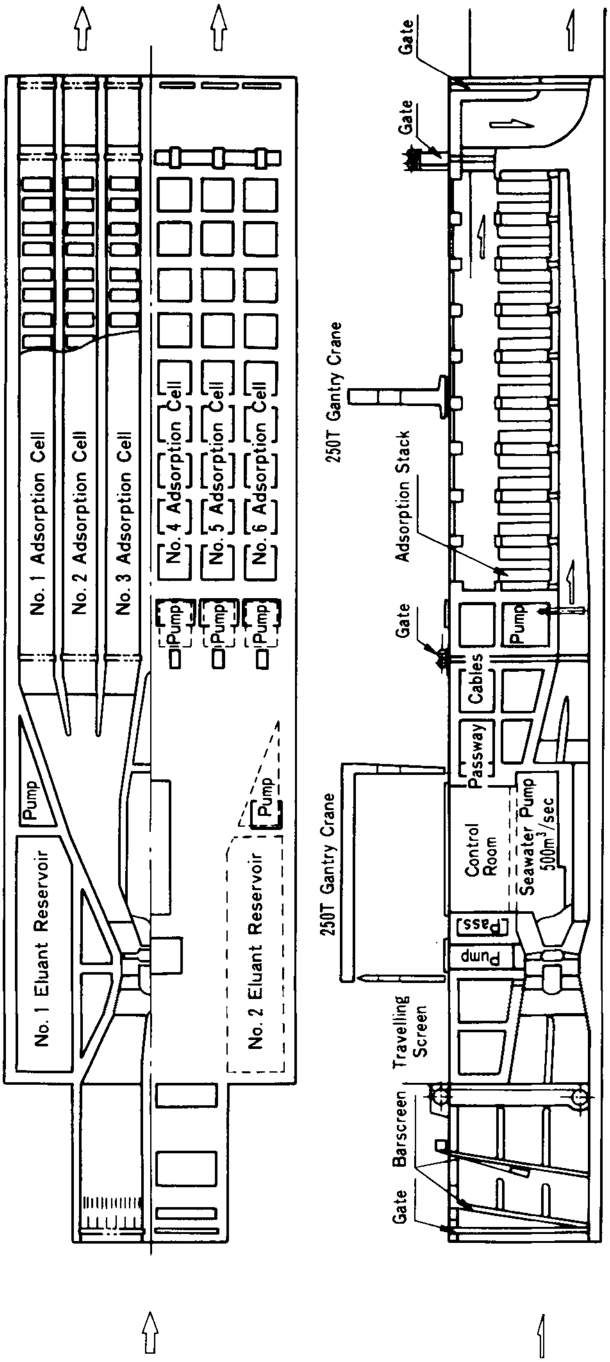



Fig. 3. Conceptual design of pumping and fixed bed system B

TABLE 9

Capital Cost Estimate for Pumping and Fixed Bed System B

| Item | Number | Thousands of Dollars* Unit Cost | Cost |
|---|---|---|---|
| Adsorption & elution facilities | | | |
| 1. Foundation works | | | 36,667 |
| 2. Units constructions | 60 | 29,333 | 1,760,000 |
| 3. Subsiding works | | | 6,667 |
| 4. Dock constructions | | | 285,333 |
| 5. Piping works | | | 10,000 |
| 6. Adsorption bed stacks | 6,480 | 42.7 | 276,667 |
| 7. Machineries | 60 | 14,167 | 850,000 |
| Subtotal | | | 3,225,334 |
| Supporting facilities | | | |
| 1. Adsorbent reactivation facilities | | | 28,333 |
| 2. Seaberth (including pipe-lines) | | | 1,333 |
| 3. Breakwater and bank-revetment | | | 19,000 |
| 4. Water intake and drainages | | | 10,667 |
| 5. Fresh water supply | | | 7,333 |
| Subtotal | | | 66,666 |
| Chemical process plant | | | 967,333 |
| Total | | | 4,259,333 |

*All costs are expressed in 1976 dollars.



TABLE 10

Operating Costs for Pumping and Fixed Bed System B

| Operating Scheme | 1st operation (4th year) | 2nd operation (7th year) | Full operation (10 th year) |
|---|---|---|---|
| Uranium production/yr | 200 t | 600 t | 1,000 t |
| | | Thousands of dollars | |
| Adsorption | | | |
| Adsorbent cost | 1,333 | 4,000 | 6,667 |
| Power cost | 10,667 | 32,000 | 53,333 |
| Labor cost | 693 | 2,080 | 3,467 |
| Elution and concentration | | | |
| Eluant and chemicals | 2,040 | 6,113 | 10,203 |
| Heavy oil and LNG | 21,770 | 65,310 | 108,850 |
| Labor cost | 2,050 | 6,150 | 10,250 |
| Supervision | 1,370 | 4,113 | 6,857 |
| Total | 39,923 | 119,766 | 199,627 |

TABLE 11

Basic Conditions of Pumping and Fixed Bed System C

| | | |
|---|---|---|
| 1. | Adsorption capacity | 200 μg-U/g-ad/10 days |
| 2. | Adsorption recovery | 80% |
| 3. | Bulk density | 1.0 g/cm$^3$ |
| 4. | Linear flow rate of seawater | 60 cm/min |
| 5. | Elution and concentration recovery | 90% |

The other conditions are the same as in Table 1.

TABLE 12

Size Summary of Pumping and Fixed Bed System C

| Item | Approximate Quantity |
|---|---|
| Total length of facility | 2.95 km |
| Width of facility | 254.5 m |
| Total volume of seawater | 2.14 x $10^4$ m$^3$/sec |
| Initial adsorbent charge | 22.0 x $10^4$ t |
| Number of pumps | 45 (include 2 spares) |
| Number of adsorption bed stacks | 4,860 |
| Power requirement | 52.4 x $10^4$ kW |
| Fresh water requirement | 19.9 x $10^4$ m$^3$/day |
| Eluant requirement | 23.9 x $10^4$ m$^3$/day |



With these new parameters, the necessary number of pumps was reduced to 45 including 2 spares, and the pumping and fixed bed system C was sized accordingly as shown in Table 12.

Capital and operating cost estimates were calculated for the pumping and fixed bed system C, and the respective results are shown in Tables 13 and 14.

With the improved capital and operating costs, the economic data for the pumping and fixed bed system A, and a construction time of 10 years, a unit cost of \$161/lb $U_3O_8$ (1976 dollars) was obtained. Summarizing the cost

TABLE 13

Capital Cost Estimate for Pumping and Fixed Bed System C

| Item | Number | Thousands of Dollars* Unit Cost | Cost |
|---|---|---|---|
| Adsorption facilities | | | |
| 1. Foundation works | | | 27,333 |
| 2. Units constructions | 45 | 29,333 | 1,320,000 |
| 3. Subsiding works | | | 6,667 |
| 4. Dock constructions | | | 190,000 |
| 5. Piping works | | | 10,000 |
| 6. Adsorption bed stacks | 4,860 | | 207,333 |
| 7. Machineries | | | 637,333 |
| Subtotal | | | 2,398,666 |
| Supporting facilities | | | |
| 1. Adsorbent reactivation facilities | | | 28,333 |
| 2. Seaberth (including pipe lines) | | | 1,333 |
| 3. Breakwater and bank-revetment | | | 19,000 |
| 4. Water intake and drainages | | | 10,666 |
| 5. Fresh water supply | | | 7,333 |
| Subtotal | | | 66,665 |
| Chemical process plant | | | 577,000 |
| Total | | | 3,042,331 |

*All costs are expressed by 1976 dollars

TABLE 14

Operating Costs for Pumping and Fixed Bed System C

| Operating scheme | 1st operation (4th year) | 2nd operation (7th year) | Full operation (10th year) |
|---|---|---|---|
| Uranium production/yr | 200 t | 600 t | 1000 t |
| | | Thousands of dollars | |
| Adsorption | | | |
| Adsorbent cost | 1,333 | 4,000 | 6,666 |
| Power cost | 11,267 | 33,800 | 56,333 |
| Labor cost | 693 | 2,080 | 3,467 |
| Elution and concentration | | | |
| Eluant and chemicals | 2,040 | 6,113 | 10,203 |
| Heavy oil and LNG | 10,867 | 32,600 | 54,333 |
| Labor cost | 2,050 | 6,150 | 10,250 |
| Supervision | 1,370 | 4,113 | 6,857 |
| Total | 29,620 | 88,856 | 148,109 |

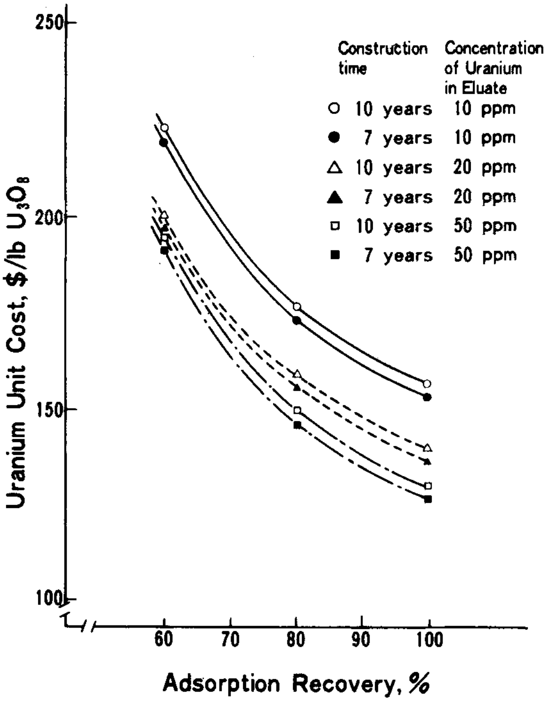



Fig. 4. Correlation of uranium unit cost and adsorption recovery



estimation results for the three systems, correlations of uranium unit cost as a function of adsorption recovery and total capital cost are shown in Figs. 4 and 5, respectively.

## V. DIRECT SEA CURRENT UTILIZATION SYSTEM

The concept of a direct sea current utilization system was also investigated. Marine structures containing many adsorption stacks are immersed in reasonably flat nearshore sea-beds to utilize the seawater current. The adsorption stacks are composed of three 5 m x 5 m x 5 m adsorption cubes with many parallel adsorption plates containing a single layer of particle

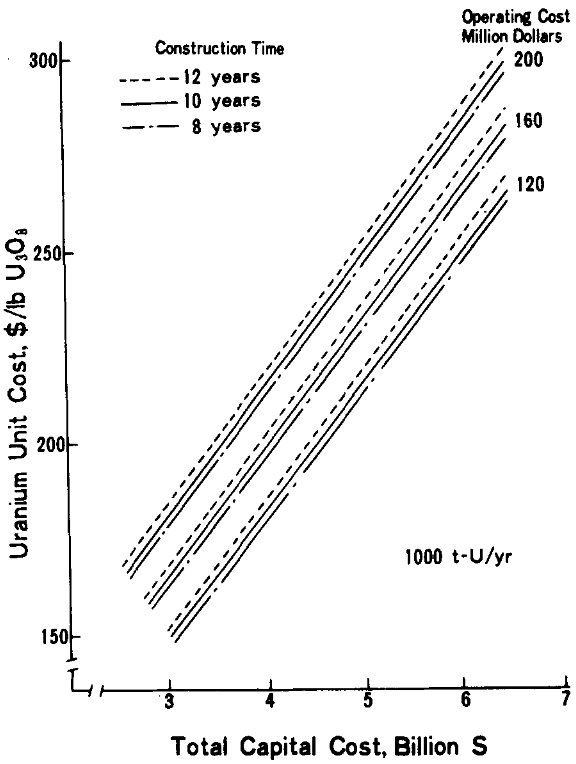



Fig. 5. Correlation of uranium unit cost and total capital cost



adsorbent on each side. These stacks are held in a single unit of 17.3 m width, 45 m height and 1.7 m length which is anchored in the sea at a depth of about 35 m. The conceptual drawing was previously shown (2). For a production rate of 1,000 t-U/yr, 30 sets of the unit structure were required.

Based on this conceptual design, a cost estimate was performed and a unit cost of \$251/lb $U_3O_8$ (1976 dollars) was obtained.

After further study, thin packed beds of adsorbent placed between two porous supporting plates appeared to be superior to the parallel adsorption plates previously considered for a direct sea current utilization system. Due to the increased amount of adsorbent in a unit volume, the number of unit structures was reduced to 20. With this improvement, capital and operating costs were reduced, and a unit cost of \$177/lb $U_3O_8$ was obtained.

## VI. CONCLUSIONS

Extensive research has been conducted in Japan to develop adsorbents for the extraction of uranium from seawater. Although hydrous titanium oxide seems to be the most promising material at present, the development of new organic resin adsorbents is worthy of further investigation. In any event, the development of improved contacting systems is considered to be very important. The conceptual designs and cost estimations of several systems have been completed. These results indicate unit prices ranging from \$334 to \$161/lb $U_3O_8$ (1976 dollars). Even though these prices were determined on the basis of some uncertain technical and economic conditions, further studies are definitely justified. A number of uncertainties associated with the process remain, and future development of this technique will require a cooperative effort between fundamental research and engineering.



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