PROSPECTS FOR THE RECOVERY OF URANIUM FROM SEAWATER

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ABSTRACT

A computer program entitled URPE (Uranium Recovery Performance and Economics) has been developed to simulate the engineering performance and provide an economic analysis of a plant recovering uranium from seawater. The conceptual system design used as the focal point for the more general analysis consists of a floating oil-rig type platform, sinlge-point moored in an open ocean current, using either high volume, low head, propeller pumps or the velocity head of the ambient ocean current to force seawater through a mass transfer medium (hydrous titanium oxide (HTO) coated onto particle beds or stacked tubes), as in most process designs previously suggested for this service. Uranium is recovered from the seawater by an adsorption process, and later eluted from the adsorber by an ammonium carbonate solution. A multi-product co-generating plant on board the platform burns coal to raise steam for electricity generation, desalination, and process heat requirements. Scrubbed stack gas from the plant is processed to recover carbon dioxide for chemical make-up needs.

The equilibrium isotherm and the diffusion constant for the uranyl-HTO system, which are needed for bed performance calculations, have been calculated based on the rather sparse data reported in the literature. In addition, a technique for calculating the rate constant of a fixed bed adsorbing system has been developed for use with Thomas' solution for predicting fixed bed performance.

The URPE program has been benchmarked against the results of previous studies by ORNL and Exxon, and found to make comparable performance and economic estimates when applied under the same set of ground rules. The URPE code was then used in an extensive series of parametric and sensitivity studies to identify optimum bed operating conditions and important areas for future research and development. The program showed that thin beds of small, thinly-coated particles were the preferred bed configuration, and that actively pumped systems out-perform current driven units.

Based on the URPE analysis, the minimum expected costs of uranium recovered from seawater would be no lower than ~316 (1979\$)/lb U_3O_8 for state-of-the-art adsorber material (capacity equal to 210 mg U/kg Ti), but might be reduced to the level of breakeven attractiveness of ~150 (1979\$)/lb U_3O_8 if at least a four-fold increase in adsorption capacity could be achieved. Specific research and development objectives other than increasing particle capacity are also indentified. Prospects are considered to be sufficiently good to warrant recommending further work.

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The work presented in this report has been performed primarily by the principal author, Frederick R. Best, who has submitted substantially the same report in partial fulfillment of the requirements for the PhD degree in Nuclear Engineering at MIT.

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CHAPTER I

INTRODUCTION

1.1 Foreword

Interest in the extraction of uranium from seawater has increased in recent years, due to concern over the future availability of moderate-cost terrestrial resources, and the growing realization that alternative sources of energy will be more costly, and available later in time, than originally hoped. Technological assessments of the practicality of uranium recovery from seawater have yielded mixed results ranging from an unpromising estimate of 1400 \$/lb yellowcake (B1), to the favorable prospects implied in the Japanese government's announced plan to have a pilot plant recovering 10 kg of uranium per year in operation by 1984 (E1). This difference in perceived feasibility is due, in part, to the level of technological perfection assumed, as well as substantial differences in the ground rules under which the evaluations were conducted. In view of these discrepancies and because the potential benefits are enormous and ubiquitous, it was considered highly desirable to attempt a more definitive technological assessment. In support of this objective the Energy Laboratory of the Massachusetts Institute of Technology funded the uranium from seawater project documented in the present work. The project had three goals:

1. to perform an assessment of state-of-the-art technology for uranium recovery from seawater;
2. to define the conditions under which uranium recovery from seawater would be economically attractive; and
3. to set objectives for research and development in this area.

To meet these objectives, a computer simulation of a uranium recovery system's engineering and economic performance was developed. The Uranium Recovery Performance and Economics (URPE) program analyzes the uranium recovery problem by linking state-of-the-art submodels of the various unit operations involved in uranium recovery.

Uranium exists in seawater predominantly as a uranyl-tricarbonate complex, at a concentration of about 3.34 ppb uranium by weight. The total uranium resource available is equal to about 4,000 million tons of U_3O_8. However, in order to recover even small amounts of uranium, large volumes of seawater must be processed. For example, a conventional LWR would recover only about 5% of its annual average uranium needs, even if all of the uranium in its condenser seawater flow could be extracted. In addition, the uranium must be recovered at a competitive cost. A value of 150 \$/lb U_3O_8 is a frequently quoted breakeven price of uranium for use in

LWRs, in comparison with breeder reactors, a number of other advanced nuclear technologies (U1), or coal-fired plants. Hence, this value is a convenient target price for the production of uranium from seawater.

Adsorption of uranium on hydrous titanium oxide is the generally preferred technique for uranium recovery from seawater, as confirmed by many independent studies. The URPE code is therefore based on modelling of an adsorption-type process. A state-of-the-art cost for uranium recovery is estimated, using input parameters characteristic of existing technology, to calculate a levelized uranium cost. Promising areas for further research and development are found by examining subunit performance data and cost components output by the code, and by calculating the sensitivity of overall production costs to engineering performance indices.

1.2 Background

Interest in the recovery of uranium from seawater varies both on a national and on a personal level, depending on the perspective from which the problem is viewed. In the United States there has not been much interest in the recovery of uranium from seawater because of the perception that terrestrial uranium resources should last well into the next century when used in conventional light water reactors, at which time breeder reactors would be widely deployed, thereby reducing the demand for yellowcake. There is already sufficient depleted uranium stored as enrichment plant tails to produce energy equal to that from the usable coal resource of the United States, if the uranium is used in a plutonium-breeder system. Thus, there is no need for uranium from seawater when the uranium (or coal) supply situation is viewed from this energy-rich perspective. However, the situation is very different when viewed from the perspective of highly industrialized, but energy-poor countries. Japan, Great Britain and the Federal Republic of Germany all have uranium from seawater programs very much larger than the efforts in this area underway in the United States. Italy, the Republic of China, Sweden, the People's Republic of China, and the Union of Soviet Socialist Republics also have, or are starting, small research programs on the recovery of uranium from seawater.

The question of the need for uranium from seawater is not based solely on the problem of energy supply and demand. The potential of terrestrial uranium as a long term energy resource depends on the deployment of the plutonium breeder reactor. The ultimate acceptability of the plutonium breeder reactor depends on international nuclear proliferation policy and public acceptability as well as on economic considerations. A national policy to forego the use of plutonium breeder technology could conceivably be enforced in order to prevent the spread of commerce in plutonium and weapons-related technology throughout the world. Since questions of non-proliferation policy go far beyond the scope of this work, we will not discuss this aspect of the problem further. We do wish to note, however, the strong feelings which exist on this topic, both on a public and governmental level, as evidenced by the perceived need for the Nonproliferation Alternative Systems Assessment Program, and the International Nuclear Fuel Cycle Evaluation program.

In any event, plutonium breeder reactors would not be widely deployed on a commercial basis unless they produced energy which was at most, no more expensive than that from alternative methods. The breeder would not be adopted in the commercial reactor market as long as uranium prices were low enough such that burner reactors could generate electricity as cheaply, or more cheaply, than breeder reactors.

A "breakeven" cost may be defined as that cost of uranium which would result in LWR busbar electricity costs equal to that produced by a breeder reactor. The tradeoff between the two systems occurs because, while breeder systems have higher capital costs (S4) than burner systems, their fuel cycle costs are lower and relatively insensitive to the price of uranium. The U.S. Department of Energy (U1) has calculated a breakeven uranium price of approximately $150 (1978 dollars) per pound of yellowcake (U_3O_8) for LWR systems competing against a variety of breeder systems. As long as yellowcake is available at or below this value, the breeder would not be adopted commercially. A value of

$150 per pound would therefore be a good target price for uranium from seawater.

Reference (U1) gives the U.S. Department of Energy estimate of U.S. uranium resources including reserves and potential resources as approximately 4 million tons for a forward cost less than or equal to $50 per pound of yellowcake. The market price would be roughly twice the forward cost (U1). At a concentration by weight of 3.3 parts of uranium per billion parts of seawater, the world's oceans contain a total of approximately 4,000 million short tons (ST) of yellowcake equivalent. Improved LWR designs requiring 150 ST U_3O_8/Gw(e)-yr on the once-through fuel cycle are in prospect. Thus, the uranium contained in the sea represents an enormous energy resource, enough to sustain thousands of LWRs for thousands of years.

Table 1.1 summarizes selected pro's and con's of the uranium from seawater concept. As in many socio-technical problems of this scope, there is no single clear-cut factor which would cause anyone to inherently prefer uranium from seawater over other available technologies. However, the full impact of the technology cannot be adequately assessed until its engineering, economic and environmental effects are known more accurately. The present work is a preliminary effort in this regard.

Table 1.1

Uranium from Seawater:

Assets and Liabilities

Item	Aspect
Extent of Resource Base	There are 4,000 million ST of yellowcake equivalent in the oceans--an assured energy resource on an enormous scale.
Availability of Sites	Seawater is directly available to any country in the world with a coastline, and indirectly to all (in international waters)
Level of Technology Required	Although the size of the plant would be large, it is merely a fluids-solids handling system.
Environmental Impact	The impact on the environment should be small, in part because plant emissions must be limited for economic reasons. Since most (90%) of the environmental impact in the current nuclear fuel cycle comes from mining and milling operations, a significant net benefit would accrue.
Attractiveness vs Alternative Technologies	As the cost of producing energy by other means continues to rise, due in part to scarcity-related escalation, uranium from seawater becomes more attractive.

Table 1.1 (continued)

Item	Aspect
Social and Political Acceptability	Uranium from seawater favors retention of existing LWR technology, and would eliminate the cost and political difficulties of a plutonium breeder, reprocessing and transportation.
Research and Development Costs	Will be low since small scale experiments will yield extrapolable results, and seawater is sufficiently uniform to assure universal applicability.
Potential for Technology Transfer	All elements are contained to some extent in seawater; as technology advances others may become extractable at a reasonable price.

1.3 Discussion

It is convenient to begin an investigation of the potential for recovery of uranium from seawater with a calculation of the basic energy balance governing the processes involved. No matter what process is used to recover uranium from seawater, large volumes of seawater must interact with large amounts of a recovery medium. As a standard of comparison, a seawater flow equal to the volumetric flow rate of the Mississippi River (2×10^{10} lbs/hr) carries sufficient uranium (400 ST) to supply the annual average fuel demand for only two 1000 Mw(e) light water reactors.

The amount of energy which the recovery system expends per unit of seawater processed must be kept small in order to insure a net positive production of energy. As shown in Appendix B, a uranium recovery system must have an overall head loss of less than about 5 psi (in the absence of all other losses) in order to collect sufficiently more energy (in the form of uranium) than it expends. This single fact has greatly influenced the choice among design alternatives as evidenced in the approach selected for the present study.

A four volume report entitled "Extraction of Uranium from Seawater," (B5, B6) has been published by Exxon under contract to the U.S. Department of Energy. This report issued in February of 1979, summarizes essentially all of the data and experience available through 1978 on uranium recovery from seawater, and documents a technical/economic evaluation of a current state-of-the-art shore-based plant design. The report is the most comprehensive and complete document on uranium from seawater issued anywhere to the present time. It considers all of the available processes for uranium recovery, and attempts to determine the technical, economic and environmental feasibility of such a project. The report's final conclusion was that the project was economically unprofitable, but probably technically and environmentally feasible. The study analyzed an actively pumped shore-based river mouth recovery plant using titanium hydroxide adsorbing material and an ammonium carbonate eluting solution. Their projected cost for uranium was $1436 (1978 dollars) per pound of U_3O_8. Prior to the Exxon report, the most frequently cited systems study was that of Oak Ridge National Laboratory (H1). They analyzed a tidally-pumped plant, also utilizing a titanium hydroxide-ammonium carbonate system. Their projected cost for uranium was $300 (1974 dollars) per pound of U_3O_8. Most other published studies on uranium from seawater have not included final production costs, focusing instead on investigation of adsorber properties. As appropriate, particular studies will be cited in the current text, even though the data may also be found in the Exxon report.

The purpose of the present work is threefold:

- to conduct an assessment of state-of-the-art technology for uranium recovery from seawater;

- to define conditions under which uranium could be economically recovered from seawater;
- to set specific objectives for research and development in the technology of uranium recovery from seawater.

The approach employed in the present work is to develop a computer simulation describing the technical/economic performance of the coupled components of a uranium recovery system, and to use the simulation to calculate the cost of uranium recovery by an optimized system design. Objectives for further research may then be deduced by analyzing the itemized breakdown of overall production costs as key input parameters are varied.

1.4 Organization of the Present Work

The present work is organized into chapters and sections in accordance with the following outline. Chapter Two describes the development of the conceptual system arrangement and mathematical models used to analyze the various sub-systems of the recovery plant. This chapter first describes how the conceptual design was developed, and then details the performance and economic models used in the computer program. Chapter Three tabulates the uranium recovery costs for the optimized system, as well as some off-optimum analyses. Additionally, Chapter Three details the sensitivity of uranium production cost to the assumptions built into the various models. Chapter Four summarizes the major results, presents the conclusions drawn from the preceding analyses, and outlines recommendations for future work. Appendices cover various topics; the major addendum, Appendix A, is the user's manual for the computer code URPE.

CHAPTER II

SYSTEM MODEL DEVELOPMENT

2.1 Introduction

This chapter details the selection of a conceptual design for a uranium recovery plant and describes the models which were developed to calculate plant performance and estimate production costs. The chapter is arranged by sections, describing the hydraulic model, the reaction kinetics model, the chemical consumption model, and the economics models. All data on the absorber of choice, hydrous titanium oxide (HTO) are taken from an Oak Ridge National Laboratory Report (H1), except for those data specifically referenced from other sources.

As mentioned in Chapter One, the overriding capability which a uranium from seawater plant must have is the ability to handle very large volumes of seawater with very small expenditures of energy. Energy is consumed in processing seawater by several mechanisms depending on the type of uranium recovery system. Energy may be required to move the seawater: pumping consumes energy directly. Energy may be required to separate seawater from some active recovery agent, inorganic, organic, inert or living. Energy may be required to directly separate the uranium from seawater (for example, by electrochemical means as in Ref. (W1)).

Energy may be required to treat secondary flow streams in the uranium recovery process (e.g., for chemical production or recovery).

Considering these energy consumption mechanisms and the sum total of prior experience as documented in the literature, the following criteria for seawater handling systems were established:

1. hydraulic head losses in the system must be kept to a minimum,
2. the seawater should not be moved through elevation changes unless the energy so expended is recoverable by some means,
3. the seawater cannot be treated in order to grossly change its chemical state,
4. the seawater cannot be heated for the purpose of improving recovery efficiency,
5. if possible, ocean currents should be used to move the seawater through the recovery system,
6. the source of seawater should be as clean as possible to minimize the need for, and pressure losses in, prefilters and to avoid fouling of the absorber bed itself,
7. the seawater intake and outlet arrangement must be such that processed seawater cannot inadvertently be reprocessed.

The above criteria relate to the seawater handling system of any uranium from seawater plant and are independent of the details of the uranium recovery process. Criteria for selecting a specific uranium recovery process must be based on considerations analogous to those used for setting the criteria for the seawater handling system. In particular, the recovery process should be one which uses minimum amounts of consumables and energy per unit of seawater processed. With these considerations in mind, the following criteria for uranium recovery processes were established:

1. the process should be highly selective for uranium in seawater to minimize bed exhaustion by unwanted co-products,
2. the process should be environmentally compatible with the local ecology,
3. the material required for the process should be inexpensive per unit of uranium processed,
4. the process should be capable of handling the large volumes of seawater required, and
5. the amount of consumables used, including energy, should be minimal.

There are many techniques which have been envisioned for recovering uranium from seawater. The most practical of these (i.e. those which survive even the most cursory screening) are biological, flotation, solvent extraction, co-precipitation, electrolysis and sorption. Schwochau, Astheimer, Schenk and Schmitz (S1) describe and evaluate these processes. Based on their analyses, biological recovery is not considered promising at this time, due in part to the lack of data on which to base an analysis. Flotation and solvent extraction require large amounts of consumables and could have a large negative impact on the biota. Co-precipitation and electrolysis both require large amounts of energy. Sorption appears to be the best technique when measured against the five criteria established for a uranium recovery process.

A sorption recovery process would consist of two main segments, a uranium loading cycle and an eluting cycle. The large amounts of seawater to be processed would be contacted with the sorber material. Uranium would be removed from the seawater either by a physical adsorption process or by an ion exchange type process. The sorber would be loaded with uranium until its optimum capacity had been achieved. The sorber would then be separated from the seawater, and the uranium eluted from it. Finally the sorber would be placed back into a uranium loading cycle.

Hundreds of materials have been tested for their performance as sorption media. Of them all, hydrous titanium oxide (HTO), $Ti(OH)_4$, has been shown by many researchers in many laboratories over the past twenty years to be the most promising medium for a sorption type uranium recovery system. HTO is highly selective for uranium in seawater. It is very insoluble in seawater and, therefore, not ecologically damaging. Titanium in the anatase form is readily available and inexpensive. Sorption has been used as an industrial process for decades, although systems in common use would require a large scale-up to provide the sorption bed area required to process the design seawater flows. Finally, the amount of consumables and energy required for a sorption process system are generally modest, and an optimizable function of the overall recovery system design, as discussed in the remainder of this report.

Although HTO is presently accepted as the most promising sorption material, recently developed ion exchange resins (B3) have demonstrated high uranium selectivity and capacity. Test data on the ion exchange resins are proprietary; however, batch tests indicate a high degree of selectivity for uranium in natural seawater and high removal efficiency. A high capacity for uranium is also expected based on the known properties of ion exchange media. Further discussion of ion exchange systems will be reserved for Chapter Three, Section Six. By combining the inherent characteristics of the sorption process with the performance criteria for the seawater handling system it is possible to develop a conceptual design for a uranium from seawater recovery system. There are several reservations to be discussed before describing the recovery system.

The major thrust of the present work was directed toward quantifying the hydraulic and chemical/kinetic characteristics of the uranium recovery process. Thus, the overall uranium recovery plant proposed represents only the first iteration on a system design , sufficient to permit credible parametric studies but not necessarily an ultimate optimum configuration. The adsorption kinetics model discussed in Section Three of this chapter is the first kinetic model for the uranium-HTO process published anywhere in the open literature. The kinetic model incorporates equilibrium and reaction rate data from several sources to develop a consistent adsorption rate model. Recommendations on follow-on efforts in ocean engineering needed to flesh out and improve upon the conceptual system are discussed in Chapter Four.

The proposed sorption process uranium recovery plant is shown in Figure 2.1. It would consist of moored floating oil-rig type platforms anchored in fifteen hundred feet of water. The plant consists of seawater intakes, facing the prevailing up-current direction, exhausting to large diffusers which reduce fluid velocity and increase fluid pressure. The fluid passes through the sorber bed proper moving upward in the top bed sections and downward in the bottom bed sections. The fluid leaving the beds is carried away by the prevailing current. A multi-product coal-fired generating plant sits on top of the platform. The rig is situated in deep water far from shore to give access to clean open ocean currents. The use of deep clean ocean water aids in preventing bed plugging due to entrained organic and inorganic material. As noted in Refs. (A1, B4 and L1), most of the ocean, below

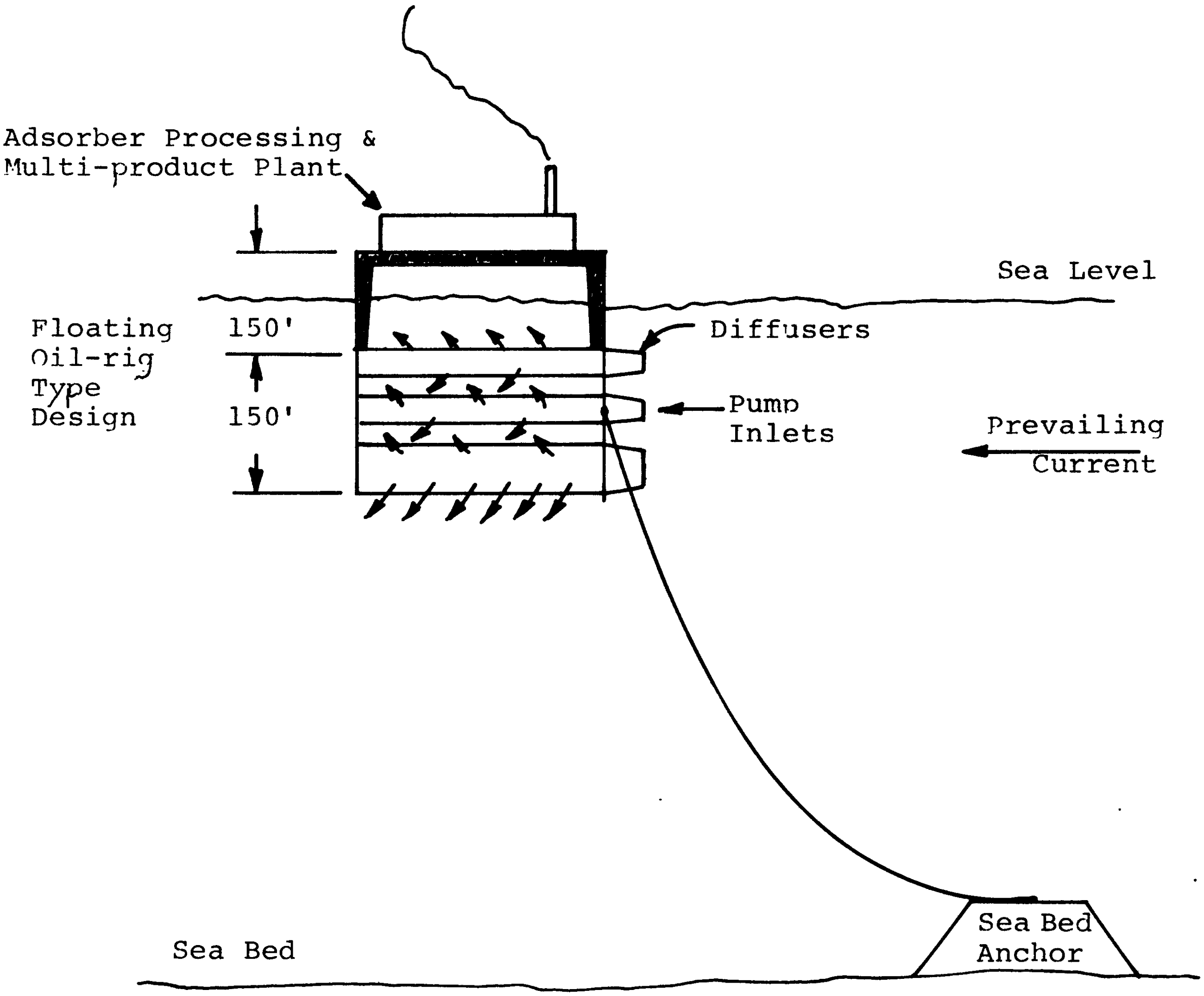


Fig. 2.1

Uranium Recovery Plant Module (Side View) the biologically active surface layer and sufficiently far from sedimentary shores, contains less than 20 ppb suspended particulate matter. The plant design therefore utilizes a simple fine mesh filter to clean the seawater prior to entry in the sorber bed proper.

The uranium recovery system is designed to incorporate an on board multi-product plant. The plant burns coal to produce steam for generating electricity, for desalination and for chemical processing. Part of the scrubbed stack gas is processed through a carbon dioxide recovery system to supply some of the plant's make-up chemical requirements. The economic models describing the multi-product plant are described in Section Five of this chapter.

The uranium recovery plant is moored in deep water rather than bottom mounted in shallower water for several reasons. Ready access to clean water has already been discussed. In addition, a single-point moor allows the plant to passively reorient itself as the local current changes direction. This insures that seawater intakes and outlets are always correctly oriented to prevent recycling of once-processed seawater. For the all-passive pumping system, which uses the current's hydraulic head, it is vital for the seawater intakes to be oriented into the oncoming current to insure that an optimal full-flow condition exists in the beds. For the actively pumped system, it may be possible by this means to obtain a pumping "assist" from the available current, and thereby reduce the number of pumps and pumping power required for the plant (although no credit is taken for this effect in the actively pumped systems analyzed in this work).

The following sections of Chapter Two describe in detail the models developed to calculate the engineering performance and the economic characteristics of the overall uranium from seawater plant. The numerical data used in a particular model are presented in the relevant subsections.

2.2 Overall Hydraulic Model

The seawater handling system of the uranium recovery plant described in the Introduction to this chapter is shown, conceptually, in Fig. 2.2. The values of V shown in the figure are fluid superficial velocity at the cross section shown. The A values are the cross-sectional areas at the sections shown. Thus, V_o and A_o are the fluid superficial velocity and system cross-sectional area at the diffuser inlet. The total frontal area of the bed is A_2. V_2 is the fluid superficial velocity in the sorber bed, which is the same as the fluid velocity at the diffuser exit. A_1 is a unit of sorber bed frontal area. For actively pumped systems, the diffuser is assumed to have a propeller type pump installed at the inlet. The head loss models for each section of the system are discussed below.

Starting at the left of the figure, water enters the diffuser and experiences entrance losses. The entrance losses are modelled by considering a large body of fluid at rest being

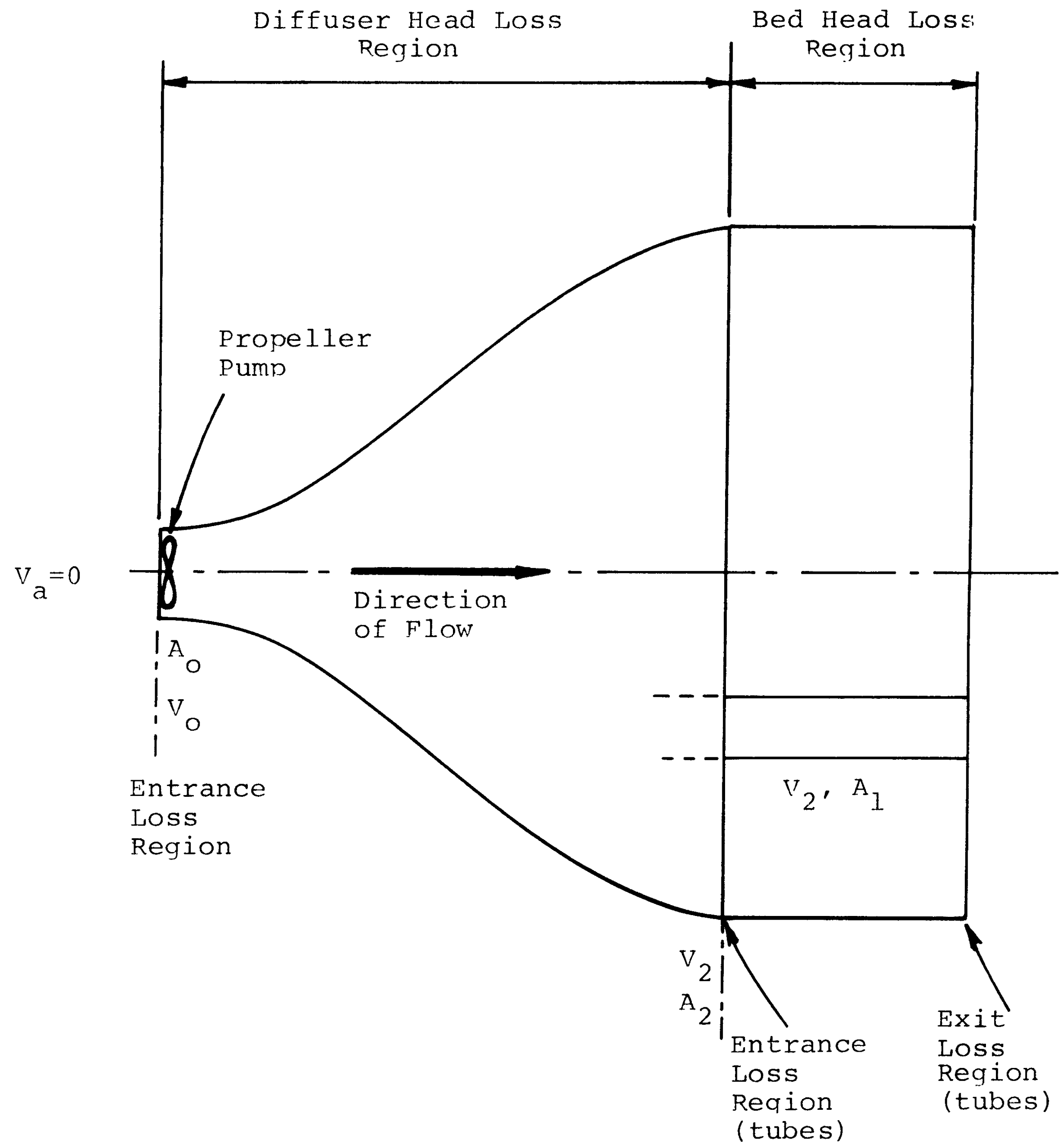


Fig. 2.2

Conceptualized Hydraulic Configuration of the Uranium Recovery System accelerated to the velocity at the inlet of the system. For well-rounded entrances, Streeter (S1) gives the head loss as

$$H_e = 0.05 \frac{V_o^2}{2g} \qquad (2.1)$$

where,

V_o = area average fluid velocity at the inlet, ft/sec

g = dimensional constant, $32.2 \frac{\text{ft-lb}_m}{\text{lb}_f\text{-sec}^2}$

0.05 = experimentally determined constant.

The water then enters the diffuser which acts to increase the pressure by changing velocity head into pressure head through an increase in the flow area and a concomitant decrease in flow velocity. Head losses in the diffuser consist of both friction losses due to shear and turbulence losses due to flow separation. From Ref. (S2), both of these effects are accounted for by the relation,

$$H_d = \frac{0.12(V_o - V_2)^2}{2g} \qquad (2.2)$$

where,

V_2 = cross section average fluid velocity at the diffuser exit, ft/sec

0.12 = experimentally determined constant

and other terms are as noted previously. Equation 2.2 assumes an optimum diffuser configuration having a diffuser length eighteen times the inlet diameter.

The fluid next experiences a head loss in entering, traversing, and exiting the sorber bed. Head loss models for the bed are covered in Subsections 2.2.1 and 2.2.2.

The overall hydraulic model for the system may be constructed by writing Bernoulli's Equation, including pump head and system friction losses, for a fluid path which begins in the ambient fluid at zero velocity far from the diffuser inlet and which terminates in the open ocean at the bed exit, where the fluid velocity is V_2. Thus,

$$\frac{p_a}{R} + \frac{k\,V_a^2}{2g} + z_a + \left[\begin{matrix}\text{Pump}\\ \text{Head}\end{matrix}\right] = \frac{p_2}{R} + \frac{k\,V_2^2}{2g} + z_2 + \left[\begin{matrix}\text{Friction}\\ \text{Losses}\end{matrix}\right] \tag{2.3}$$

where

a,2 are subscripts indicating the datum point,

R = fluid density, lb/ft^3

z = height above some reference level.

Pump Head is the increase in head supplied by the pump(s) (for actively pumped systems),

Friction Losses = the head losses in the system, and

k = kinetic correction factor, accounting for the fact that the flow at a section may be laminar and therefore actually carrying more kinetic energy than the area averaged velocity would indicate; k equals 1 for turublent flow, and 2 for laminar flow conditions.

Equation 2.3 may be simplified and rearranged by noting that: (1) p_a and p_2 are both at ocean ambient pressure and therefore cancel; (2) z_a and z_2 are at the same height above reference (by design), thus cancelling; and (3) V_a is selected to be far from the diffuser inlet and equal to zero for actively pumped systems. For actively pumped systems, Eq. 2.3 may be rearranged to give the overall hydraulic model of the seawater handling system,

$$\left[\begin{array}{c}\text{Pump}\\ \text{Head}\end{array}\right] = \frac{k\,V_2^2}{2g} + \left[\begin{array}{c}\text{Friction}\\ \text{Losses}\end{array}\right] \qquad (2.4)$$

For passive ocean interceptor systems, Eq. 2.3 may be rearranged to obtain (with pump head equal to zero, but ambient ocean velocity, V_a, non-zero),

$$\left[\begin{array}{c}\text{Friction}\\ \text{Losses}\end{array}\right] = \frac{1}{2g}\left[V_a^2 - k\,V_2^2\right] \qquad (2.5)$$

The Friction Loss terms in Eqs. 2.4 and 2.5 include the total friction losses in the seawater handling system including inlet losses, diffuser losses and bed losses. The bed loss terms for packed particle beds and "stacked tube" beds are specified in Sections 2.2.1 and 2.2.2, respectively.

2.2.1 Packed Particle Bed Hydraulic Model

The overall hydraulic model for a seawater handling system has been presented in Section 2.2. The hydraulic model for a particular bed design, namely the packed particle bed system, is developed in this section.

Packed particle bed sorption systems typically consist of beds of particles having diameters from one quarter of an inch down to three thousandths of an inch or less. The particles are randomly arranged in beds such that the void fraction (the fractional volume of the bed exterior to the particles themselves) typically ranges from 0.4 to 0.6. Pressure loss correlations for packed particle bed systems are available. Packed particle beds effectively have no distinct entrance and exit loss effects as do tubes, for example, because the tortuous internal paths never allow a distinct flow pattern to develop. Rohsenow, et al. (R1), or Perry, et al. (P1), recommend for packed bed pressure drop calculations:

$$H_b = \left[\frac{1-v_1}{v_1^{\,3}}\right] \frac{V_2^2\, L_9}{D\, g} \left[\frac{150(1-v_1)}{N} + 1.75\right] \qquad (2.6)$$

where,

v_1 = bed void fraction,

V_2 = superficial velocity, ft/sec

L_9 = bed thickness, ft

D = particle diameter, ft

N = Reynolds number,

$$= \frac{R\, V_2\, D}{v} \qquad (2.7)$$

v = viscosity

and R,g are as before, while 150 and 1.75 are experimentally determined numbers. Equation 2.6 is valid in the range

$$0.01 < N < 2500(1-v_1) \qquad (2.8)$$

The packed particle beds are held in place, top and bottom, by fine mesh screens which also act as pre-filters for the particle bed proper. Assuming that the mesh opening is equal to one-fourth the particle diameter (to prevent the particles from passing through) and that the wire diameter of the mesh is equal to one-half the mesh opening (typical for fine mesh screens), Perry (P1) recommends:

$$H_S = 27,600 \frac{V_2^2}{N^2\ 2g} \qquad (2.9)$$

where,

H_S = the screens' head loss, ft.

Rewriting Eq. 2.4 with the head loss terms explicitly accounted for, gives

$$\begin{bmatrix}\text{Pump}\\ \text{Head}\end{bmatrix} = \frac{k\ V_2^2}{2g} + H_e + H_d + H_b + H_s$$

Substituting the expressions for H_e, H_d, H_s, and H_b gives the total pump head requirement:

$$\begin{bmatrix}\text{Pump}\\ \text{Head}\end{bmatrix} = \frac{k\ V_2^2}{2g} + \frac{0.05V_o^2}{2g} + \frac{0.12(V_o-V_2)^2}{2g} + \frac{27,600\ V_2^2}{N^2 2g}$$

$$+ \left[\frac{1-v_1}{v_1^{\ 3}}\right] \frac{V_2^2\ L_9}{D\ g} \left[\frac{150(1-v_1)}{N} + 1.75\right] \qquad (2.10)$$

From continuity,

$$V_2 = \frac{A_o}{A_2} V_o \quad ,$$

and Eq. 2.10 may be rearranged to give

$$\begin{bmatrix} \text{Pump} \\ \text{Head} \end{bmatrix} = \frac{V_2^2}{2g} \left[k + 0.05 \left(\frac{A_2}{A_o} \right)^2 + 0.12 \left(\frac{A_2}{A_o} - 1 \right)^2 + \frac{27,600}{N^2} \right.$$
$$\left. + 2 \left(\frac{1-v_1}{v_1^3} \right) \frac{L_9}{D} \left(\frac{150(1-v_1)}{N} + 1.75 \right) \right] \qquad (2.11)$$

The hydraulic work expended by the pump is equal to the volumetric flow rate times the pump differential pressure. The pump differential pressure is the pump head times the fluid density. The electrical power, P, required to drive the pump is the hydraulic power divided by the pump efficiency, Q_7.

$$P = \frac{V_2 A_2 \; R}{Q_7} \begin{bmatrix} \text{Pump} \\ \text{Head} \end{bmatrix} \qquad (2.12)$$

The final expression for system pumping power P in megawatts electric is then,

$$P = \frac{0.001356}{Q_7 {*} 2 {*} 1000 {*} g} \; R \; A_2 V_2^3 \left[k + 0.05 \left(\frac{A_2}{A_o} \right)^2 + 0.12 \left(\frac{A_2}{A_o} - 1 \right)^2 \right.$$
$$\left. + \frac{27,600}{N^2} + 2 \left(\frac{1-v_1}{v_1^3} \right) \frac{L_9}{D} \left(\frac{150(1-v_1)}{N} + 1.75 \right) \right] \qquad (2.13)$$

Equation 2.13 is the hydraulic model of the seawater handling system (for packed bed systems) used in the computer code URPE described in Appendix A. In the code, fluid superficial velocity, V_2, is represented by variable U1; experience has shown that k_f the kinetic energy correction factor, should be set equal to a value of one; in the code the ratio A_2/A_o is represented by A_7. The numerical constants outside the brackets in the expression are conversion factors, included here to complete the documentation (0.001356 kw-sec/ft-lb, 1000kw/MW).

For passive ocean interceptor operation, Eq. 2.5 is solved for the maximum bed thickness allowable for the given hydraulic conditions. The ambient ocean current is used to supply the required pressure head. Program URPE, Appendix A, checks to insure that the user specifies an allowable configuration.

2.2.2 Stacked Tube Hydraulic Model

Early in the development of a conceptual design for a uranium recovery system, it was recognized that pumping seawater would require a major expenditure of energy. The stacked tube bed system was developed in an effort to reduce the pumping energy expended per unit of uranium recovered. Section 2.3 documents the differences in mass transfer between the two systems. Basically, the mass transfer coefficient of a packed bed system is generally higher than the mass transfer coefficient in a tube system. However, the pumping power of the packed particle bed system is also (and considerably) higher than that of a stacked tube system having the same characteristic particle/tube dimension. Therefore, trade-offs between these factors are possible which might make an optimized tubular system preferable. The stacked tube system configuration under consideration is shown in Fig. 2.3.

Seawater flows longitudinally inside and outside the tubes. The wall thickness of the tubes is given by,

$$T_4 = 0.047882*D + 6.461 \times 10^{-4} \qquad (2.14)$$

where,

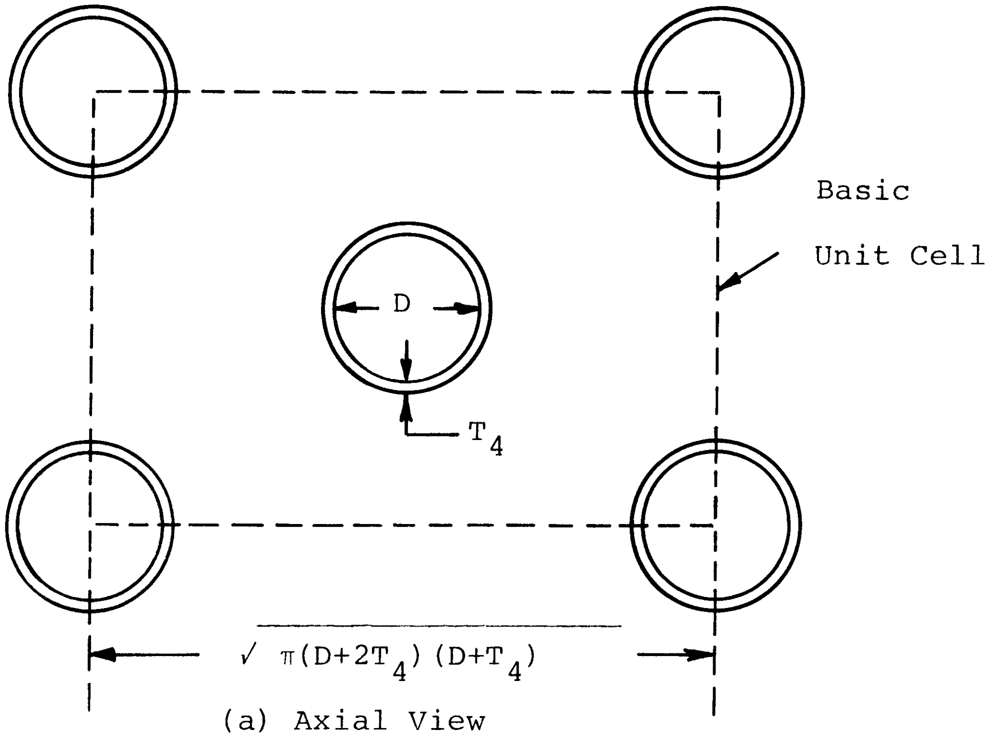
D = tube inner diameter, ft, and

T_4 = tube wall thickness, ft

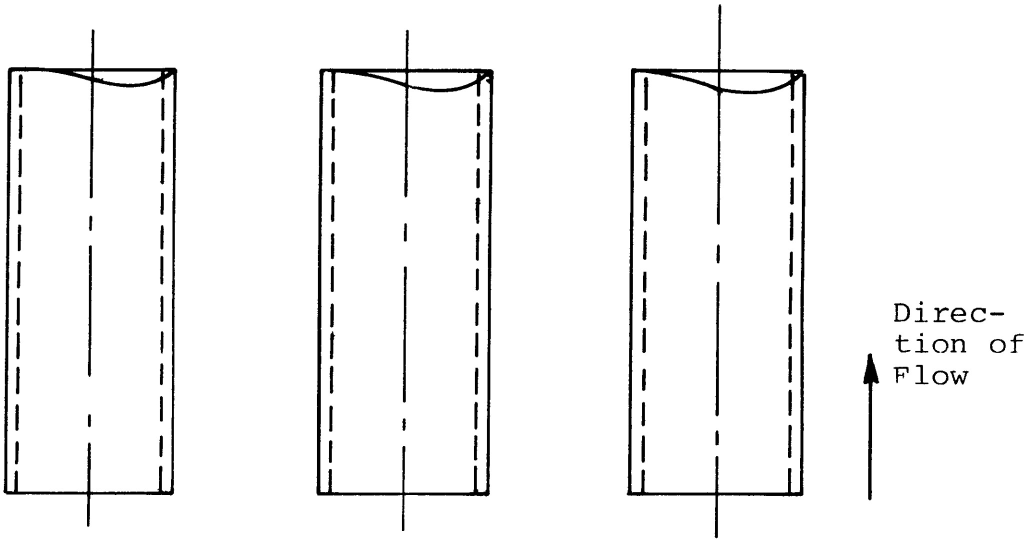
Equation 2.14 gives wall thicknesses characteristic of condenser tubing, and may be fit to data from any piping table (e.g., (Pl)).

The tubes shown in Fig. 2.3 are arranged in a square array,and spaced so that the hydraulic diameter of the flow area outside the tubes is equal to the inside diameter of the tubes. This causes the frictional pressure drop axially along the outside of the tubes to be equal to the pressure drop axially along the inside of the tubes. Thus the fluid velocities inside and outside the tubes are equal. This is done so that the outside surface of the tubes may be used as a mass transfer surface which is as effective as the inside surface of the tubes. The following paragraphs describe the bed head loss models to be used in the overall hydraulic model embodied in Eq. 2.4.

Fluid in the stacked tube bed system experiences entrance



(a) Axial View



(b) Longitudinal View

Fig. 2.3

Stacked Tube Sorber Bed Arrangement

head losses on entering the tubes from the diffuser outlet, frictional head losses in travelling the length of the tube, and finally, tube exit head losses. As in Section 2.2.1, V_2 is the superficial velocity of the fluid in the tube region; V_2 is also the fluid velocity at the exit of the diffuser, and is related to the actual fluid velocity, V_1 within the tubes by the geometry of the cross sectional flow areas. Note that for the stacked tube geometry, the ratio of the flow area in the bed region to the total flow area is equal to the void fraction for the stacked tube bed,

$$v_1 = \frac{D}{D+2*T_4} \tag{2.15}$$

where, v_1 is the stacked tube bed void fraction.

Thus,

$$V_2 = v_1 V_1 \tag{2.16}$$

Idel'Chik (I1) recommends the following for entrance head losses under low velocity conditions:

$$H_i = \frac{P_5}{2g} \left(\frac{V_2}{v_1}\right)^2 \tag{2.17}$$

where all variables are as previously noted, and P_5 is given graphically as a function of Reynolds number and void fraction (actually, the ratio of flow cross section to total cross section). The following functions have been (conservatively) fit to the graphs:

$$P_5 = 3.455 + \frac{24.44}{N} - v_1 \qquad N \leq 10 \qquad (2.18a)$$

$$P_5 = 12.032 - 2.5847 \text{ Log } N - 1.2\ v_1, \quad 10 < N < 50 \quad (2.18b)$$

$$P_5 = 3.2486 - 0.3524 \text{ Log } N - 0.7\ v_1 \qquad 50 < N \qquad (2.18c)$$

and

$$P_{5\text{minimum}} = 0.2 \qquad \text{all } N \qquad (2.18d)$$

Equation 2.18d above expresses the fact that the minimum value permitted for P_5 is 0.2. In practice, URPE calculates P_5 from Eqs. 2.18a, b or c, compares the value to 0.2, setting P_5 equal to 0.2 if the calculated value is less than 0.2.

The head loss in the tubes, expressed as a function of the superficial velocity (Eq. 2.16), is given by the standard Darcy-Weisbach formula,

$$H_t = \frac{F* \ L_9}{2g \ D} \left(\frac{V_2}{v_1}\right)^2 \qquad (2.19a)$$

with all variables defined as before, and

$$F = \frac{64}{N} \qquad \text{for } N < 2{,}000 \qquad (2.19b)$$

and

$$F^{-0.5} = 0.86 \text{ Ln}(N\ F^{0.5}) - 0.8$$

$$\text{for } N > 10{,}000 \qquad (2.19c)$$

Equation 2.19c is solved iteratively by the code. For most practical systems, the Reynolds number is very much less than 2000, and Eq.2.19c is seldom used.

The head loss at the exit of the tubes is given by Streeter (S2) as

$$H_o = \frac{k}{2g} \left(\frac{V_2}{v_1} \right)^2 \qquad (2.20)$$

where,

k is equal to 2 for laminar flow and 1 for turbulent flow

The stacked tubes are modelled as being held in place by the same type of mesh screening which holds the packed particle beds in place. The screening also acts as a pre-filter for the tubes. Equation 2.9 is used to calculate the head loss due to the screens, H_s.

Collecting tube and diffuser head loss terms, as in Sec. 2.2.1, the pumping power in megawatts is given by,

$$P = \frac{0.001356}{Q_7 * 2 * 1000 * g} R A_2 V_2^3 \left[0.05 \quad A_7^2 + 0.12(A_7 - 1)^2 + \frac{27,600}{N^2} + \frac{(2k + P_5 + F * L_9 / D)}{v_1{}^2} \right] \qquad (2.21)$$

where all variables are as previously defined, and

R = fluid density, lb/ft^3,

A_2 = bed frontal area, ft^2,

V_2 = superficial velocity in the bed, ft/sec,

Q_7 = pump electrical-to-hydraulic conversion efficiency,

A_7 = ratio of bed frontal area to intake area,

v_1 = bed void fraction,

k = 2 for laminar flow, and 1 for turbulent flow in the tubes,

P_5 = determined from Eqs. 2.18 a, b, c, d,

F = determined from Eqs. 2.19b, c,

g = dimensional constant, 32.2 $\text{ft-lb}_m/\text{lb}_f\text{-sec}^2$

Equation 2.17 is used directly in the URPE program described in Appendix A. The passive ocean interceptor system is analyzed by substituting Eqs. 2.17, 2.19, 2.20 and 2.9 into Eq. 2.5 and solving for the maximum bed thickness allowable under the given hydraulic conditions. The program checks in this manner to insure that the user specifies an allowable bed configuration.

2.3 Adsorption Kinetics Model

The introduction to Chapter Two described the selection criteria which were used to choose sorption as the reference uranium recovery process, and hydrous titanium oxide (HTO) as the preferred sorption material. The term sorption is used rather than a more descriptive term such as adsorption, absorption or ion exchange because the exact mechanism by which the HTO removes the uranium from seawater is unclear based on the information available in the open literature. Very recently, Ozawa, Murata, Yamamoto and Nakajima (O1, O2) have published a series of reports which indicate that adsorption is the mechanism by which uranium is removed from seawater. However, data published by Keen (K1) indicates an ion exchange type mechanism, although Keen expressed some doubts about his experimental conditions. With the exception of the reports by Ozawa, et al., the published information on HTO is insufficiently detailed to allow a rigorous comparison between experiments. Due to this lack of detailed information, a generalized adsorption process was selected as the basis for the reaction kinetics model used in the present analysis.

Common design practice for adsorption processes is based on assuming that the bed saturates progressively from inlet to outlet, and that until saturation is reached, very little of the species of interest escapes through the bed. This is not the case for practical uranium recovery systems. Very little of the bed can be allowed to approach saturation and continue to have seawater pumped through it because this wastes pumping power. Thus the beds have to be thin by industrial standards of practice.

Although sophisticated computer programs for analyzing bed performance are available (P1), it was felt that the increased accuracy obtainable by using them did not justify their use, considering the level of accuracy of the available data on bed adsorption properties. Therefore, a bed performance computer model was developed specifically for the present application. The model is more exact than industrial design practice, capable of analyzing thin beds, and at the same time simpler than the most exact analyses possible. The development of the model is explained in the following paragraphs.

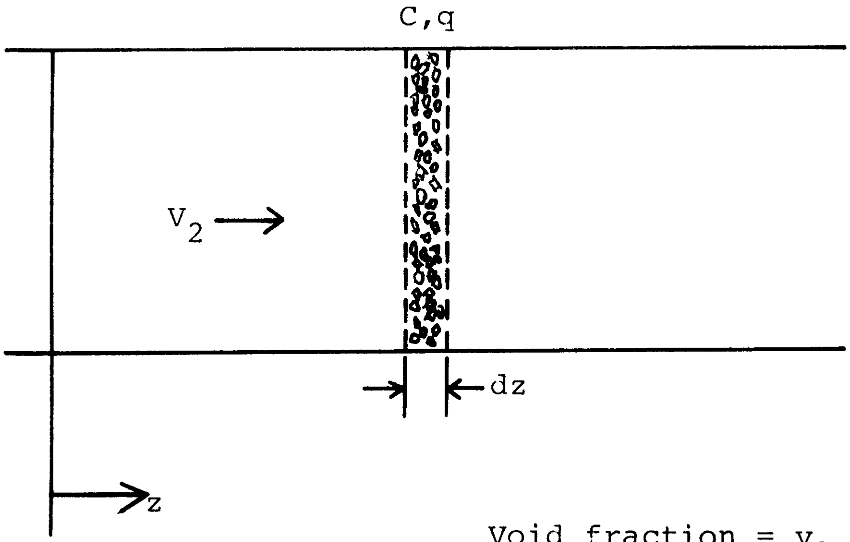
Equation 2.22 (B5) is the basic equation describing the uranium-HTO reaction,

$$Ti(OH)_4 + UO_2(CO_3)_3^{-4} \rightarrow Ti(OH)_2\,O_2 \cdot UO_2 + CO_3^{-2} + 2HCO_3^{-1} \qquad (2.22)$$

The generalized adsorption process used to model the uranium-HTO system is based on the approach used by Sherwood, Pigford and Wilke (S3), and Opler and Hiester (O3). The system which they analyzed is shown schematically in Fig. 2.4, where V is the fluid superficial velocity, v_1 is the bed void fraction and R is the bulk density of the solid. C is the concentration of uranium in the fluid at a point z and time t, and q is the concentration of uranium in the solid at the point z and time t. Equation 2.23 is derived by writing a material balance on the uranium in the solid and liquid phases in the bed element dz; thus,

$$\frac{\partial C}{\partial t} + \frac{R}{v_1}\frac{\partial q}{\partial t} + V\frac{\partial C}{\partial z} = 0 \qquad (2.23)$$

This equation in two unknowns, C and q, requires another equation and boundary conditions for solution. Following Sherwood, et al., and Opler, et al., we assume that the driving force for mass transfer is due to the difference in uranium concentration in the fluid phase and the solid phase.



Void fraction = v_1

solid phase bulk density = R_2

Fig. 2.4 Model Configuration for a Fixed Bed Adsorber (S3)

The equilibrium values of these concentrations for the adsorption process of Eq. 2.22 are given by,

$$K = \frac{(C_o - C)q}{(q_o - q)C} \tag{2.23}$$

where,

C_o = concentration of uranium in seawater,

q_o = adsorber capacity for uranium in seawater of concentration C_o,

C, q = equilibrium values of uranium in seawater and adsorber respectively,

K = equilibrium constant.

K is determined by performing equilibrium experiments.

At any instant, the uranium concentrations in the fluid and solid phases will generally be different than the values given by Eq. 2.23; i.e., the system is usually in a non-equilibrium state. The difference between the actual uranium concentrations and the equilibrium uranium concentrations is the driving force for mass transfer. Equation 2.24 relates these differences in concentration to mass transfer into the adsorber. Thus,

$$R \frac{\partial q}{\partial t} = K_4 a \left[C\left(1 - \frac{q}{q_o}\right) - \frac{(C_o - C)}{K} \frac{q}{q_o} \right] \tag{2.24}$$

where,

K_4 = the kinetic coefficient, a function of the bed mass transfer properties,

a = surface area per unit volume of bed, and other variables are as described previously. K_4 is the rate constant for the bed, and is derived from experimentally measured values of fluid side convective mass transfer and solid phase conduction.

Equations 2.23 and 2.24 have been solved in the literature for a variety of boundary conditions. Equation 2.25 (S3) is the solution for an adsorber bed with the initial uranium concentration in the solid phase equal to zero and the inlet uranium concentration in the fluid equal to C_o. Equation 2.25 gives the uranium concentration in the adsorber as a function of time and position in the bed,

$$\frac{q}{q_o} = \frac{1 - J(nT,\ n/K)}{J(n/K, nT) + [1 - J(n, nT/K)] \exp[(1-K^{-1})(n-nT)]} \tag{2.25a}$$

where,

$$n = \frac{K_4 az}{V} \text{ - dimensionless distance,} \tag{2.25b}$$

$$nT = \frac{K_4\ a\ C_o}{R\ q_o} \left(t - \frac{zv_1}{V} \right) \text{ - dimensionless time,} \tag{2.25c}$$

$$J(x,y) = 1 - e^{-y} \int_0^x e^{-s}\ I_o(2\sqrt{ys})\ ds, \tag{2.25d}$$

$$I_o(2w) = 1 + \frac{(w)^2}{(1!)^2} + \frac{(w)^4}{(2!)^2} + \frac{(w)^6}{(3!)^2} + \ldots \tag{2.25e}$$

Equation 2.25 must be integrated over the volume of the bed to find the total uranium contained in the adsorber of the bed at a given time. Equation 2.25 is integrated numerically in the URPE code. The code must evaluate Eq. 2.25 at many locations throughout the thickness of the bed. Equation 2.25d must be evaluated three times for each evaluation of Eq. 2.25a, and Eq. 2.25a must be evaluated at however many locations are required through the bed. For this project, Eq. 2.25e was substituted into Eq. 2.25d and the result integrated term by term. This gave a recursion formula for Eq. 2.25d, as follows,

$$
\begin{aligned}
J(x,y) = 1 - e^{-x-y} \Bigg[& e^{x}-1 \\
& + \frac{y}{1!}\left(-\frac{x}{1!} + 1\frac{(e^{x}-1)}{1!}\right) \\
& + \frac{y^{2}}{2!}\left(\frac{-x^{2}}{2!} + \frac{2}{2!}\left(\frac{-x}{1!} + 1\,\frac{(e^{x}-1)}{1!}\right)\right) \\
& + \frac{y^{3}}{3!}\left(\frac{-x^{3}}{3!} + \frac{3}{3!}\left(\frac{-x^{2}}{2!} + \frac{2}{2!}\left(\frac{-x}{1!} + \frac{1(e^{x}-1)}{1!}\right)\right)\right) \\
& + \ldots \\
& + \ldots \\
& + \ldots \\
& + \ldots \Bigg]
\end{aligned}
\qquad (2.26)
$$

Equation 2.26 is used to evaluate Eq. 2.25 at the required locations in the bed. However, in order to evaluate Eq. 2.25, the bed constants K and K_4 must be determined. K and K_4 were evaluated for this work by analysis of published data as explained below.

2.3.1 Analysis of Published Data

A major problem with most uranium-HTO data published to date has been a lack of work at concentrations typical of uranium in natural seawater and below, the very region in which a real uranium recovery system will have to operate. There have been a few exceptions. Keen (K1) published capacity data using natural seawater, but did not publish equilibrium data at concentrations below that of uranium in seawater. Ozawa, et al. (O1, O2), have performed some experiments at sub-seawater concentrations, but these were run starting with uranium spiked to a concentration of 10.1mg U per m^3 (9.9 ppb U in seawater), roughly three times the natural value. The only published data using natural seawater un-spiked in uranium and measured at sub-seawater concentrations, appears to be that of Ogata and Kakihana (O4). Table 2.1 shows the data of interest.

Their experiment was carried out by placing 30 grams of the HTO in a tank, adding 300 liters of natural seawater, stirring for 40 minutes, and allowing the tank to stand 6 to 12 hours. At the end of this period, the HTO and supernatant were separated, and the HTO used in another cycle. This process was repeated in 300 liter increments to the values shown in Table 2.1. The original uranium concentration in the seawater was measured at 3.6 μg per liter or 3.53 ppb U. The authors did not give the experimental precision of this

Table 2.1

Measured Uranium Adsorption in Hydrous

Titanium Oxide (04)

Adsorbent	Quantity (g)	Seawater (Liters)	$\frac{\mu g\ U}{g\ adsorbent}$	% Recovery
HTO	30	1,800	148	69
HTO	30	3,000	196	54

measurement. The concentration of uranium in the adsorbent was measured by a fluorescence technique described in the paper. The data of Table 2.1 may be used to calculate an equilibrium isotherm curve for the uranium-HTO system in the following way. First, Fig. 2.5 is plotted from the two data points of Table 2.1. These two data points are then connected by the solid straight line. This line defines the approximate cumulative uranium recovery as a function of the volume of seawater. The actual uranium recovery in the 300 liter sample taken at the 3000 liter point is actually much less than the 54% shown. By calculating the actual uranium recovery fraction in the 300 liter sample about the 3000 liter point, it is possible to calculate the equilibrium concentration of the uranium in the 300 liter sample of seawater. From the cumulative uranium recovery, it is possible to calculate the uranium concentration in the adsorber, and thus obtain a data point on the equilibrium uranium-HTO curve.

The desired uranium concentrations may be found by assuming a linear relationship between uranium adsorption and the volume of seawater processed. Fitting a straight line to the data of Fig. 2.5 gives,

$$F_1 = 0.914 - 1.25 \times 10^{-4} V \qquad (2.27)$$

where,

F_1 = uranium adsorbed ÷ uranium in total seawater,
V = volume of seawater processed (liters).

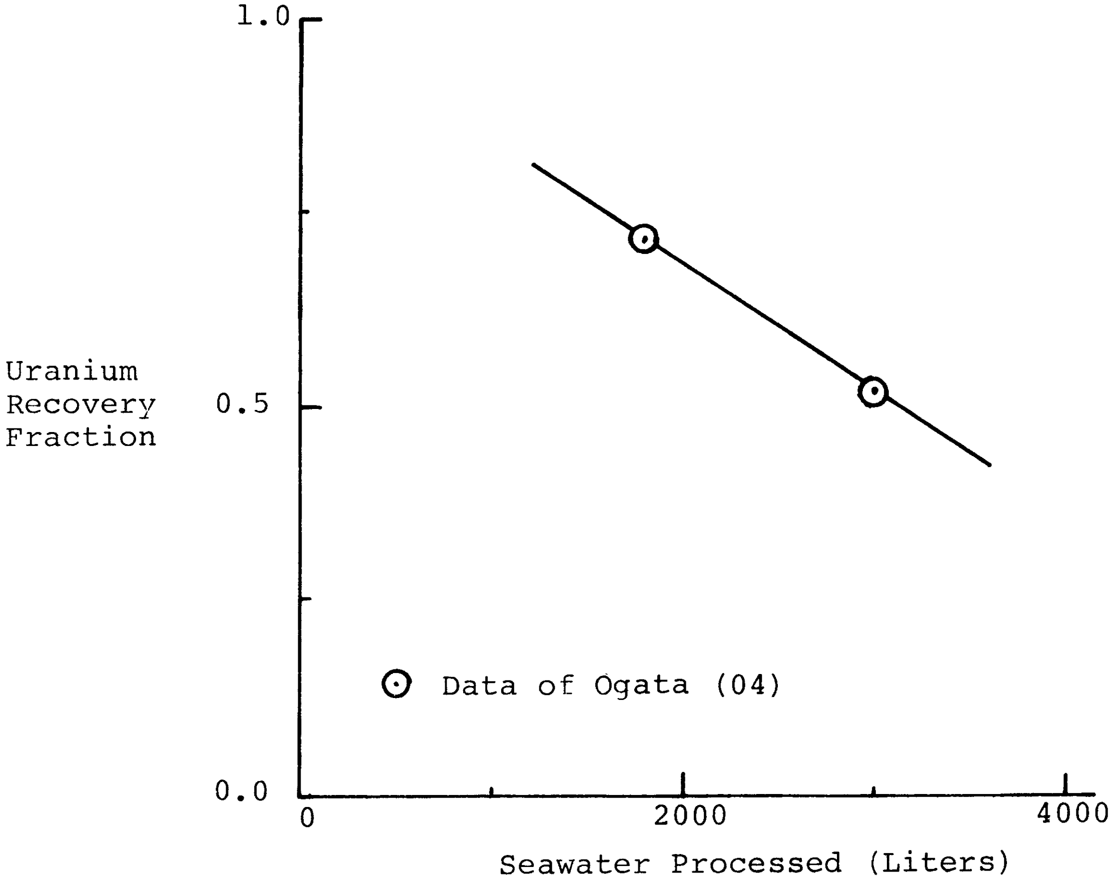


Fig. 2.5 Uranium Recovery Fraction versus Volume of Seawater Processed

The uranium concentration in the adsorber is given by multiplying Eq. 2.27 by the total amount of uranium in the seawater processed, and dividing by the weight of the adsorber. The uranium concentration in the adsorber, q, is given by,

$$q = 1.13 \times 10^{-7}\, V[0.914 - 1.25 \times 10^{-4}\, V] \qquad (2.28)$$

where,

q = lb U per lb HTO.

The fractional amount of uranium adsorbed from any volume of seawater, ΔV, is just the difference between Eq. 2.27 evaluated at V, times the uranium in volume V, and evaluated at $V + \Delta V$, times the uranium in volume $V + \Delta V$, divided by the uranium in ΔV. Evaluating Eq. 2.27 for the 300 liter samples of interest, the fractional amount of uranium removed from the seawater is,

$$F_2 = 0.952 - 2.5 \times 10^{-4}\, V \qquad (2.29a)$$

where F_2 is the fractional amount of uranium adsorbed. The amount of uranium remaining in the seawater is just $1-F_2$. Using the initial reported uranium concentration of 3.53 ppb, the final concentration of uranium in the seawater is,

$$C = 3.53\ (0.048 - 2.5 \times 10^{-4}\, V) \qquad (2.29b)$$

where

C = uranium concentration in seawater, ppb.

Table 2.2 lists the calculated uranium concentrations versus the volume of seawater processed. Fig. 2.6 shows the data plotted as an equilibrium graph. The solid line shows the equilibrium curve, Eq. 2.23, fit to the data. The equilibrium constant, K, was found to have a value of 2.28. The fact that K is larger than 1 is important because it indicates that a so-called favorable isotherm condition exists. Adsorption beds with K greater than 1 can be loaded to a higher average uranium concentration than beds with K less than 1 for the same amount of seawater processed. K greater than 1 means that the amount of adsorber, and therefore the size and cost of the bed, will be less than the size and cost of beds having K less than 1, designed to recover the same amount of uranium.

The three triangle-enclosed points shown on Fig. 2.6 are taken from the data of Ozawa (O5). They show the same trend as the calculated equilibrium curve. It is important to remember that the calculated equilibrium curve is based on experiments using natural seawater and that Ozawa's points are based on seawater enriched to 9.9 ppb U. It is important for future uranium from seawater studies that the true adsorption isotherms for the uranium-HTO system be measured.

Having determined the equilibrium constant, K, the value of the kinetic rate constant, K_4, must next be determined. Following the method of Sherwood, et al. (S3), the overall mass transfer process is analyzed in two steps,

Table 2.2

Adsorption Isotherm Data

Volume Seawater (liters)	C (ppb)	q $\frac{\text{lb U}}{\text{lb seawater}}$ $(\times 10^{-6})$
1800	1.75	149
2100	2.02	165
2400	2.28	177
2700	2.55	187
3000	2.82	194

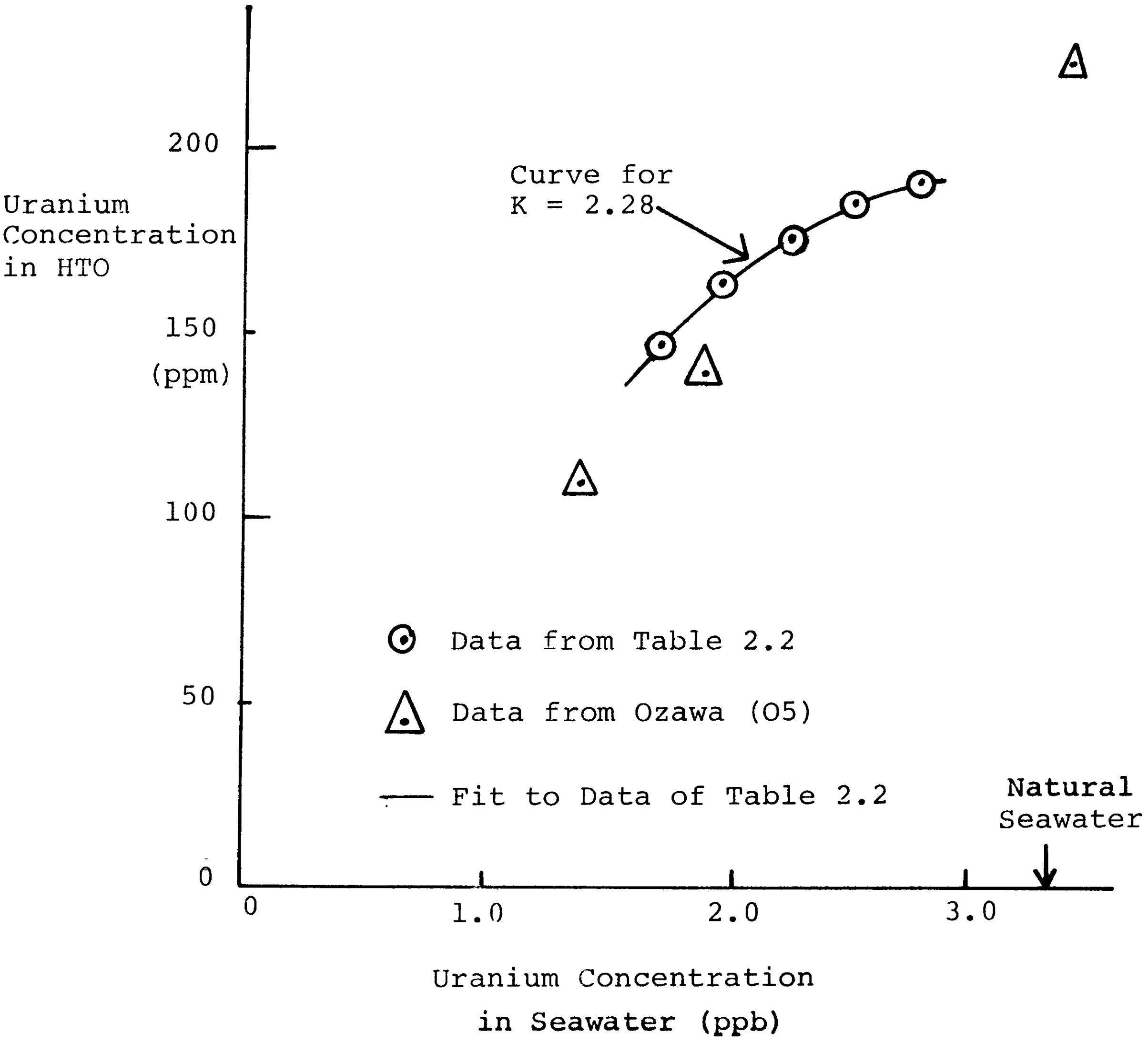


Fig. 2.6 Uranium - HTO Adsorption Isotherm

from the bulk fluid to the surface of the adsorber, and from the surface of the adsorber into its interior. First, the mass transferral from the bulk of the fluid to the solid-fluid interface is set equal to the uranium increase in the adsorber particle,

$$R \frac{\partial q}{\partial t} = K_f a(C-C_i) \qquad (2.30)$$

where

variables are as defined above, and

K_f = fluid mass transfer coefficient, ft/sec

C_i = uranium concentration at the interface, moles uranium/ft^3 seawater

Next, the uranium transferred from the surface of the particle to the interior is set equal to the uranium increase in the particle,

$$R \frac{\partial q}{\partial t} = R\ K_p a(q_i-q) \qquad (2.31)$$

where

K_p = solid phase mass transfer coefficient, ft/sec

q_i = uranium concentration in the solid at the interface, moles uranium/lb adsorber

C_i and q_i are also related through the equilibrium equation, Eq. 2.23, evaluated at the fluid-solid interface,

$$q_i = \frac{q_o\ K\ (C_i/C_o)}{1 + (K-1)(C_i/C_o)} \qquad (2.32)$$

Equating Eqs. 2.30 and 2.31, substituting Eq. 2.32 for q_i, and solving the result for C_i/C_o gives a quadratic solution,

$$\frac{C_i}{C_o} = \frac{-b \pm \sqrt{b^2 + 4(K-1)}}{2(K-1)} \tag{2.33}$$

in which,

$$b = 2 + \left(\frac{K_p R \, q_o}{K_f \, C_o} - 1 \right) K \tag{2.34}$$

Now, equating Eq. 2.30 and Eq. 2.24 gives,

$$K_4 a \left[C(1-\frac{q}{q_o}) - \frac{(C_o-C)}{K} \frac{q}{q_o} \right] = K_f \, a(C-C_i) \tag{2.35}$$

Up to the present, standard practice in using Eq. 2.35 (and, in fact, the method used by Sherwood, et al.) has been to assume a proportionate-pattern adsorption system.

A proportionate-pattern system is one in which K equals one and the ratio C/C_o equals q/q_o throughout the bed. This assumption allows Eqs. 2.33 and 2.35 to be solved simultaneously to obtain K_4. It is possible, however, to relax the requirement of proportionate-pattern behavior, K=1, and obtain a general relationship for K_4 in terms of K_f and K_p. Consider Eq. 2.35.

Equation 2.35 is true at all times and all locations in the bed, including the initial conditions just after flow has entered the bed inlet and before any buildup of uranium in the adsorber has occurred. For this condition, C is equal to C_o and q is equal to q_o. Substituting these conditions into

Eq. 2.35, together with Eq. 2.33 for C_i/C_o, gives the expression for the kinetic rate constant K_4 in terms of bed parameters (with the negative root of the solution deleted),

$$K_4 = K_f \left[1 - \frac{-b + \sqrt{b^2 + 4(K-1)}}{2(K-1)} \right] \qquad (2.36)$$

where all terms are as previously defined, and

$$b = 2 + \left(\frac{K_p \; R \; q_o}{K_f \; C_o} - 1 \right) K \qquad (2.37)$$

The fluid side and solid side mass transfer coefficients must be known in order to calculate the overall kinetic rate constant. The fluid side mass transfer coefficients are discussed in the sections which follow. For the solid side mass transfer coefficient, Sherwood, et al. (S3), recommend the use of:

$$K_p = \frac{10 \; E}{D(1 - v_1)} \qquad (2.38)$$

$$a = \frac{6\left(1-v_1\right)}{D} \qquad (2.39)$$

where,

E = diffusion coefficient inside the particle, ft^2/sec

and all other terms are as described previously.

The diffusion coefficient for uranium in HTO is an artificial aspect of the overall adsorption model. If data on the pore size of the HTO particles were available, a better model, based on uranium conduction in the fluid-filled pores, could be constructed. No concurrent bed kinetic data and particle pore size data have been published to date. In fact, the diffusion coefficient for uranium in HTO has not yet been published in the open literature. However, it can be estimated from the data of Keen (K1).

In Keen's experiment, particles of HTO were exposed to a continuously replenished natural seawater environment. Assuming the surface of the particles was in equilibrium with the concentration of the uranium in seawater, Eq. 2.31 may be integrated with respect to time, to give:

$$q = q_i(1 - e^{-K_p at}) \qquad (2.40)$$

Early in the experiment, for small t, Eq. 2.40 may be simplified to:

$$q = q_i \; K_p at \qquad (2.41)$$

Substituting Eqs. 2.38 and 2.39 into Eq. 2.41 and solving for E gives,

$$E = \frac{q}{q_i} \; \frac{D^2}{60t} \qquad (2.42)$$

Table 2.3 lists the data taken from Keen's experiment, and the diffusivity calculated using Eq. 2.42. The calculated diffusivity of 5.2 x 10^{-15} ft^2/sec is much smaller than the diffusivity of most diffusing species (P1), and supports Keen's observation that only very thin layers of adsorber are active

Table 2.3

Uranium Diffusivity Data (Kl)

Particle diameter = 0.3mm = 9.84×10^{-4} ft

Equilibrium capacity = 276×10^{-6} lb U/lb HTO

Uptake at 10 days = 77×10^{-6} lb U/lb HTO

Calculated diffusivity (our analysis)

= 5.2×10^{-15} ft^2/sec

in the uranium recovery process. An alternative means of estimating the uranium-HTO diffusivity was also utilized.

Figure 2.7 shows uranium uptake data from a different experiment of Keen's (K1) for HTO in a packed bed test system. Table 2.4 lists the data available from Keen's paper as well as the data which was estimated in order to permit further analysis. A curve was fit to Keen's data using Eq. 2.25, the data of Table 2.4, and treating K_4, the kinetic rate constant, as a free parameter. A least squares fit of the data was obtained with $K_4 = 1.0 \times 10^{-5}$ ft/sec. The uranium-HTO diffusivity was then calculated using Eq. 2.36, the data of Table 2.4, and $K_4 = 1.0 \times 10^{-5}$ ft/sec. The calculated diffusivity, $E = 4.73 \times 10^{-15}$ ft^2/sec, is within 10% of the diffusivity estimated using Eq. 2.42, $E = 5.2 \times 10^{-15}$ ft^2/sec. Note that the techniques used to arrive at these two numbers are totally separate; it is therefore encouraging to see how closely the two numbers agree.

In summary: data, especially kinetic data, on the uranium-HTO system in the published literature is sparse. However, using the information available, the uranium-HTO equilibrium constant and uranium-HTO diffusivity have been estimated. Additionally, a general expression for the bed reaction rate constant as a function of bed physical parameters and operating conditions has been developed. As more data on uranium-HTO becomes available, it will be necessary to update the values of certain parameters (K, E, etc.), or even perhaps

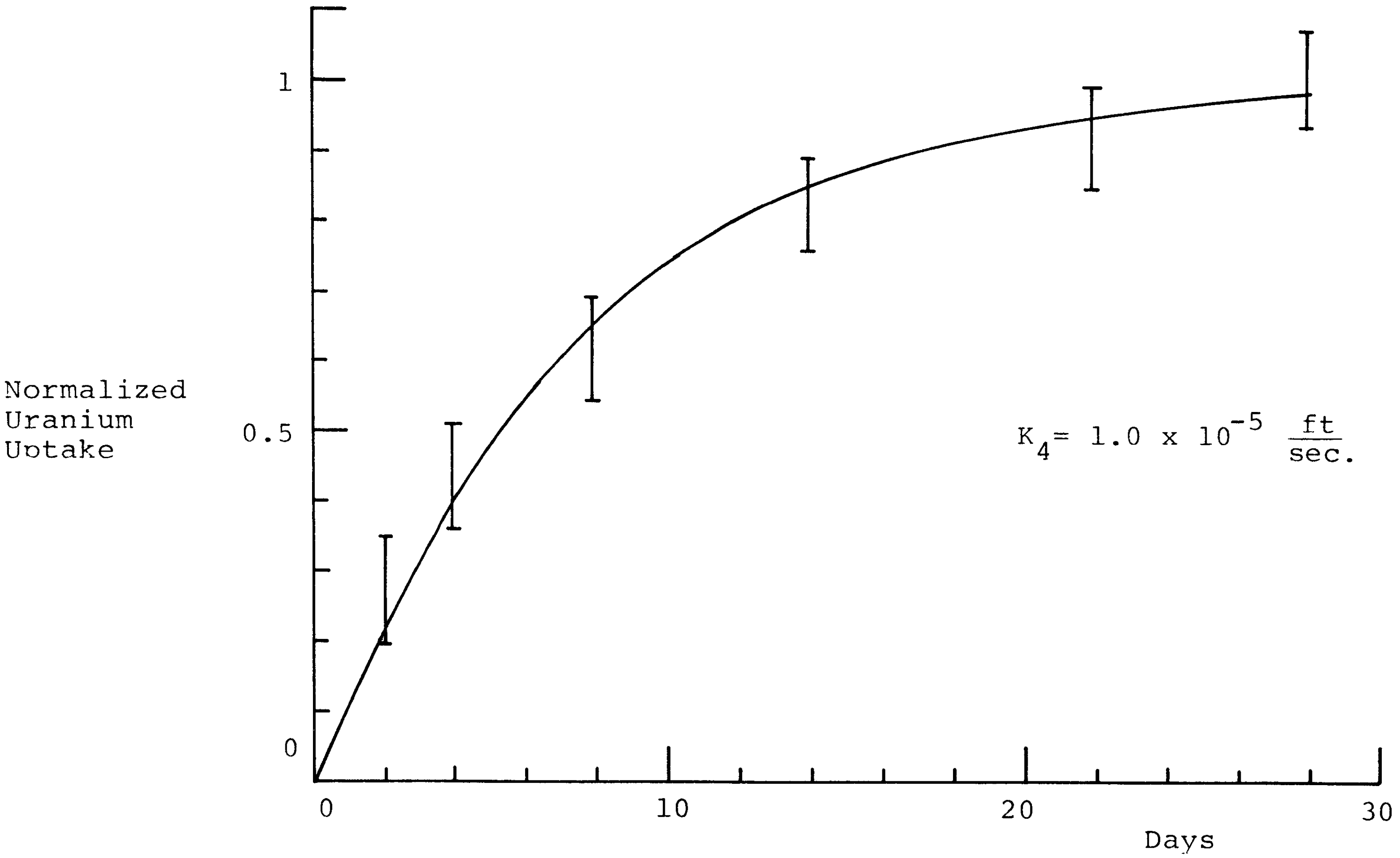


Fig. 2.7. Curve Fit of Data (Kl) to Determine Reaction Rate Constant, K_4

Table 2.4

Bed Properties Used to Determine the Reaction Rate Constant, K_4

A. Bed Data from Keen (K1):

Superficial fluid velocity, V_2 = 0.01378 ft/sec
Particle diameter, D = 0.000377 ft
Bed thickness, L_9 = 0.0833 ft
Adsorber uranium capacity, Q_9 = 196×10^{-6} lb U/lb HTO

B. Estimated Data:

Concentration of uranium in seawater, C_o = 3.34 ppb
Equilibrium constant, K = 2.28
Dry particle density, R_2 = 93.6 lb/ft^3
Bed void fraction, v_1 = 0.40

---

to change the model entirely. This may be particularly true for the internal diffusion model, which could be replaced by a pore diffusion model (P1) as soon as kinetic data for an adsorber with measured pore size is available. Until then, the kinetic calculations in the URPE code are based on using Eqs. 2.25 and 2.36, together with the fluid phase and solid phase mass transfer coefficients discussed in the sections which follow.

2.3.2 Packed Particle Bed Adsorption Kinetics Model

The fluid phase mass transfer coefficient, solid phase mass transfer coefficient, and certain bulk bed properties must be known in order to use Eqs. 2.25 and 2.36 to calculate adsorption bed kinetic behavior. The particle bed properties are described in the following paragraphs.

A composite sorber particle having an outer HTO coating on an inert core was selected for the design because of the low diffusivity of uranium in HTO. Using solid HTO particles would result in a partially unused and therefore more costly HTO inventory. Figure 2.8 shows the composite particle. The outer particle diameter is D and the coating thickness is T_3. Selection of an optimum particle size and coating thickness is based on an overall system optimization as discussed in Chapter Three.

The void fraction of the packed particle bed is designated v_1; void fraction is used as a primary variable by the

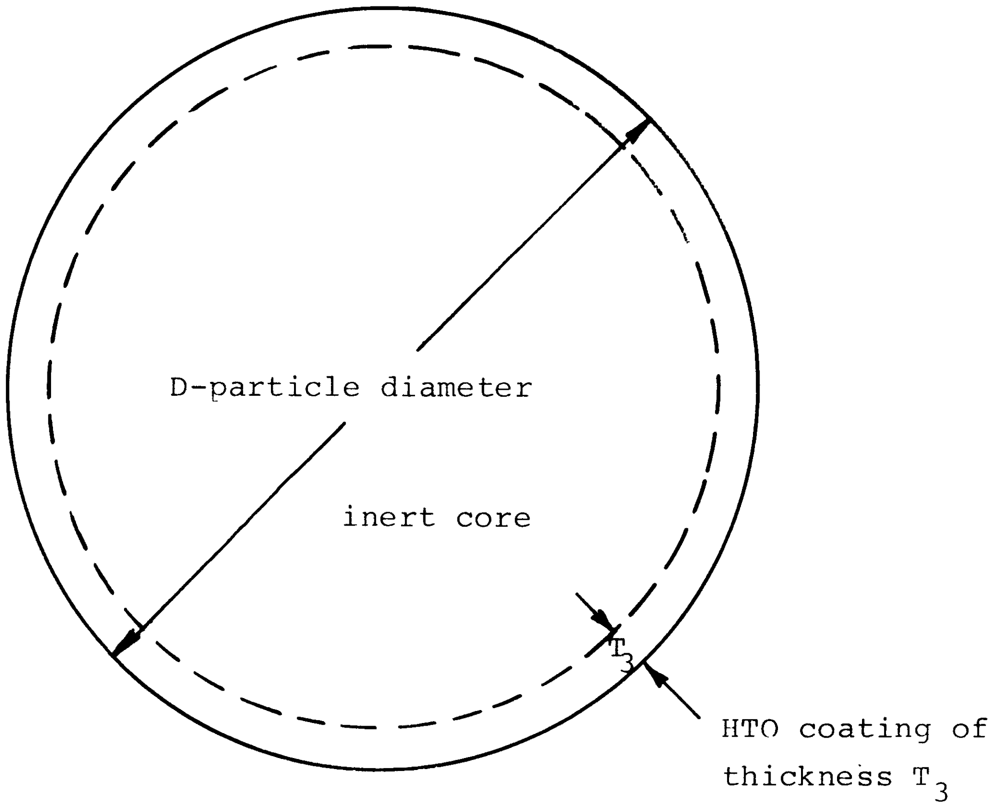


Fig. 2.8

Composite Adsorber Particle

simulation program. Typical void fractions in randomly packed particle beds range from 0.4 to 0.6. The surface area per unit volume of bed is given by Eq. 2.39. The ratio of the volume of active adsorber to particle volume is given by,

$$v_2 = 1 - \left(1 - \frac{2T_3}{D}\right)^3 \qquad (2.43)$$

where,

v_2 = the ratio of active volume to total particle volume

Sherwood, et al. (S3), recommend the form shown in Eq. 2.44 below for a fluid mass transfer coefficient, and supply the data necessary to fit the curve to a range of Reynolds numbers from 0.1 to 10,000. Equation 2.44, as presented here, represents data over a range of Reynolds numbers from 0.1 to 1,000.

$$K_f = 2.09\ V\ N^{-0.585}\ S^{-2/3} \qquad (2.44)$$

where,

V = fluid superficial velocity in the bed, ft/sec

N = bed Reynolds number

$$N = \frac{R\ V\ D}{u} \qquad (2.45)$$

u = fluid viscosity, ft^2/hr

S = Schmidt number

$$S = \frac{u}{E_f} \qquad (2.46)$$

E_f = molecular diffusion coefficient for the uranium species in water, ft^2/sec

Based on several authors' experiments, Bettinali (B1) recommends a diffusion coefficient of between 1.3 and 3×10^{-6} cm^2/sec. For a value of 2.2×10^{-6} cm^2/sec (8.52×10^{-6} ft^2/hr) and a viscosity equal to $0.0599 ft^2/hr$ (typical of 40°F seawater (S2))the Schmidt number equals 7030. This value of the Schmidt number is used throughout the work which follows because water temperature was not treated as a primary variable. Although it is generally accepted that the seawater temperature should be as high as possible to improve the adsorption rate (B5, S1), no further work was done to specify a site, except to recommend operating in tropical currents.

Equation 2.38 gives the solid phase mass diffusion coefficient for particles composed totally of active adsorber. The particles used in this design are composed of inert cores with an active adsorber coating. The diffusion model on which Eq. 2.38 is based (S3) assumes that the interior of the particle has a flat uranium concentration distribution; i.e., the particle interior uranium concentration is everywhere equal. Therefore, in the coated particle analysis, D was replaced by $2T_3$, twice the distance from the coated adsorbing surface to a zero mass flux boundary (e.g., the inner surface of the active adsorber coating). Equation 2.38 becomes,

$$K_p = \frac{10\ E}{2T_3(1-v_1)} \tag{2.47}$$

where all variables are as previously defined.

Equations 2.25, 2.44, 2.45, 2.46 and 2.47 form the model used in the simulation program, URPE, to calculate the adsorption of uranium from seawater. The user should be aware that the bulk density of adsorber (as used for example in Eq. 2.22c) is the bulk density of active adsorber material and does not include the inert material of the particle core. Thus the bulk density (of active adsorber) to be used in Eq. 2.25c is given by,

$$R = (1-v_1)v_2 \; R_2 \qquad (2.48)$$

where,

R_2 = is the wet active adsorber density (lb/ft^3).

Additionally, the liquid phase and solid phase concentrations of uranium used in Eq. 2.25, C (moles uranium/volume seawater) and q (moles uranium/lb adsorber), are written in the alternative units: C*(lb U/lb seawater) and q*(lb U/lb active adsorber) in the URPE code. In other words, in the code, C is replaced by C* times the density of seawater. Because C's and q's always appear in ratios, the conversion factor from moles of uranium to pounds of uranium (in both) cancels.

The next section of this work details the development of a similar model for stacked tube adsorption beds.

2.3.3 Stacked Tube Adsorption Kinetics Model

Figure 2.9 shows the cross section of an adsorber tube. The inner diameter of the tube is D; the total wall thickness

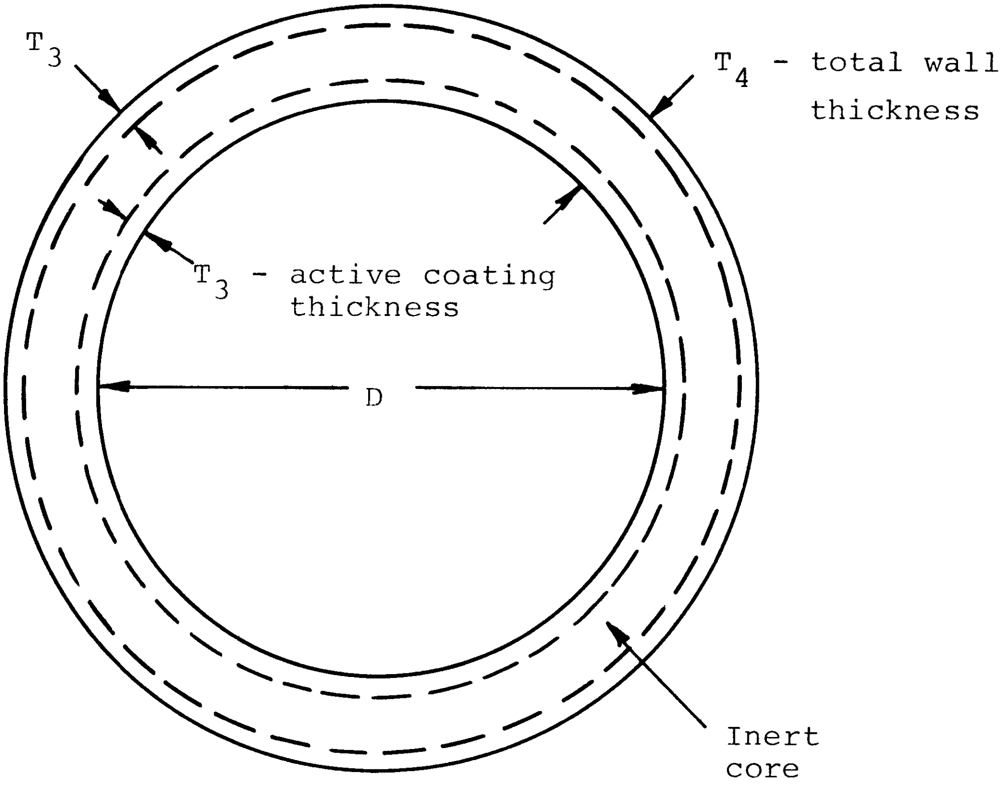


Fig. 2.9

Composite Stacked Tube Adsorber

is T_4 and the active adsorber coating thickness is T_3. As discussed in Sec. 2.2, seawater flows axially inside and outside the tubes. Thus, both the inner and outer tube walls are adsorbing surfaces. An active coating on a solid tube was selected for the design, for the reasons discussed in Sec. 2.3.2. Selection of an optimum particle size and coating thickness is based on an overall system optimization as discussed in Chapter Three.

As described in Sec. 2.2.2, the void fraction for a stacked tube bed is given by Eq. 2.15. The surface area per unit volume is given by,

$$V_3 = \frac{3D + 2\,T_4}{(D + 2T_4)(D + T_4)} \qquad (2.49)$$

where,

V_3 = surface area per unit volume $(\frac{1}{ft})$

and other variables are as previously defined.

The ratio of the volume of active adsorber material to the volume of tube wall material is given by

$$V_2 = \frac{T_3(6D + 4T_4 + 3T_3)}{4T_4\,(D + T_4)} \qquad (2.50)$$

Sherwood, et al. (S3), recommend the following equation for turbulent flow in tubes,

$$K_f = 0.0149\ V\ N^{-0.12}\ S^{-2/3} \qquad (2.51)$$

where,

V = the cross section average velocity in the tube, ft/sec

In order to express all velocities in the code as superficial velocities, V is replaced by the bed superficial velocity, V_2, divided by the void fraction.

Sherwood, et al. (S3), recommend the Chilton-Colburn analogy for a mass transfer coefficient in the laminar flow regime. Thus, for laminar flow,

$$K_f = \frac{8\ V\ S^{-2/3}}{N} \qquad (2.52)$$

The same solid phase diffusion model (Eq. 2.47) can be used for coated tubes as was used for coated particles. Similarly, by virtue of the definitions employed for v_1 and v_2, the expression for bulk adsorber density, Eq. 2.48, also applies for stacked tubes. Finally, the change of units for uranium concentration in the fluid and solid, as described in Sec. 2.3.2, also applies in the stacked tube model.

2.4 Chemical Consumption Model

The uranium-HTO recovery process requires that the uranium adsorbed into the HTO be desorbed for ultimate recovery. Ammonium carbonate was selected as the eluant because it can be stripped from the eluted solution by heating, and recycled for further use. This allows a large savings in chemical consumable costs. However, some ammonium carbonate is unavoidably lost in the bed and the ammonium carbonate stripper systems.

Ammonium carbonate is lost in the bed because some of it is retained in the bed even after fresh water washes are employed to remove it. Ammonium carbonate is also lost due to the design characteristics of the stripper system.

Data on the chemical consumption of the uranium-HTO process are very sparse. The most detailed quantitative data available seems to be that of Harrington, et al. (H1). They report that after a four-bed-volume wash with fresh water, the HTO in the bed retained 0.08 lb of ammonia and 0.04 lb of carbon dioxide per pound of titanium. They reference a Batelle Memorial Institute Report (B8) for information on stripper losses.

The Batelle report indicates that ammonia is lost in the stripper due to the formation of a stable ammonia solution at a concentration of 0.02 M. This ammonia is subsequently lost to the plant. Carbon dioxide is lost through bleed-off in the stripper tower. The carbon dioxide losses amount to 6% of the carbon dioxide entering the tower in the eluting solution.

Using the above data the ammonia lost in the adsorber bed per hour is just the total amount of HTO in the adsorber bed times the amount of ammonia adsorbed per unit weight of HTO, divided by the total duration of a load-elution cycle. The total duration of a wash-elution cycle is given by

$$V_8 = 4.64\ L_9 + 8 \tag{2.53}$$

where,

V_8 = wash-elution cycle time (hr)

L_9 = bed thickness (ft)

and 4.64 is taken from the data of Harrington, et al., based on an optimum eluting time, and 8 is taken as an arbitrary additional dead time to allow for process turnaround. The bed loading time (V_9) is user specified as a primary input variable in the URPE code.

The weight of active HTO in the bed is just the bed frontal area (A_2) times the bed thickness (L_9) and bulk HTO density. Bulk HTO density is defined as the weight of HTO divided by the total bed volume; or, expressed in terms of active adsorber density (R_2), bed void fraction (v_1) and active-to-total adsorber volume ratio (v_2),

$$\text{Bulk HTO density} = R_2(1-v_1)v_2 \qquad (2.54)$$

The rate of ammonia loss in the bed is,

$$\begin{array}{l}\text{Ammonia Lost}\\ \text{in Bed}\end{array} = \frac{0.08(0.4133)R_2(1-v_1)v_2A_2L_9}{V_8 + V_9} \left[\frac{\text{lb NH}_3}{\text{hr}}\right] \qquad (2.55)$$

and the rate of carbon dioxide lost in the bed is,

$$\begin{array}{l}\text{Carbon Dioxide}\\ \text{Lost in Bed}\end{array} = \frac{0.04(0.4133)R_2(1-v_1)v_2A_2L_9}{V_8 + V_9} \left[\frac{\text{lb CO}_2}{\text{hr}}\right] \qquad (2.56)$$

where,

0.4133 = the weight of titanium per unit weight of HTO; this converts lb/lb Ti to lb/lb HTO.

The rate of ammonia lost in the stripper is just the adsorber bed volume ($A_2 \times L_9$), times the number of bed volumes of ammonium carbonate used for the elution (here a value of 4 is assumed following the advice of Ref. (H1)), times the concentration of the ammonia lost in the stripper (0.02 M NH_3 = 2.12×10^{-2} lb NH_3/ft^3 solution), divided by the total cycle time ($V_8 + V_9$),

$$\begin{matrix}\text{Ammonia Lost}\\ \text{in Stripper}\end{matrix} = 4(2.12 \times 10^{-2}) \frac{A_2 L_9}{V_8 + V_9} \left[\frac{\text{lb } NH_3}{\text{hr}}\right] \qquad (2.57)$$

The total rate of ammonia lost in pounds per hour (C_6) is equal to the sum of Eqs. 2.55 and 2.57,

$$C_6 = \frac{A_2 L_9}{V_3 + V_9} [0.08(0.4133) R_2 (1 - v_1) v_2 + 4(2.12 \times 10^{-2})] \left[\frac{\text{lb } NH_3}{\text{hr}}\right] \qquad (2.58)$$

The amount of carbon dioxide lost in the stripper is more difficult to derive. The amount of carbon dioxide lost in the stripper is equal to 6% of the carbon dioxide which enters the stripper. The solution which enters the stripper has already been depleted in carbon dioxide due to the absorption of carbon dioxide in the bed material. Thus the amount of carbon dioxide lost in the stripper is given by,

$$\left[\begin{matrix}CO_2 \text{ Lost}\\ \text{in Stripper}\end{matrix}\right] = 0.06 \left[\begin{matrix}CO_2 \text{ Entering} & - & CO_2 \text{ Lost}\\ \text{Beds} & & \text{in Beds}\end{matrix}\right] \qquad (2.59)$$

$$\left[\begin{matrix}CO_2 \text{ Lost}\\ \text{in Stripper}\end{matrix}\right] = 0.06 \left[\begin{matrix}CO_2 \text{ Entering}\\ \text{Beds}\end{matrix}\right] - 0.06 \left[\begin{matrix}CO_2 \text{ Lost}\\ \text{in Beds}\end{matrix}\right] \qquad (2.60)$$

The total carbon dioxide lost is the sum of the losses in the bed and in the stripper,

$$\begin{bmatrix}\text{Total } CO_2\\ \text{Losses}\end{bmatrix} = \begin{bmatrix}CO_2 \text{ Lost}\\ \text{in Beds}\end{bmatrix} + \begin{bmatrix}CO_2 \text{ Lost}\\ \text{in Stripper}\end{bmatrix} \qquad (2.61)$$

Substituting Eq. 2.60 into Eq. 2.61 and collecting terms,

$$\begin{bmatrix}\text{Total } CO_2\\ \text{Losses}\end{bmatrix} = 0.94 \begin{bmatrix}CO_2 \text{ Lost}\\ \text{in Beds}\end{bmatrix} + 0.06 \begin{bmatrix}CO_2 \text{ Entering}\\ \text{Beds}\end{bmatrix} (2.62)$$

The cycle average rate of carbon dioxide entering the beds is just the concentration of the ammonium carbonate solution (0.1M = 0.274 lb CO_2/ft^3 solution), times the volume of the beds ($A_2{*}L_9$), times the number of volumes (4), divided by the total cycle time ($V_8 + V_9$). Substituting this and Eq. 2.56 into Eq. 2.62 gives the total carbon dioxide loss rate C_7(lb CO_2/hr),

$$C_7 = \frac{A_2L_9}{V_8+V_9}\ [0.94(0.04)0.4133R_2(1-v_1)v_2+0.06(4)0.274] \left[\frac{\text{lb } CO_2}{\text{hr}}\right]$$

(2.63)

Equations 2.58 and 2.63 constitute the complete chemical loss rate model. Note that due to the use of values of v_1 and v_2 which are properly defined for both particle bed and stacked tube systems, the same basic equations can be used to analyze both systems. Equation 2.63 is based on using a 0.1 M ammonium carbonate eluting solution, as the data of Ogata (O4) indicate. Harrington, et al. (H1), and Binney (B5), based their analyses on a 1M solution. Table 2.5 compares the results of Eq. 2.58 and 2.63 (adjusted to a 1M ammonium carbonate solution) with the analyses of Harrington and Binney; as the table shows, our results are compatible with theirs. Chapter Three discusses the effect on total product cost of varying the concentration of the eluting solution.

The sections which follow describe the economic models associated with the performance models described in the previous sections.

2.5 Overall Economics Model

Sections 2.2 through 2.4 describe the models which are used to calculate the engineering performance of the uranium recovery systems described in Section 2.1. The purpose of this section is to detail the economic models which are used in conjunction with the performance models to calculate uranium production costs.

The cost of producing uranium is calculated by using a levelized cost model of the form (D1),

$$U_2 = \frac{H_1 \sum [\text{Capital Cost}] + [\text{Annualized Operation \& Maintenance Costs}]}{M_8\ 2204} \quad \left[\frac{\$}{\text{lb } U_3O_8}\right] \qquad (2.64)$$

where,

U_2 = levelized cost of U_3O_8 production (\$/lb U_3O_8),

H_1 = annual fixed charge rate (%/year ÷ 100),

Table 2.5

Comparison of Uranium Recovery System Chemical Consumption Models

	ORNL (H1)	Present Work
A[*]		
lb NH_3/lb U	310	267
lb CO_2/lb U	830	1045
	Exxon (B5)	
B[*]		
lb NH_3/lb U	611	513
lb CO_2/lb U	628	615

[*] Where A is the ORNL design case and B is the Exxon design case.

M_8 = actual annual U_3O_8 production rate (MT U_3O_8/year),
(rated capacity times capacity factor)
2204 = number of lb/MT

"Capital Cost" is the summation of all major capital cost components, present-worthed to the start of plant operation. Operation and maintenance costs include all consumable and service charges. Consumables would include water, chemicals, HTO make-up, etc. Service charges would include shipping charges for carrying consumables to and from the plant, operator salaries and the like.

The performance and economic models used in this work are based on a delivered plant capacity of M_8 metric tonnes of U_3O_8 per year. Since plants are not routinely capable of continuously operating at 100% of rated capacity year in-year out, actual plant performance is taken into account by use of a plant capacity factor. The plant capacity factor, F_9, is defined as the total number of equivalent full-capacity operating hours in a year divided by the number of hours in a year. In the work which follows, all components are sized on the basis of rated capacity, M_8/F_9: the actual output of the plant is always M_8 MT U_3O_8, however.

The annual fixed charge rate, H_1, apportions the capital cost of the plant as a uniform annual payment, which accounts for taxes, stock dividends, bond payments and depreciation charges. For private ownership, and assuming no salvage value, H_1 is given by,

$$H_1 = \frac{\frac{1}{1-\tau}}{\sum_m \frac{1}{(1+x)^m}} - \frac{\tau d'}{1-\tau} + \pi \qquad (2.65)$$

where

π = annual local taxes and insurance as a fraction of capital cost,

m = life of the facility (yr),

d' = factor for straight line depreciation = $\frac{1}{m}$

τ = average tax rate

x = discount factor

Assuming state taxes, τ_s, are deductible from the federal income tax, τ_f, the average tax rate is given by

$$\tau = \tau_f(1- \tau_s) + \tau_s \qquad (2.66)$$

The discount factor, x, is given by,

$$x = f_b r_b (1-\tau) + f_s r_s \qquad (2.67)$$

where

f_b, f_s = the fraction of borrowed capital which comes from bonds and stocks respectively,

r_b, r_s = the rate of return on bonds and stocks respectively

For public ownership, and assuming no salvage value, the fixed charge rate is just the rate of return on bonds. Table 2.6

Table 2.6

Typical Values for the Economic Parameters which Determine the Fixed Charge Rate H_1

Parameter	Private	Public
A. Assumed Values:		
τ_f	0.48	0
τ_s	0.07	0
r_b	0.12 yr^{-1}	0.10 yr^{-1}
r_s	0.18 yr^{-1}	0
m	30 yrs	30 yrs
π	0.03	0
f_s	0.5	0
f_b	0.5	1
B. Calculated Results:		
d'	0.0333 yr^{-1}	0.0333 yr^{-1}
τ	0.5164	0
X	0.119 yr^{-1}	0.10 yr^{-1}
H_1	0.2493 yr^{-1}	0.10 yr^{-1}

shows the assumed values for the various economic parameters and the resulting fixed charge rates. It is clear that the method of financing the project will have a strong effect on product cost.

2.5.1 Pump Capital Cost Model

Following the form of the overall economic model developed in the previous section, the contribution of the capital cost of the pumps and motors, B_9(\$/lb U_3O_8), to the uranium production cost is calculated by,

$$B_9 = \frac{H_1 \; W_9 \; P \; Q_7 \; 1000 \; (1.1)}{M_8 \; 2204} \left[\frac{\$}{\text{lb } U_3O_8}\right] \qquad (2.68)$$

where,

W_9 = the unit cost of the pumps (\$/Kw-shaft),

P = total pumping power (Mw(e)),as derived in Section 2.2,

Q_7 = Mw-shaft/Mw(e) - pumping efficiency

1.1 = factor to include 10% spares to allow for breakdown or maintenance,

and 1000 is the conversion from Mw to kw, with all other variables as previously defined. After an extensive survey of pump availability, Broussard (B2) identified a minimum pump plus motor cost of 134\$/Kw-shaft (1978 \$) for a pump rated at 672 Kw-shaft. Since W_9 is a variable in the code, the user may input whatever pump unit cost is desired.

2.5.2 Bed Capital Cost Model

The total cost of the adsorber bed is made up of two parts, a capital cost component which is treated as an initial titanium inventory, and a bed attrition loss cost component which is treated as a consumable item. This section details the initial titanium inventory capital cost component for use in the overall economic model developed in Section 2.5.

The capital cost of the HTO inventory of the adsorber bed is found by multiplying the total bed volume ($A_2 * L_9$) times the bulk density of active adsorber ($R_2(1-v_1)v_2$) times the in-place cost of the active adsorber, W_6($/lb). The contribution of the capital cost of the initial HTO inventory to total cost is,

$$\begin{array}{c}\text{Titanium}\\\text{Inventory}\end{array} = \frac{H_1 \ A_2 L_9 (1-v_1) v_2 \ R_2 W_6}{M_8 \ 2204} \left[\frac{\$}{\text{lb } U_3O_8}\right] \qquad (2.69)$$

where,

W_6 = installed bed cost ($/lb HTO).

W_6 is an input variable in the URPE program. The unit cost of the bed, W_6 ($/lb HTO), should reflect the cost of purchasing, preparing and fabricating the adsorber bed. The market price of TiO_2 is $0.41 per pound (C1), or $0.28 per pound HTO equivalent. A price of $0.80 per pound HTO is used to take into account purchasing, preparation and fabrication costs. This mark-up from the cost of TiO_2 to installed cost of HTO is similar to the ratio used by Harrington, et al. (H1). In our case it includes the cost of the inert substrate. The bed material is held in place by a wire reinforced mesh screen. Typical prices for these screens are 0.25 $\$/ft^2$ (M1). This is doubled to approximate total installed cost. The contribution of the capital cost of the bed structure to total cost is,

$$\text{Bed Structure} = \frac{H_1\ A_2\ 0.5}{M_8\ 2204} \tag{2.70}$$

The total allocated bed cost is the sum of Eqs. 2.69 and 2.70,

$$B_8 = \frac{H_1 A_2}{M_8\ 2204}\left[L_9 (1-v_1)\, v_2 R_2\ W_6 + 0.5\right] \left[\frac{\$}{\text{lb } U_3O_8}\right] \tag{2.71}$$

where,

B_8 = allocated bed capital cost, $/lb U_3O_8

A_2, the total bed frontal area, is found by dividing the desired uranium production rate, M_9, by the average uranium production rate per unit of bed frontal area. The desired uranium production rate is given by,

$$M_9 = \frac{M_8 (0.848)\, 2204}{8766\ F_9} \left[\frac{\text{lb U}}{\text{hr}}\right] \tag{2.72}$$

where 0.848 is used to convert from lb U_3O_8 to lb uranium, 2204 is lb/MT, 8766 is the hrs/yr and F_9 is the plant capacity factor.

The average uranium production rate per unit of bed frontal area is found by multiplying the total amount of HTO per square foot in the bed by its calculated average fraction of uranium uptake, Q from Eq. 2.25, and by its uranium capacity, Q_9(lb U/lb HTO); dividing this by the total cycle time, $V_8 + V_9$, gives the average production rate. The required bed area A_2 is given by dividing this into M_9,

$$A_2 = \frac{M_9 (V_8 + V_9)}{Q\ Q_9\ R_2 (1-v_1) v_2\ L_9} \left[ft^2 \right] \qquad (2.73)$$

2.5.3 Balance of Plant Cost Model

The balance of plant costs are composed of two parts, the chemical system, and the moored platform. The capital cost of the bed structure, handling equipment, auxiliary systems, etc.,is accounted for by the use of a Lang factor. The capital cost of the moored platforms is handled separately.

A Lang factor, H_2, is an empirically determined number which reflects the cumulative experience of the chemical engineering industry in relating the total capital cost of a plant to the capital cost of the major components in the plant. For the uranium from seawater plant, the major capital cost items are the capital cost of the adsorber beds and the capital cost of the pumps and motors.

Table 2.7 shows the various Lang factors, from Backhurst and Harber (B7), which were used for this analysis. The

Table 2.7

Uranium from Seawater

Lang Factors

A. **Process Requirements**	Factor
Fluids Processing	0.45
Minimal Instrumentation	0.05
Outdoor Structure	0.05
New Plant	1.00
	A = 1.55
B. **Plant Structure**	
Simple Engineering	0.20
Large Size	0.05
Contingency	0.50
	B = 0.75

Overall Lang Factor = $(1+A)(1+B) = 4.46 \equiv H_2$

factors chosen reflect the fact that the uranium recovery plant is to be a large outdoor structure processing fluids with a low instrumentation requirement, but a large allowance for contingencies. The balance of plant (BOP) capital cost is given by,

$$\left[\text{BOP}\right] = H_2 \text{ (Capital Cost of Pumps and Beds)} \qquad (2.74)$$

The cost of the structure which holds the beds is based on the cost of a large 8-pile petroleum platform as described in Ocean Industry (O6). The platform is three hundred feet tall and moored in fifteen hundred feet of water. The cost of mooring the platform is taken from Douglas (D2), as analyzed by Broussard (B2). The cost of the platform is given by,

$$\left[\text{Platform Cost}\right] = 1150\ T_p\ e^{0.006\ T_p} \qquad (2.75)$$

where,

T_p = platform height (ft)

and the cost is in 1978 dollars (multiply by 1.1 to inflate to 1979 dollars).

The cost of mooring is a function of the mooring depth, T_m, the current, and the frontal area of the structure moored. For a two knot current Broussard's data (inflated to 1979 dollars) gives a mooring cost per square foot of structure of,

$$\left[\frac{\text{Mooring Cost}}{\text{ft}^2}\right] = 0.02\ T_m + 522 \quad \left[\frac{\$}{\text{ft}^2}\right] \qquad (2.76)$$

Assuming that the area of the frontal structure will be equal to the bed intake area, the total cost of the structure and the mooring is given by multiplying Eq. 2.77 by the intake area, A_2/A_7, and adding the result to Eq. 2.75. Dividing the total by the amount of U_3O_8 produced gives the allocated initial capital cost of the platform-mooring system, B_2(\$/lb U_3O_8),

$$B_2 = H_1 \frac{\left[(0.02\ T_m+522)A_2/A_7 + 1265\ T_p\ e^{0.006\,T_p}\right]}{M_8\ 2204} \qquad (2.78)$$

It is recognized that the economic model provided by Eq. 2.78 is only a rough approximation, and should be improved as better and more explicit designs are proposed.

2.5.4 Multi-Product Plant Cost Model

The uranium from seawater plant consumes electricity, steam, carbon dioxide, ammonia, and fresh water in the process of recovering uranium from seawater. The at-sea siting of the plant requires that these consumables be shipped in or generated at the plant. Henry King, a student at M.I.T., designed a multi-product plant burning coal to raise steam for generating electricity, desalinating seawater and chemical processing. Additionally some of the scrubbed stack gases are processed to recover carbon dioxide for chemical make-up. Ammonia is the only consumable chemical which must be shipped to the plant (although on site production would also be possible using nitrogen from the air and electrolytically generated hydrogen).

King fit unit cost equations to existing data on the cost of electricity and desalination plants. Equation 2.79 gives the unit cost of electricity, W_7 (mills/kw-hr),

$$W_7 = \frac{1000}{8766\ F_9}\left[H_1\ 1348\ \left(\frac{P_8}{50}\right)^{-0.425} + 31.42\ \left(\frac{P_8}{50}\right)^{-0.321}\right] + \frac{0.142\ W_3}{Q_8} \qquad (2.79)$$

where,

W_7 = cost of electricity (mills/kw-hr),
P_8 = effective plant rating (Mw(e)),
H_1 = fixed charge rate (1/yr),
F_9 = plant capacity factor,
W_3 = cost of coal (\$/ton delivered),
Q_8 = thermal efficiency (kw(e)/kw(t)),

1000 is the number of mills per dollar, 8766 is the number of hours per year and 0.142 converts \$/ton coal to mills/kw(t)-hr assuming 12,000 BTU/lb coal. P_8 is designated the "effective" plant rating because it reflects the fact that the plant generates electricity as well as supplying back pressure steam to the desalination plant and the ammonium carbonate stripper. An expression for the effective plant rating will be derived following the development of the unit cost expression for the desalination and carbon dioxide recovery plants.

Equation 2.80 from King's work gives the unit cost of fresh water:

$$W_8 = \frac{1000}{365.25\ F_9}\left[H_1\ 3.64\left(\frac{X}{50}\right)^{-0.2} + 0.07\left(\frac{X}{50}\right)^{-0.31}\right] + \frac{0.083\ f}{p} \qquad (2.80)$$

where,

W_8 = cost of water ($/1000 gal)

X = desalination plant capacity (Mgal/day)

p = performance ratio of desalination plant (lb water produced/1000 BTU)

f = fuel cost (¢/MBTU)

The last term on the right of Eq. 2.80 expresses the cost of energy to the desalination plant. For a back-pressure turbine system, this may be expressed in terms of the cost of electrical energy foregone due to the diversion of steam for desalination. This expression is given by Nobahar (N1),

$$f = 29.3\ G\left(1 - \frac{T_c}{T_s}\right) W_7 \qquad (2.81)$$

where,

f = apportioned fuel cost (¢/MBTU)

T_c= condensing temperature (°R)

T_s= diverted steam temperature (°R)

G = empirically derived factor = 0.7

and, 29.3 converts mills/kw-hr to ¢/MBTU. For a condenser temperature of 100°F and a diverted steam temperature of 212°F, Eq. 2.81 gives

$$f = 3.42\ W_7 \tag{2.82}$$

Desalination capacity, X, is a function of bed volume and the duration of the load-wash-elute-wash cycle. Figure 2.10 shows the steam and water flow streams for the desalination plant output, bed wash water, turbine steam flow, stripper steam flow and desalination (input) steam. The fresh water flow to the beds, F_2, for a 3-bed volume wash per cycle is, (see Fig. 2.10 to identify flow streams):

$$F_2 = \frac{3\ A_2L_9\ 62.4}{V_8 + V_9} \left[\frac{\text{lb}}{\text{hr}}\right] \tag{2.83}$$

The ammonium carbonate eluting solution requires a 79°F temperature increase (on entering the stripper column) after leaving a regenerative heat exchanger. For 4 bed volumes of solution per cycle, using the back pressure steam at 212°F (h_{fg} = 971 BTU/lb) and a solution specific heat of 1 BTU/lb-°F, the required steam flow, F_4, to the stripper is,

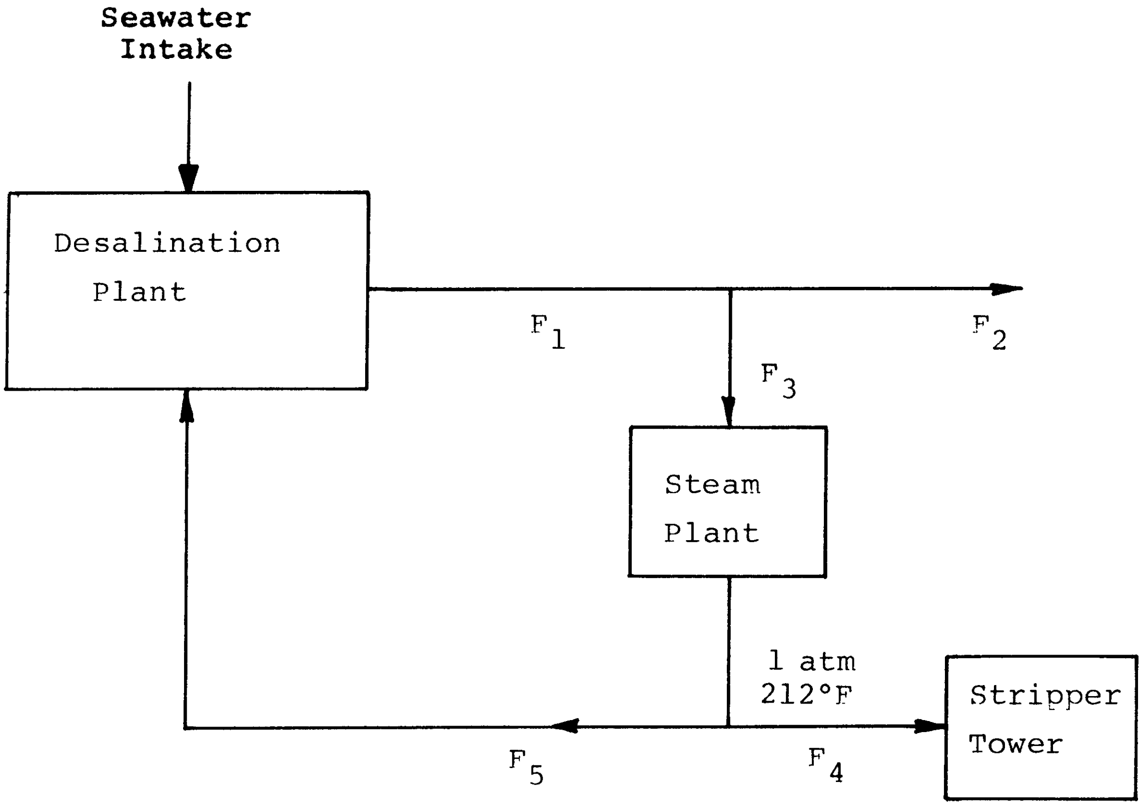


Fig. 2.10

Fluid Paths in the Multi-product Plant

$$F_4 = \frac{4\ A_2L_9\ 62.4}{V_8 + V_9} (0.0813) \left[\frac{\text{lb}}{\text{hr}}\right] \qquad (2.84)$$

The desalination plant produces water at a performance ratio of p lb water/1000 BTU. Using this and 971 BTU/lb steam, the required steam flow rate, F_5, is related to the water production rate, F_1, by

$$F_5 = \frac{1.03}{p} F_1 \left[\frac{\text{lb}}{\text{hr}}\right] \qquad (2.85)$$

By noting that the water production rate, F_1, is equal to $F_2 + F_4 + F_5$, the water requirement may be determined as a function of bed volume and performance ratio. Thus the desalination plant capacity, is

$$F_1 = \frac{3(62.4)A_2L_9}{V_8 + V_9} + 4(0.0813)(62.4)\frac{A_2L_9}{V_8+V_9} + \frac{1.03}{p} F_1 \qquad (2.86)$$

and solving Eq. 2.86 for desalination capacity gives,

$$F_1 = \frac{3.33}{1-\frac{1.03}{p}} (62.4) \frac{A_2L_9}{V_8+V_9} \left[\frac{\text{lb}}{\text{hr}}\right] \qquad (2.87)$$

Converting Eq. 2.87 to Mgal/day, then substituting it and Eq. 2.82 into Eq. 2.80 gives the final expression for the cost of water,

$$W_8 = \frac{1000}{365.25\ F_9} \left[H_1\ 3.64 \left(\frac{1.19\text{x}10^{-5}}{1-\frac{1.03}{p}} \frac{A_2L_9}{V_8+V_9} \right)^{-0.2} + 0.07 \left(\frac{1.19\text{x}10^{-5}}{1-\frac{1.03}{p}} \frac{A_2L_9}{V_8+V_9} \right)^{-0.31} \right] + \frac{0.284\ W_7}{p} \left[\frac{\$}{1000\text{gal}}\right] \qquad (2.88)$$

The performance ratio, p, of a desalination plant expresses the relationship between the fresh water output and steam input. It is a measure of the efficiency of the desalination plant and reflects the use of capital intensive heat transfer equipment. A high performance ratio will generally reflect a high capital cost desalination plant. Therefore, although p is an explicit variable in Eq. 2.88, it cannot be changed without also changing the other cost terms.

The cost of carbon dioxide production from stack gas was determined by fitting the standard unit cost equation to the data prepared by the Pullmann Kellogg Corporation for the U.S. Department of Energy (P2). Equation 2.89 is the unit cost equation for carbon dioxide production,

$$W_4 = \frac{1}{F_9}\left[H_1(0.346)(C_7)^{-0.2606} + 0.00865(C_7)^{-0.0872}\right] \tag{2.89}$$

where,

W_4 = unit cost of carbon dioxide (\$/lb CO_2)

C_7 = plant capacity (lb CO_2/hr)

H_1 = annual fixed charge rate (1/yr)

F_9 = plant capacity factor

and the other constants are empirically determined. The operation and maintenance term of Eq. 2.89 includes a fuel cost of 218 ¢/MBTU for supplied steam. In order to account for varying steam supply costs in the multi-plant model, the O/M term was multiplied by the cost of steam in the multi-product plant, 3.42 W_7 (¢/MBTU) from Eq. 2.82 divided by 218 ¢/MBTU. The final equation for W_4 is then,

$$W_4 = \frac{1}{F_9}\left[0.346\ H_1(C_7)^{-0.2606} + \frac{3.42\ W_7}{218}\ 0.00865(C_7)^{-0.0872}\right] \tag{2.90}$$

Having determined the steam loads for the desalination and carbon dioxide plants, it is possible to derive the effective electrical plant rating, P_8, discussed with respect to Eq. 2.79.

P_8 is the equivalent plant electrical rating which would result if the total steam flow were used to generate only electricity, instead of some electricity and some steam loads.

The steam demand required for desalination is the plant desalination capacity divided by the performance ratio,

$$\begin{bmatrix}\text{Desalination}\\ \text{Steam}\end{bmatrix} = \frac{3.33(62.4)1000}{(p-1.03)}\ \frac{A_2L_9}{V_8+V_9}\left[\frac{\text{BTU}}{\text{hr}}\right] \tag{2.91}$$

The steam demand required for the ammonium carbonate stripper system is equal to the volume of eluate times the specific heat of the solution times the temperature increase,

$$\begin{bmatrix}\text{Stripper}\\ \text{Steam}\end{bmatrix} = 4(62.4)79\ \frac{A_2L_9}{V_8+V_9}\left[\frac{\text{BTU}}{\text{hr}}\right] \tag{2.92}$$

Because the carbon dioxide stack gas recovery system must replace losses of only 6% of the stripper system CO_2

throughput, its steam demand is small in comparison with the stripper steam demand, and will therefore be neglected.

The equivalent electrical capacity, P_9, of these steam demands is equal to the sum of Eqs. 2.91 and 2.92, multiplied by the efficiency calculated in Eq. 2.81 and converted from BTU to Mw,

$$P_9 = \left[\frac{3.33(1000)}{p - 1.03} + 4(79)\right] \frac{62.4(0.1167)}{3413(1000)} \frac{A_2 L_9}{V_8 + V_9} \left[\text{Mw}\right] \quad (2.93)$$

The effective electrical capacity for use in Eq. 2.79 is the sum of the pumping power from either Eq. 2.13 or 2.21, and the equivalent electrical capacity of Eq. 2.93,

$$P_8 = P_9 + P \quad (2.94)$$

The unit costs derived from the output of the multi-product plant model are used to calculate the cost of consumables as discussed in the following sections.

2.5.5 Pumping Power Cost Model

The allocated cost of electrical pumping power, B_7, is calculated by multiplying the pumping power of Eq. 2.13 or 2.21 by the hours of operation, 8766 F_9, and the cost of electricity from Eq. 2.79, and dividing by the U_3O_8 production,

$$B_7 = \frac{P\ 8766\ F_9\ W_7}{M_8\ 2204} \left[\frac{\$}{\text{lb } U_3O_8}\right] \quad (2.95)$$

2.5.6 Chemical Consumption Cost Model

The allocated cost of carbon dioxide consumption, B_4, is found by multiplying the carbon dioxide consumption rate, C_7, of Eq. 2.63 by the hours of operation, 8766 F_9, and unit cost, W_4, of Eq. 2.90, and dividing by the U_3O_8 production,

$$B_4 = \frac{C_7 \; 8766 \; F_9 W_4}{M_8 \; 2204} \quad \left[\frac{\$}{\text{lb } U_3O_8}\right] \tag{2.96}$$

The allocated cost of ammonia, B_3, is similarly derived,

$$B_3 = \frac{C_6 \; 8766 \; F_9 W_5}{M_8 \; 2204} \quad \left[\frac{\$}{\text{lb } U_3O_8}\right] \tag{2.97}$$

2.5.7 Water Consumption Cost Model

The allocated cost of fresh water, B_5, is found by multiplying the bed volume by 3 times the hours of operation, times the unit cost, divided by the total cycle time and uranium production, as recommended by Harrington (H1),

$$B_5 = \frac{3 \; A_2 L_9 \; 7.48 \; (8766) F_9 W_8}{1000 (V_8 + V_9) 2204 \; M_8} \quad \left[\frac{\$}{\text{lb } U_3O_8}\right] \tag{2.98}$$

2.5.8 Bed Attrition Loss Model

Hydrous titanium oxide is lost from the beds due to mechanical erosion and solubility losses. Solubility losses occur principally during the elution process rather than during the uranium loading cycle because HTO is very insoluble in seawater (solubility product $\leq 10^{-40}$ (B5)). It is also only very slightly soluble in the eluting solution. Mechanical erosion includes bed particles which break up into fines and are washed out of the bed. It seems likely that for pure HTO, which is reportedly chalky, soft and friable, the major loss mechanism would be through mechanical loss of fines as opposed to solubility losses. However, the model used is based on data which includes mechanical losses as well as solubility losses.

The only quantitative data on HTO bed loss is a British experiment (K2) in which they reported passing 500 m^3/day of seawater through a 10 cm thick bed at superficial velocities between 0.15 and 0.56 cm/sec on a 10 day load-elute cycle for one year. The combined bed loss due to mechanical erosion and solubility losses was reported to be <5% by volume. Using the lower velocity value (for conservatism), the calculated bed cross section is 3.85 m^2. The corresponding bed volume would be 0.385 m^3, and the volume loss in a year would be $0.05/yr \times 0.385\ m^3 = 0.680\ ft^3/yr$. Assuming a void fraction of 0.4, the actual volume of bed <u>material</u> lost would be $(1-0.4)0.68 = 0.41\ ft^3/yr$. The seawater flow of 500 m^3/day is equal to 4.11×10^8 lb seawater/yr. The volumetric loss rate of bed material, A_8, would therefore be $0.41\ ft^3/yr \div 4.11 \times 10^8$ lb seawater/yr, or $9.95 \times 10^{-10}\ ft^3$ material/lb seawater. Using this value, the allocated cost of active bed material lost is,

$$B_6 = \frac{R\ V_2\ A_2\ 3600(8766)\ F_9\ Z_5\ A_8\ \mathbf{v}_2\ R_2 W_6}{M_8\ 2204} \qquad (2.99)$$

where,

B_6 = allocated cost of bed material lost ($/lb U_3O_8)

R = seawater density (lb/ft^3)

V_2 = bed superficial velocity(ft/sec)

A_2 = bed frontal area (ft^2)

F_9 = plant capacity factor

Z_5 = seawater flow duration ÷ total cycle time

A_8 = volumetric material loss rate (ft^{3}material/ lb seawater)

v_2 = active particle volume ÷ total particle volume

R_2 = active adsorber density(lb/ft^3)

W_6 = installed cost of adsorber ($/lb HTO)

M_8 = U_3O_8 annual production (MT)

3600 sec/hr, 8766 hr/yr and 2204 lb/MT are, of course, conversion factors.

Equation 2.81 is based on the assumption that of all the material carried out of the bed, only the v_2 fraction is active adsorber and therefore an appreciable economic loss.

It is clear that further experiments on HTO bed loss mechanisms are required, since bed effluent containing only 1 ppm of HTO can have a very large economic impact on the cost of uranium production. This problem would be aggravated should it be necessary to use fluidized beds to avoid plugging or fouling, or if bed slurry pumping were used during chemical recovery operations.

2.6 Chapter Summary

In this chapter we have detailed the development of the performance and economic models which are used to calculate uranium recovery costs. The models are used in the simulation code URPE very nearly as they appear in this chapter. The differences are due either to combining several constants into one number, or the programming restrictions of the Tektronix 4051. The following chapters detail the results of using URPE to analyze candidate recovery systems.

CHAPTER III

SIMULATION RESULTS

3.1 Introduction

Chapter Two described the development of the performance and economics models to be used to analyze the proposed uranium recovery system. The ultimate objectives of the present analysis are to perform an assessment of the state-of-the-art technology for uranium recovery, to define the conditions under which uranium recovery from seawater would be economically attractive, and to set objectives for research and development in the technology of uranium recovery from seawater. Chapter Four will discuss the areas of research and development which hold the most potential for reducing uranium production costs, while the present chapter meets the first and second of the project's objectives through a discussion of the results of running the simulation code for a wide range of input parameters and modeling assumptions.

The chapter begins with a summary of the system model. The sensitivity of the results to the accuracy of the major sub-system models is then described. Next, the code is used to compare the cost of uranium calculated by the URPE code with the cost of uranium calculated in the Exxon and Oak Ridge studies. The results of an overall system optimization and parametric study are then presented, followed by a discussion of the effects of very large changes in adsorption capacity and pumping power requirements.

3.2 Description of the System Model

The URPE uranium recovery system is based on an adsorption process in which hydrous titanium oxide (HTO) adsorbs uranium from seawater. As detailed in Chapter Two, the plant consists of a deep-water-moored oil-rig type platform which supports a pump-diffuser (or for passive systems, a diffuser only) supplying seawater at very low velocity to an adsorbing system. The recovery cycle consists of a uranium loading period, during which seawater passes through the bed, followed by a fresh water wash, followed by an ammonium carbonate elution to desorb the uranium, followed by a fresh water wash, and then by return to a loading period. The uranium-rich ammonium carbonate solution is stripped of ammonia and carbon dioxide which are recycled to produce fresh ammonium carbonate solution. The uranium is ultimately recovered by an ion exchange process.

A multi-product chemical plant, on board the platform, burns coal to produce steam for electrical generation, ammonium carbonate stripper operation and desalination. Part of the scrubbed stack gas is absorbed to supply make-up carbon dioxide. Coal and ammonia are brought to the plant by ship (although it would also be possible to synthesize ammonia (D3) on board).

The computer simulation calculates uranium production costs as a function of the physical properties of the adsorber system and the user input bed operating conditions. Table 3.1 lists the values of the physical properties which are used in the standard URPE analysis. The user input variables for bed operating conditions are the superficial velocity in the bed, the adsorber characteristic dimension (particle diameter or tube inner diameter), the bed thickness, the bed loading time, the bed-to-intake area ratio, and the active adsorber coating thickness.

The system is optimized by a direct search of the six variable space to locate the minimum in the cost of uranium production. The resulting optimum depends on the physical properties of the system and the economic factors used in the analysis. Table 3.2 lists the economic factors used in the present analysis. The following sections detail the results of running the URPE code.

3.3 Sensitivity of the Results to the Accuracy of the Models Employed

As of January 1980, the URPE code is the first documented attempt, in the open literature, to develop an overall computer simulation incorporating adsorption kinetics and capable of optimizing system operation as a function of bed operating conditions. Because of the sparse data base available, many of the models used in the code will have to be updated or replaced as more definitive information becomes

Table 3.1

Physical Properties Used in the URPE Analysis

Adsorber Properties:

Uranium Capacity, Q_9 = 8.68×10^{-5} lb U/lb HTO (210 mgU/Kg Ti)

Uranium-HTO Equilibrium Constant, K = 2.28

Diffusivity of Uranium in HTO, S_1 = 4.73×10^{-15} ft^2/sec

Schmidt number for the uranyl species in seawater, S = 7030

Attrition Rate, A_8 = 9.95×10^{-10} $\frac{ft^3 \text{ adsorber}}{\text{lb seawater}}$

Density of HTO coating, R_2 = 93.6 lb/ft^3 of coating

Bulk Void Fraction, (outside volume ÷ total bed volume) v_1 = 0.40 for particles; a function of diameter for tubes

Seawater Properties:

Uranium Concentration, C_9 = 3.34×10^{-9} lb U/lb seawater

Seawater Density, R = 63.7 lb/ft^3

Viscosity, V = 3.74 lb_m/ft-hr

System Operating Characteristics:

Pre-elution fresh water wash (lost to sea) = 3 bed volumes

Ammonium carbonate elution = 4 bed volumes

Post-elution freshwater wash (recovered for further use) = 4 bed volumes

Table 3.1 (continued)

Physical Properties Used in the URPE Analysis

System Operating Characteristics:

Ammonium Carbonate eluting solution concentration = 0.1 M

Table 3.2

Economic Factors Used in the URPE Analysis

Annual Fixed Charge Rate, H_1 = 25% per year for private ownership
= 10% per year for government ownership

Uranium Production rate, M_8 = 200 MT U_3O_8 per year

Lang Factor, H_2 = 4.46

Plant Capacity Factor, F_9 = 0.80

Pump Capital Cost, W_9 = 150 \$/kw-shaft

Hydrous Titanium Oxide Cost, W_6 = 0.83 \$/lb HTO

Ammonia Cost, W_5 = 0.10 \$/lb ammonia

Coal Cost, W_3 = 40 \$/Ton at the port (12,000 BTU/lb)

Bed Support Material = 0.50 \$/ft^2 of bed

Round Trip Distance from plant-to-port, N_9 = 3000 nautical miles

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available. In order to determine which components of the overall model have the greatest effect on uranium production cost, a sensitivity analysis was performed. The sensitivity analysis was carried out by arbitrarily changing (increasing or decreasing) the performance characteristics of a model in the code. For example, the sensitivity of total cost to the fluid side mass transfer coefficient was determined by increasing (or decreasing) the fluid side mass transfer coefficient by 20% and running the code. The resulting (unoptimized) total cost was compared with the base case total cost. The base case used for these comparisons was the "optimum" packed bed system (discussed in Section 3.5). Table 3.3 shows the results of the sensitivity analysis. The case numbers referenced in Table 3.3 refer to the URPE runs tabulated in Appendix C.

The single largest change, Case 8, is brought about by eliminating the solid phase resistance to mass transfer. Note that this case involves the total elimination of solid phase mass transfer resistance, not merely an increase of 20%, as in most other variations tabulated. The relatively large impact of the solid phase resistance on total production cost indicates that a major area for future work lies in developing improved sorber materials.

A better indication of the effect of errors in the solid phase mass transfer model may be obtained by noting the effect of 20% changes in the model, as shown by Cases 6 and 7. These cases show a decrease in uranium production cost of 2.8% for a 20% increase in solid phase mass transfer, and a

Table 3.3

Sensitivity of Total Cost ($/lb U_3O_8) to Modeling Accuracy

Case No.	Assumed Change in the Model	$\frac{\text{\% Change in Cost}}{\text{\% Change in Model}}$
1.	Base Case	
	Pumping Head	
2.	+20%	0.18
3.	-20%	-0.19
	Fluid Side Mass Transfer	
4.	+20%	-0.01
5.	-20%	0.02
	Solid Side Mass Transfer	
6.	+20%	-0.14
7.	-20%	0.21
8.*	Eliminating Solid Side Resistance	-0.80
	Ammonia Consumption	
9.	+20%	0.12
10.	-20%	-0.12
	CO_2 Consumption	
11.	+20%	0.01
12.	-20%	-0.01
	Balance of Plant Cost	
13.	+20%	0.39
14.	-20%	-0.39

*Case 8 sensitivity = % Change in Cost ÷ 20%

Table 3.3 (Continued)

Sensitivity of Total Cost ($/lb U_3O_8) to

Modeling Accuracy

Case No.	Assumed Change in the Model	$\frac{\%\ \text{Change in Cost}}{\%\ \text{Change in Model}}$
	Attrition Rate	
15.	+20%	0.04%
16.	-20%	-0.04%
	Water Consumption	
17.	+20%	0.17
18.	-20%	-0.17
	Fixed Charge Rate	
19.	+20%	0.75
20.	-20%	-0.75
	Plant Capacity Factor	
21.	+20%	-0.50
22.	-20%	0.75
	Bed Void Fraction	
23.	+20%	+0.04
24.	-20%	+0.29

4.1% increase in production cost for a 20% decrease in solid phase mass transfer. These changes are larger than, but roughly comparable to the changes due to similar errors in the pressure drop model, the ammonia consumption model, and the water consumption model. Thus all of these factors have about equal importance in their impact on the performance model.

The small changes in uranium production cost resulting from changes in the fluid side mass transfer model reflect the fact that the solid phase mass transfer process appears to be the controlling factor in transferring uranium from the bulk fluid to the solid phase. Similarly, the small changes in cost due to changes in the carbon dioxide consumption model indicate that the low unit cost of carbon dioxide (as produced by the multi-product plant) effectively isolates total cost from changes in carbon dioxide consumption. The small change in total cost due to changes in the attrition model seems to bear out the current feeling within the British and German projects, that attrition will not be the major problem it was felt to be in the original Oak Ridge assessment.

In the economics model, the fixed charge rate and capacity factor are about twice as important as the balance of plant factor. However, any one of these factors produces effects which are larger than any of the performance model effects.

Cases 23 and 24 show the sensitivity of total cost to bed void fraction. A void fraction of 0.40 is close to the optimum value since either an increase or decrease causes production costs to increase.

The use of ± 20% as a variation around the reference value is not intended to indicate the expected accuracy of the basic model in predicting a given value. For example, the measured pump head of a system might be more than 20% greater than the value calculated using the basic pressure drop model. The expected uncertainty associated with each of the models is shown in Table 3.4. Lacking experimental data, the expected accuracies quoted in this table are judgemental estimates (from the source document when available). The large upper side uncertainty quoted for the solid phase mass transfer model is meant to indicate the potential for improving the solid phase diffusion.

It should be possible to significantly improve the particle phase diffusion by using porous particles and allowing the uranyl species to diffuse into the particle in the fluid filled pores. The potential benefit of utilizing fluid phase diffusion instead of solid phase diffusion is reflected in the possible upper limit of a +1000% improvement suggested in Table 3.4. Furthermore, even neglecting the possibility of using pore diffusion, the diffusivity of uranium in solid HTO may actually be larger than the estimates of the present work. Because of this it would appear likely that solid-side mass transfer is actually larger

Table 3.4

Expected Uncertainty Associated with System Models

Model	Uncertainty	Comment
Pumping Head	±50%	Expert consensus on such relations (R1)
Fluid Side Mass Transfer	±300%	Estimate from Fig. 6.18 of (S3)
Solid Side Mass Transfer	+1000%, -50%	Upper limit is based on improvements possible using porous particles
Ammonia Consumption	±100%	Our estimate
CO_2 Consumption	±100%	Our estimate
Balance of Plant Cost	±50%	Based on comparison with (H1) and (B5)
Attrition Rate	+200%, -50%	Estimated from the spread of experimental data (B5)
Water Consumption	±50%	Our estimate
Fixed Charge Rate	±20%	Based on current market variation
Plant Capacity Factor	+15%, -40%	Our estimate
Bed Void Fraction	+50%, -20%	Includes the range of possible settled bed void fractions (P1)

than estimated using the present model and adsorber properties.

It is felt that the models and physical properties used in the URPE code form the best, consistent, simulation presently available for a uranium recovery system. However, uncertainties in the data are such that, at the present stage of development, the URPE code should be used primarily to give performance trends, and not to make absolute cost predictions.

3.4 Comparison with Other Designs

3.4.1 Comparison between URPE and ORNL Designs

Oak Ridge National Laboratory (H1) and Exxon Nuclear Corporation (B5, B6) have both published cost estimates for the recovery of uranium from seawater. Using their respective bed operating conditions and economic ground rules, the URPE code was run to obtain comparative cost estimates. Table 3.5 lists the assumptions from the ORNL study which were input into the URPE code for comparison with ORNL results. The original ORNL cost estimates and URPE results in 1966 \$/lb U, were adjusted to 1979 \$/lb U_3O_8 by assuming an average uniform inflation rate of 7%, and a lb U/lb U_3O_8 correction of 0.85. Table 3.6 shows the ORNL and URPE results.

Oak Ridge National Laboratory performed their analyses for a tidally pumped system, and also estimated that the cost of an actively pumped system would not be very different from the tidal costs. With this in mind, the URPE code was run, using the data of Table 3.5, for actively pumped, URPE[a],

Table 3.5

Oak Ridge Ground Rules (H1)

Pumping System:	Tidal
Plant Capacity	435 MT U_3O_8/yr
Plant Capacity Factor	0.85
Fixed Charge Rate	11%/yr
HTO Capacity	240 mg U/kg Ti (9.92 x 10^{-5} lb U/lb HTO)
Eluting Solution	1 M ammonium carbonate
Wash-elute-wash cycle	24 hrs.
Unit Costs (1966 ORNL Estimates):	
Ammonia	0.05 $/lb
Carbon Dioxide	0.03 $/lb
Water	0.05 $/k gal
HTO	0.41 $/lb
Bed Conditions:	
Fluid Superficial Velocity	0.0194 ft/sec
Particle Diameter	0.00348 ft
Bed Depth	1.30 ft
Loading Time	96 hrs
HTO Coating Thickness	9.84 x 10^{-5} ft (0.03 mm)

Table 3.6

Comparison of Oak Ridge and URPE Results

	Oak Ridge	URPE[a]	URPE[b]	URPE[c]
Performance:				
Uranium Recovery	80%	10%	10%	9%
Bed Area (ft^2)	$1.1x10^7$	$9.0x10^7$	$9.0x10^7$	$9.4x10^7$
Attrition (lb HTO/lb U_3O_8)	140	37	37	42
Ammonia (lb/lb U_3O_8)	263	3574	3574	2459
Carbon Dioxide (lb/lb U_3O_8)	704	8464	8464	4035
Economics (all costs in 1979 \$/lb U_3O_8)				
Adsorbent losses	139	31	31	35
Chemicals	82	633	633	296
Water	2	17	17	282
Pumping Power	0	82	0	71
Annualized capital, maintenance, and labor	404	677	624	638
Total 1979\$/ lb U_3O_8	627	1440	1305	1322

[a] URPE, active pumping, ORNL unit costs and bed operating conditions.

[b] URPE, current interceptor, ORNL unit costs and bed operating conditions.

[c] URPE, active pumping, data of Tables 3.1 and 3.2, ORNL bed operating conditions.

and passive ocean interceptor, URPE^b, systems. URPE^c was run for an actively pumped system having the same plant capacity, bed superficial velocity, particle size, HTO coating thickness, bed thickness, and loading time as the ORNL study, but using the physical and economic parameters of Tables 3.1 and 3.2. Thus, URPE^a and URPE^b used essentially ORNL physical parameters and economic ground rules but with the URPE code's normal performance models. URPE^c used its normal physical and economic parameters (government ownership of the plant), as well as its normal performance models.

The differences between the ORNL results and the URPE a and b results are due, almost entirely, to the difference in the calculated uranium recovery efficiency. The ORNL study estimated an 80% recovery efficiency for their bed operating conditions, based on Keen's (K1, K2) data extrapolated to ORNL bed conditions. The URPE code kinetics model calculates a 10% uranium recovery efficiency for the same conditions. This results in the URPE code estimated bed area being almost exactly eight times the ORNL bed area. This bed area (and volume) increase, together with the URPE chemical loss model, leads to the increased chemical consumption shown. The difference in attrition between the two studies is a result of the URPE code's use of recent English HTO attrition data (B5) and the URPE bed loss model. The difference in water cost is explained by the difference in bed volumes, and, therefore, total water consumed. The difference in the annualized capital costs between the ORNL value and the URPE a and b values is attributed to the Lang factor used in the URPE model.

The small performance difference bewteen URPE^{a,b} and URPE^{c} is due to the use of more conservative adsorber properties in the normal URPE model than in the ORNL study. The reduced chemical consumption of URPE^{c} relative to URPE^{a,b} is the net result of the opposing effects of using a 0.1 M eluting solution and an increased ammonia unit cost. The large increase in water cost for URPE^{c} is a result of the use of desalinated water, costing much more than the ORNL and URPE^{a,b} unit cost.

Overall, the results shown in Table 3.6 indicate that the URPE performance and economics models employ more conservative assumptions than those made by ORNL, except for the elution and attrition models, which are based on data not available at the time of the ORNL study. The URPE^{c} production cost, being within about a factor of two of the ORNL production cost, is within the error band estimated by the ORNL study. The fact that the URPE cost is higher than the ORNL cost gives some assurance that the calculated uranium recovery costs in the present work are not being wildly underestimated.

3.4.2 Comparison Between URPE and Exxon Designs

Table 3.7 lists the assumptions from the Exxon study (B5, B6) which were input into the URPE code to generate output for comparison with the Exxon results. The Exxon cost

Table 3.7

Exxon Ground Rules

Pumping System:	**Active Pumping**
Plant Capacity	500 MT U_3O_8/yr
Plant Capacity Factor	0.90
Fixed Charge Rate	11%/yr
HTO Capacity	210 mgU/kg Ti (8.68 x 10^{-5} lb U/lb HTO)
Eluting Solution	1 M ammonium carbonate
Wash-elute-wash cycle	160 hrs
Pumping Power	450 Mw(e)
Unit Costs:	
Ammonia	0.059 \$/lb (0.13 \$/kg)
Carbon Dioxide	0.025 \$/lb (0.055 \$/kg)
Electricity	21.8 mills/kw-hr
HTO	0.50 \$/lb HTO (1.10 \$/kg HTO)
Pump Cost	466 \$/kw(e)
Bed Conditions:	
Fluid Superficial Velocity	0.0130 ft/sec (0.4 cm/sec)
Particle Diameter	0.000492 ft (80-100 mesh)
Bed Depth	2.46 ft
Loading Time	490 hrs
HTO Coating Thickness	9.84 x 10^{-5} ft (0.03 mm)
Void Fraction	0.68

estimates were made for the fourth quarter of 1978. The 1978 dollar estimates are presented and employed un-altered, because any correction would be inconsequential in view of the overall accuracy of the results.

The Exxon design case is based on use of a continuously reprocessed, slightly fluidized bed. The overall design is a mixture of several different concepts. However, most of the basic bed parameters actually come from Exxon's fixed bed up-flow design. Therefore, the adsorption kinetics model used in URPE should give a rough estimate of Exxon's bed performance.

The void fraction of the bed was calculated by using the original Exxon fixed bed void fraction and expanding the bed depth to 2.46 ft. The calculated void fraction is 0.68. The Exxon study gives a void fraction range of 0.65 to 0.70. A void fraction of 0.68 is slightly outside the range of allowed void fractions (0.4 to 0.6) for the URPE bed pressure drop model. However, for the Exxon design, the bed pressure drop is only a small fraction of the overall system pressure drop. Hence, URPE bed pressure drop errors are insignificant compared to the head losses of the seawater handling system. The area ratio input to the URPE code (see the discussion of the hydraulics model in Chapter Two) was adjusted such that the resulting pumping power of 450 MWe duplicated the value quoted for the Exxon design. Table 3.8 compares the Exxon and URPE results. Appendix C lists the URPE output for these

Table 3.8

Comparison of Exxon and URPE Results

	Exxon	URPE[a]	URPE[b]	URPE[c]
Performance:				
Uranium Recovery (in bed)	80%	83%	57%	82%
Bed Area (ft^2)	$2.1x10^7$	$1.9x10^7$	$2.1x10^8$	$1.7x10^7$
Attrition (lb HTO/lb U_3O_8)	56	22	12	37
Ammonia (lb/lb U_3O_8)	518	448	458	457
Carbon dioxide (lb/lb U_3O_8)	533	586	1060	279
Economics[d]				
Adsorbent losses	28	11	6	19
Chemicals	91	37	48	38
Water		25	53	27
Pumping Power	58	70	6	85
Annualized capital, maintenance, and labor	1260(563)[e]	414	220	481
Total 1978-79 \$/lb U_3O_8	1437(740)[e]	557	333	650

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[a] URPE, run using all Exxon ground rules Table 3.6.

[b] URPE, run using Exxon economic ground rules Table 3.6 and optimized bed conditions.

[c] URPE, run using Exxon bed conditions and plant capacity Table 3.6 and URPE ground rules, Tables 3.1 and 3.2 for government ownership.

[d] All costs are shown in 1978-1979 \$/lb U_3O_8.

[e] No interest on capital during construction.

cases.

The performance models in URPE gave results which compare favorably with the Exxon design data. The slightly higher recovery efficiency calculated by the URPE[a] code results in a smaller bed area. These results are somewhat misleading. The overall Exxon recovery efficiency is 67%, due to allowance for losses in the eluate and ion exchange recovery systems. This would make the differences in the areas somewhat larger than shown in Table 3.8, but this effect is probably compensated for by the improved mass transfer expected for the fluidized bed. The amounts of ammonia and carbon dioxide consumed are about the same. The Exxon study assumed an HTO inventory volumetric loss of 0.5% per cycle. It isn't clear whether this is a function of eluate, adsorbent, or seawater flow rate. Nevertheless, it seems reasonable that the Exxon design should experience a higher attrition loss rate than predicted by the URPE model, because the Exxon design is based on a fluidized bed adsorbent-slurry handling system. Such a design would be expected to have a higher attrition rate than a fixed bed system.

The chemical cost shown in the Exxon study is not the sum of the products of the ammonia and carbon dioxide losses times their respective unit costs (which would give a total chemical cost of 44 \$/lb U_3O_8). Since the component costs which go into the total chemical cost are not explained in the Exxon report, it is not possible to comment on the disparity between the two studies.

URPE water costs are based on use of desalination, whereas Exxon employs river water, and thus these values are not comparable. It is of interest to note, however, that the cost of even desalinated water is only 5% of the total production cost.

The discrepancy in pumping power cost comes about because the URPE code pumping power was set equal to 450 Mw(e). Even though the URPE code only charges for electricity when the seawater pumps are actually running, the Exxon system apparently does not use the full rated grid power for seawater pumping. The rated power for all seawater pumps totals about 358 Mw(e). The remaining 92 MW(e) goes to fresh water, eluate, slurry, and miscellaneous loads, and its cost is presumably apportioned to these activities.

The most significant difference between the URPE and Exxon cost projections occurs in the annualized capital cost term. There are two major reasons for this difference. First, the Exxon study considers plant construction time and the interest on capital during the construction period, while the URPE code does not. Second, the equivalent Lang factor calculated from the Exxon capital and total production costs is equal to about 6.0, while the URPE Lang factor is only 4.46. Of the two reasons, the interest on capital during construction is the most important, accounting for 83% of the difference between the two annualized capital cost estimates. The Lang factor discrepancy accounts for only 17% of the difference.

The URPE system was formulated based on shipyard style production of oil-rig type platforms. It is unlikely that the construction of such a system would require fifteen years, as in the case of the extensive civil works envisioned for both the ORNL and Exxon plants. However, it cannot be denied that interest on capital during construction is an important economic factor, and should be included in the URPE analysis as soon as a specific plant design is developed. It should be possible to develop a correction for interest during construction based on an average interest rate, the construction period, and the total equipment and balance of plant capital cost; this simple multiplicative corrector can then be readily applied to the relevant capital costs input to URPE. For purposes of comparison, the de-escalated annualized capital and total costs for the Exxon study are shown in brackets in Table 3.8.

Having made the above adjustments to the Exxon estimate of uranium production cost, the Exxon cost of 740 \$/lb U_3O_8 compares reasonably well with the URPE value of 557 \$/lb U_3O_8. The 33% difference between the two values is smaller than the combined uncertainty in the basic performance models.

The URPE^b case, shown in Table 3.8, is based on the same performance models, sorber properties, and economic ground rules as the URPE^a case. However, the URPE^b case is calculated using the optimized bed operating conditions listed in Appendix C. The optimum bed operating conditions occur at reduced values of fluid velocity, bed thickness, bed loading time, and particle coating thickness, with increased particle diameter. The result of these changes is a reduction in the pumping and HTO inventory related costs, and an increase in the use of consumable chemicals. The overall production cost is reduced because the production cost is capital intensive. URPE[b] demonstrates that optimizing bed conditions can lead to significant production cost reductions. It must be borne in mind that the cost reductions shown in Table 3.8 are strictly true only for the URPE fixed bed system. In the fluidized bed Exxon design, the particle size and fluid velocity are not independent parameters, but are related through the hydrodynamics of the fluidized bed. Therefore, for the Exxon design, the bed operating conditions listed in Appendix C could not occur unless the density of the adsorber particles could be reduced. This possibility is discussed in Chapter Four.

Table 3.8 lists the performance and economics results calculated by the URPE code using the unoptimized Exxon bed operating conditions, U_3O_8 production capacity and bed void fraction, but with the normal URPE ground rules for government ownership from Tables 3.1 and 3.2. The principal reasons for the differences between URPE[a] and URPE[c] are that the URPE model calculates a shorter wash-elute-wash time than the Exxon design, and uses an HTO cost twice that of the Exxon estimate. URPE[c] is included in Table 3.8 so that a direct comparison may be made between the Exxon and URPE results, just as the ORNL and URPE results were compared previously.

In summary, the comparison between the Exxon and URPE results shows that the two models are in fair agreement. The most significant difference between them arises from the interest on capital during construction.

3.5 System Optimization and Parametric Variation about the Optimum

3.5.1 System Optimization

Sections 3.2 and 3.3 summarize the URPE system's models, physical properties and economic input data. Section 3.4 compares URPE calculations with the two other design studies available. Having established thereby standards for the performance and expected accuracy of the URPE code, this section discusses optimized URPE-analyzed systems. The following analyses use the sorber properties and economic ground rules of Tables 3.1 and 3.2 with the fixed charge rate appropriate for private investment. The URPE code is capable of analyzing both particle bed and stacked tube adsorber systems. Particle beds receive more discussion than stacked tube systems because particle beds are the more familiar mass transfer devices, and, in the course of the analysis, proved to be the less expensive of the two systems.

Table 3.9 and Appendix C list the calculated performance and economic data for the optimized packed bed

Table 3.9

Optimized Packed Bed and Stacked Tube Systems with Active Pumping

	Packed Bed	Stacked Tube
A. Bed Operating Conditions:		
Superficial Velocity (ft/sec)	0.00355	0.00816
Characteristic Dimension (ft)	0.000212	0.000344
Bed Thickness (ft)	0.0387	0.339
Loading Time (hr)	32	69
Area Ratio	2200	982
Coating Thickness (ft)	1.74×10^{-5}	2.15×10^{-5}
B. Calculated Performance:		
Uranium Recovery	74%	40%
Bed Area (ft^2)	3.34×10^{7}	2.44×10^{7}
Loading Fraction	82%	76%
Pumping Power (Mw(e))	48	38
Effective Plant Size (Mw(e))	90	178
C. Calculated Unit Costs:		
Water ($/kgal)	5.5	4.3
Electricity (mills/kw-hr)	61	51
Carbon Dioxide ($/lb CO_2)	0.014	0.012
Ammonia ($/lb NH_3)	0.10	0.10

Table 3.9 (continued)

Optimized Bed and Stacked Tube Systems

with Active Pumping

	Packed Bed	Stacked Tube
D. Economics:*		
Adsorbent Losses	11	8
Chemical Make-up	39	52
Water	63	164
Pumping Power	46	31
Annualized Capital, Maintenance and Labor	156	227
Total \$/lb U_3O_8	315	482

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[*] All costs are in 1979 \$/lb U_3O_8

and stacked tube uranium recovery systems. As discussed in Chapter Two, the basic characteristics for a packed bed mass transfer system are high mass transfer and pressure drop per unit of bed depth, when compared with stacked tube systems. These characteristics strongly influence the optimized designs.

For similar characteristic dimensions, the packed bed superficial velocity is less than half the stacked tube velocity, and the bed thickness is roughly one-tenth as much. This results in the uranium recovery efficiencies and bed areas shown. The calculated loading fraction (percent of maximum adsorption capacity) is similar for both systems. The stacked tube design is a high seawater through-put, low recovery system, and the packed bed design is a low seawater through-put high recovery system. This results in the packed bed system having a much lower bed capital and balance of plant cost per unit of uranium recovered than the stacked tube system. The pump related costs for the stacked tube system are not sufficiently lower than those of the packed bed system to offset the bed cost difference. The overall result is that the packed bed system produces uranium at 65% of the cost of the stacked tube system.

During the process of finding the optimum stacked tube configuration, it was found that the total cost was a function of the minimum wall thickness of the tubes, as well as the adsorber coating thickness. For the tube diameters and lengths of interest, it was felt that because of the lack of radial pressure gradients the minimum tube wall thickness could be reduced from values predicted by the original condenser tube thickness model, to values characteristic of tubes which are more like soda straws. The final model used for tube wall thickness is listed in the program of Appendix A. The minimum wall thickness is 1.67×10^{-4} ft (0.002 inch).

Table 3.10 and Appendix C list the characteristics of optimized stacked tube and packed bed systems for the passive ocean interceptor design concept. As would be expected, the characteristic dimension of the passive systems is larger than the characteristic dimension of the active systems. This is a direct result of the limited head available from the current compared with that readily provided by a pump. Unfortunately, the larger the characteristic dimension (particle diameter or tube inner diameter), the lower the mass transfer rate per unit of bed depth. The passive systems adjust for the reduced recovery rate by increasing the bed area. As bed area increases, the cost of chemicals required for reprocessing increases, as well as the cost of bed structural material. The ultimate trade-off between active and passively pumped systems is based on pumping costs versus the cost of chemicals and bed structural material. For typical costs of chemicals and bed structural material, and assuming an electricity cost of 50 mills/kw-hr, the breakeven unit capital cost of pumps is found to be about 500 $/kw. URPE uses a unit cost of 150 $/kw,

Table 3.10

Optimized Packed Bed and Stacked Tube Systems of the Passive Ocean Interceptor Type

	Packed Bed	Stacked Tube
A. Bed Operating Conditions:		
Superficial Velocity (ft/sec)	0.00207	0.00189
Characteristic Dimension (ft)	0.000591	0.000505
Bed Thickness (ft)	0.0543	0.0880
Loading Time (hr)	51.0	73.2
Area Ratio	2830	3110
Coating Thickness (ft)	$2.14\text{x}10^{-5}$	$2.78\text{x}10^{-5}$
B. Calculated Performance:		
Uranium Recovery	48%	40%
Bed Area (ft^2)	$8.19\text{x}10^{7}$	$10.2\text{x}10^{7}$
Loading Fraction	72%	69%
Pumping Power	NA	NA
Effective Plant Size (Mw(e))	99.2	145
C. Calculated Unit Costs:		
Water ($/kgal)	4.71	4.46
Electricity (mills/kw-hr)	56.7	56.7
Carbon Dioxide ($/lb CO_2)	0.012	0.012
Ammonia ($/lb NH_3)	0.10	0.10

Table 3.10 (continued)

	Packed Bed	Stacked Bed
D. Economics:[b]		
Adsorbent Losses	8.3	9.8
Chemical Make-up	49.6	56.6
Water	126	174.6
Pumping Power	NA	NA
Annualized Capital, Maintenance and Labor	267	357
Total \$/lb U_3O_8	451	598

[a] Calculations based on a 4 mph current.

[b] All costs are in 1979 \$/lb U_3O_8.

based upon a review of industrial cost data. It therefore seems unlikely that passive current interceptor systems, using the present designs, could ever produce uranium more cheaply than actively pumped systems. However, this judgment could be reversed if a better method for eluting the uranium from the adsorber could be found, or if the total cost of the wash water could be significantly reduced.

Continuing the discussion of Table 3.10, it is seen that the passive system bed areas are 3 to 4 times the actively pumped system bed areas. This leads to increased chemical, water and bed capital costs, which more than offset the saving due to deleting pump related costs. Appendix C also lists the results for a packed bed passive system operating with a 2 mph current instead of a 4 mph current. The 2 mph results confirm the expected trends. Particle size and bed area increase still further, resulting in a total production cost of 775 \$/lb U_3O_8. Although it is theoretically possible to reduce passive system production costs by using higher speed currents, the practical impossibility of finding a sufficiently steady, high velocity current effectively rules out passive systems for the present.

There are several key features of the URPE optimized designs which require further comment. The fluid superficial velocity, bed thickness, and seawater loading time are unusually low by conventional standards. The low superficial velocity and bed thickness are the result of a balance between the cost of pumping water to the beds, and the cost of bed structure and reprocessing chemicals. As superficial velocity decreases, pump costs decrease, but the mass flux of uranium decreases, and bed area must increase to keep the production rate constant. As bed area increases, the cost of bed structure and reprocessing chemicals also increase.

3.5.2 Parametric Variation about the Optimum

A sensitivity study was performed to investigate the sensitivity of total cost to the variation of key parameters. Starting from the optimized bed operating conditions, each of the bed parameters was varied over a wide range while holding all other bed parameters constant. Figures 3.1 through 3.6 and Table 3.11 show the results of these analyses, and Appendix C lists the URPE output, from which the plots were made.

The data shows that (in decreasing order of sensitivity) the important parameters are coating thickness, loading time, superficial velocity, characteristic dimension, bed thickness, and finally, area ratio. The strong sensitivity to coating thickness has not previously been noted. In fact, no published analysis has used a different coating thickness since Keen's original estimate. Although a technique for coating HTO on an inert core has not yet been demonstrated, this sensitivity indicates a high payoff for a successful coating process.

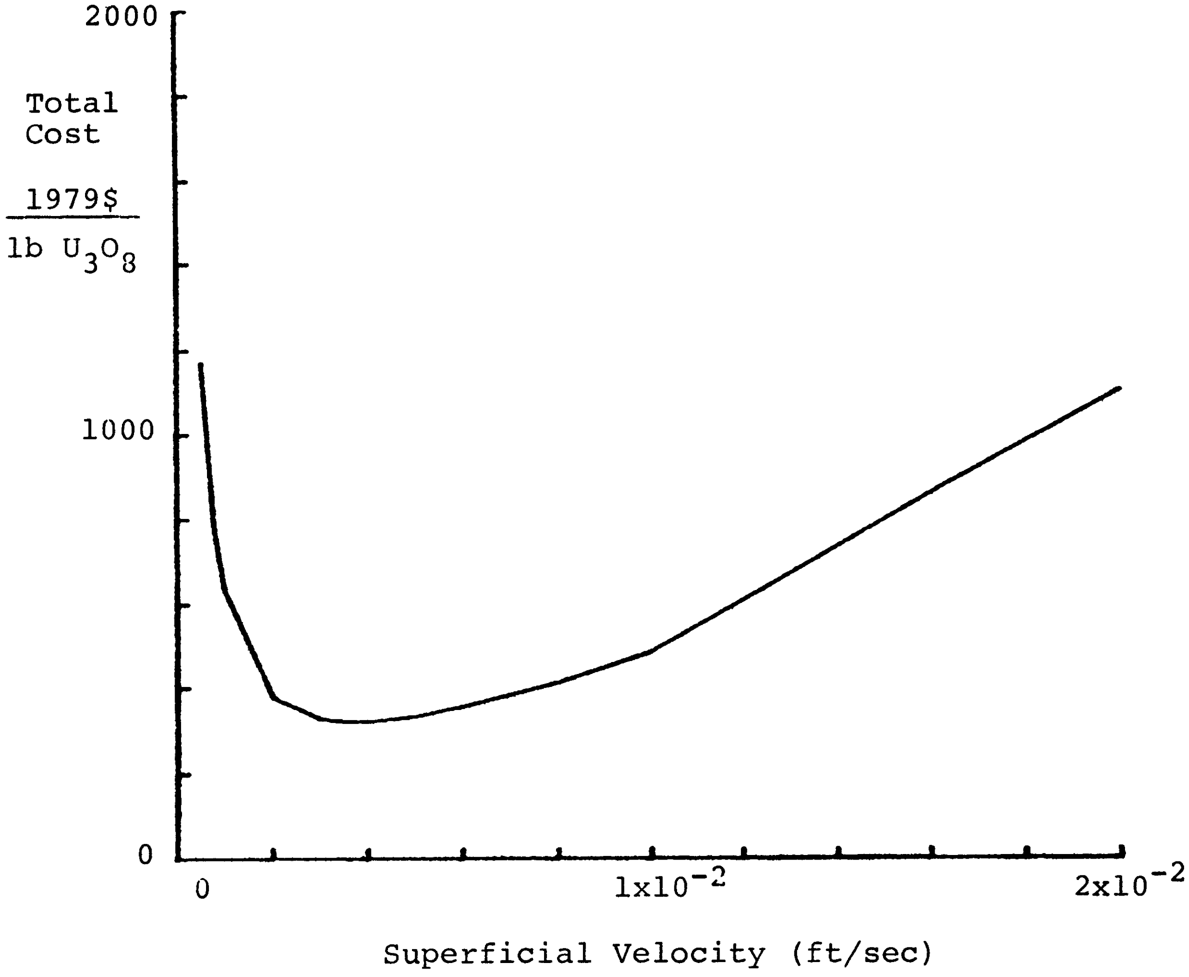


Fig. 3.1 Total Cost as a Function of Superficial Velocity

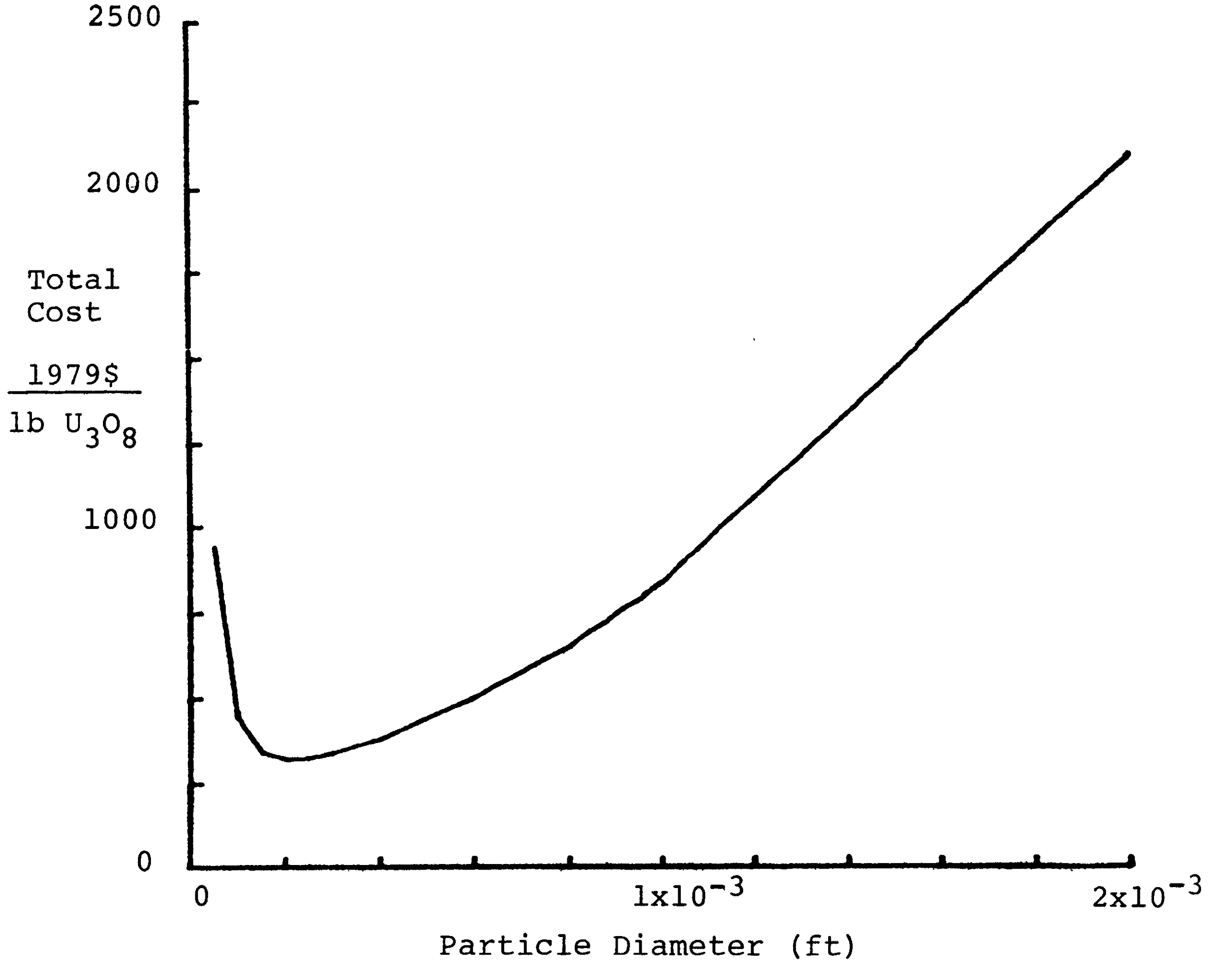


Fig. 3.2 Total Cost as a Function of Particle Diameter

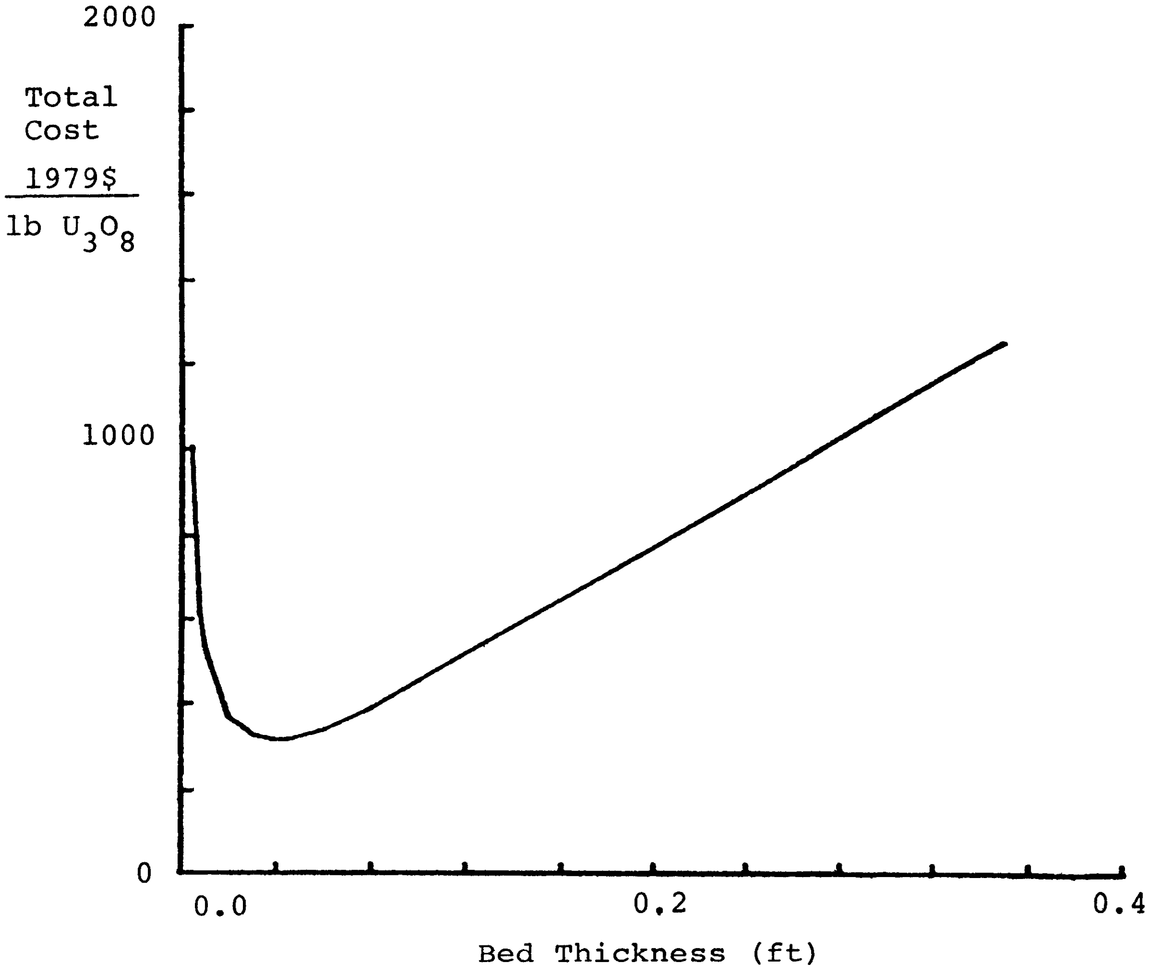


Fig. 3.3 Total Cost as a Function of Bed Thickness

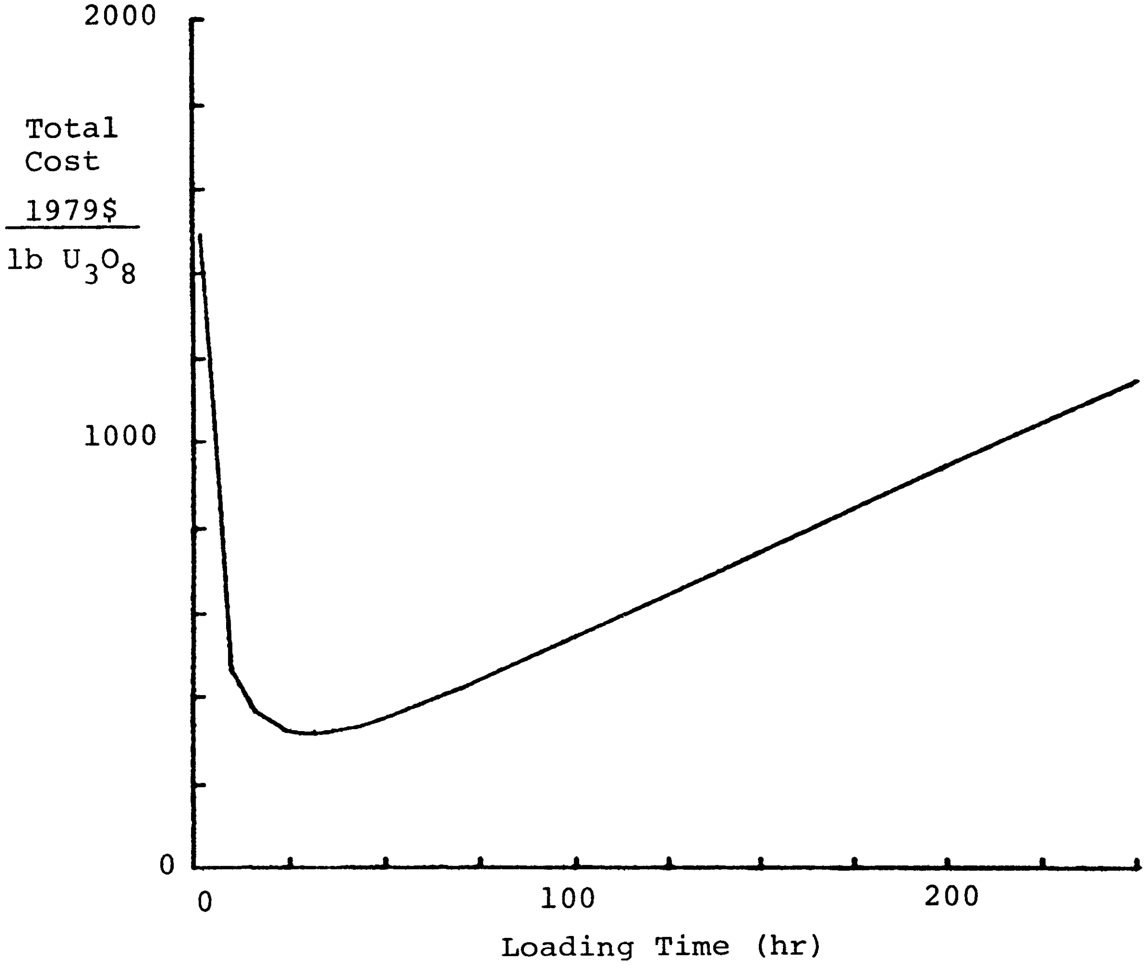


Fig. 3.4 Total Cost as a Function of Loading Time

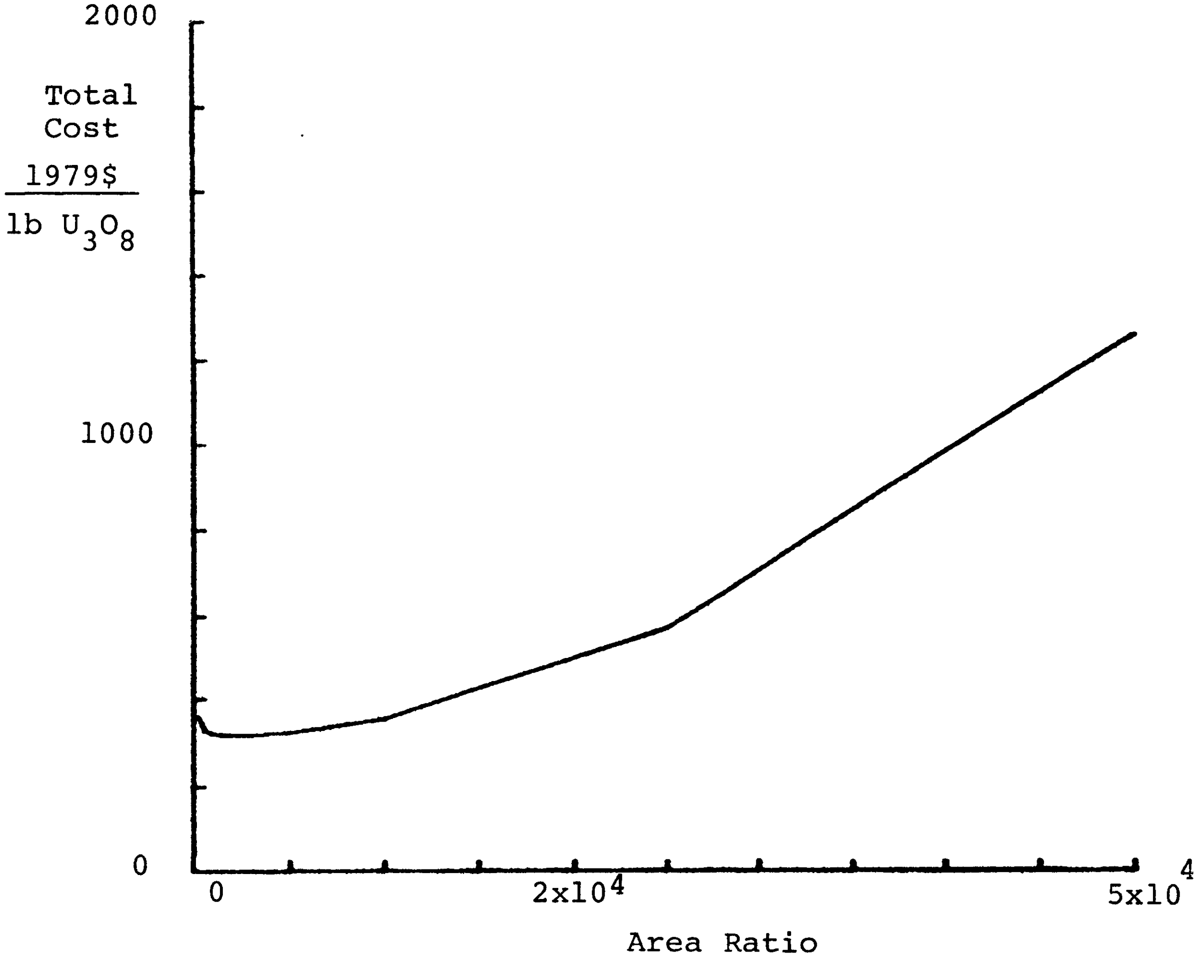


Fig. 3.5 Total Cost as a Function of Area Ratio

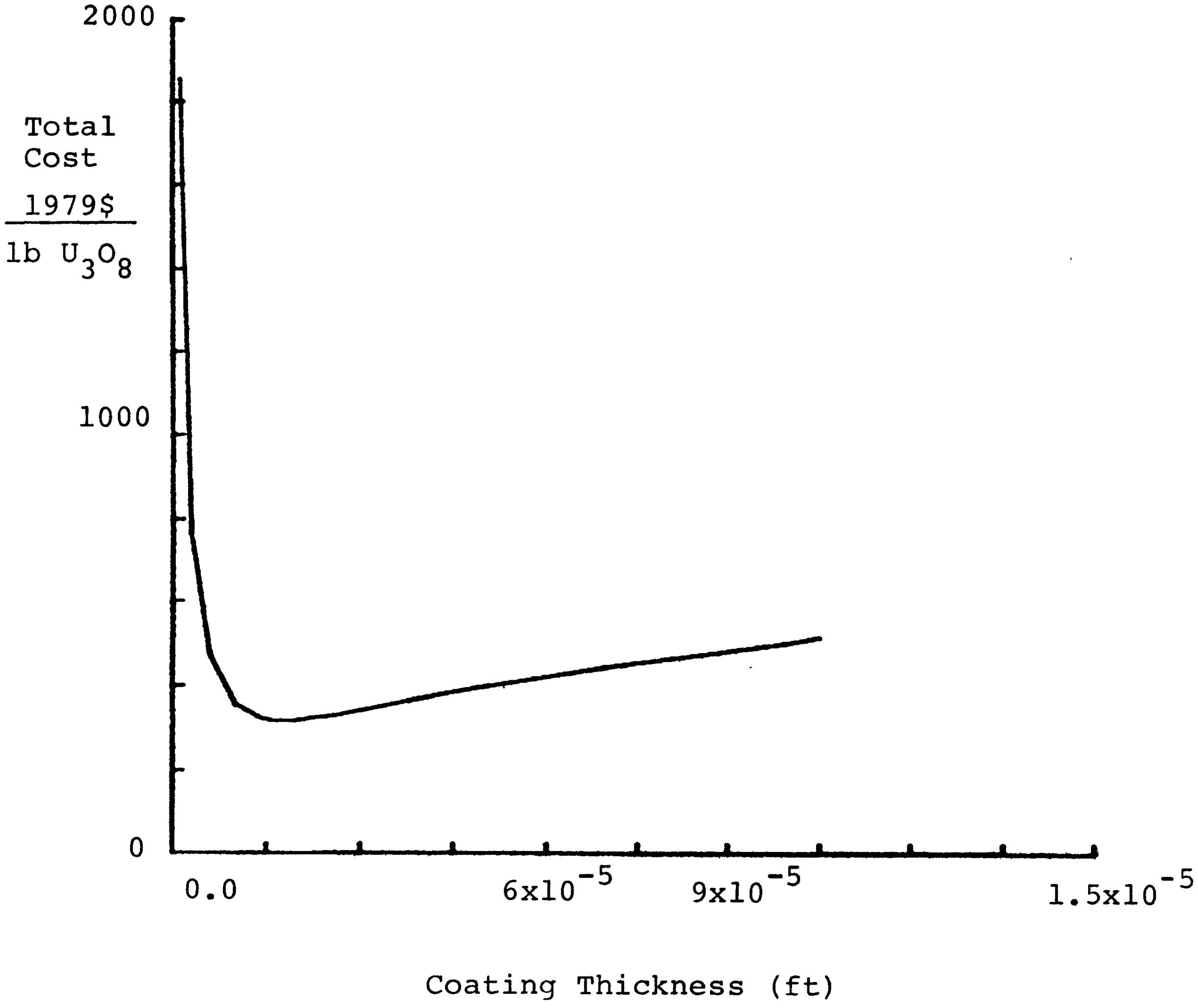


Fig. 3.6 Total Cost as a Function of Coating Thickness

Table 3.11

Sensitivity of Total Cost to Bed Operating Conditions

Parameter	Sensitivity % Change in Cost per % Change in Parameter
Superficial Velocity	
Decrease	3.2
Increase	0.54
Characteristic Dimension	
Decrease	2.6
Increase	0.67
Bed Thickness	
Decrease	2.4
Increase	0.37
Loading Time	
Decrease	4.0
Increase	0.39
Area Ratio	
Decrease	0.16
Increase	0.14
Coating Thickness	
Decrease	5.2
Increase	1.0

The strong sensitivity of total cost to changes in the bed operating conditions indicates the importance of optimizing these parameters. However, the practicality of achieving the optimum conditions in an operating system is in question. In particular, the optimum bed thickness seems to be very thin. It may be possible and more practical to replace the packed bed with a sheet of a very porous solid, rather than attempting to lay down a uniform particle bed 1/2 inch thick. Otherwise considerable fluid may pass through the bed without undergoing particle contact. This may also argue in favor of the use of fluidized beds.

Note that the optimum loading time is short. The optimization process is forcing us to approach a continuous reprocessing system by making the loading time so short. This is attributed to the use of the original ORNL model of bed elution, which is not a kinetic elution model, but assumes that essentially all of the uranium is eluted in a relatively fixed period of time. In fact, as the uranium loading decreases, the uranium eluted per unit time decreases. The overall effect could well drive the optimization to slightly longer loading times. However, this is not expected to be a large effect since, in all cases, eluting time is a small fraction of loading time. Nevertheless, the elution model should be improved as new elution kinetic data and more detailed plant designs become available.

Finally, the tables, figures, and data show that the results predicted by the URPE model are very sensitive to further decreases in the bed operating parameters: i.e., the costs rise sharply as the subject parameters are reduced from their optimum values in Figs. 3.1 through 3.6. Recognizing that the optimum is a function of performance and economic models, it still seems unlikely that anything short of gross changes in the models will cause the optimum to shift to much lower values of the bed operating parameters. These operating conditions may therefore be viewed as a lower bound to the envelope of bed parameters.

3.6 The Effect of Large Changes in Adsorption Capacity and Pumping Requirements

Adsorption capacity and pumping power requirements are two of the most important and contested parameters in the analysis of uranium from seawater systems. Adsorption capacity is important for obvious reasons. That the capacity of HTO for uranium is a contested property is clear from the wide range of values reported for capacity. Although the pumping power required for any given system design is not disputed, the choice of system conceptual design to minimize pumping power requirements does depend on how important pumping power is considered to be by the designer.

A study of the effect of increasing adsorption capacity and pumping power was performed in order to assess the impact of these items on optimized uranium production cost. The study was performed by starting from the optimized base case, increasing the item of interest, and re-optimizing the entire uranium recovery system design.

The adsorption capacity was varied, starting with the base case value of 8.68×10^{-5} lb U/lb HTO (210 mg U/kg Ti), and increasing the capacity to a maximum value of 3×10^{-2} lb U/ lb HTO (72,580 mg U/kg Ti). This range includes all of the reported values of HTO capactiy, including experiments in spiked seawater, and concludes with a capacity which might be typical of an ion exchange resin. Figure 3.7 shows the data plotted from the URPE output listed in Appendix C.

The data shows the maximum improvement which might be expected as sorber capacity increases. Very large (but not physically impossible) increases in sorber capacity would be required to bring production cost down to the range of the 1979 spot market price for U_3O_8, 40 $/lb. However, the capacity need only be increased to 3.5×10^{-4} lb U/lb HTO (847 mg U/kg Ti) in order to produce uranium at a price of 150 $/lb U_3O_8, the breakeven price. It is recognized that it is unlikely that a single recovery system model could accurately predict production costs over such a wide range of sorber capacity. However, the trend of decreasing cost with increasing capacity is so strong that work to improve sorber capacity, or identify alternate adsorbers having a high capacity, should clearly be carried out.

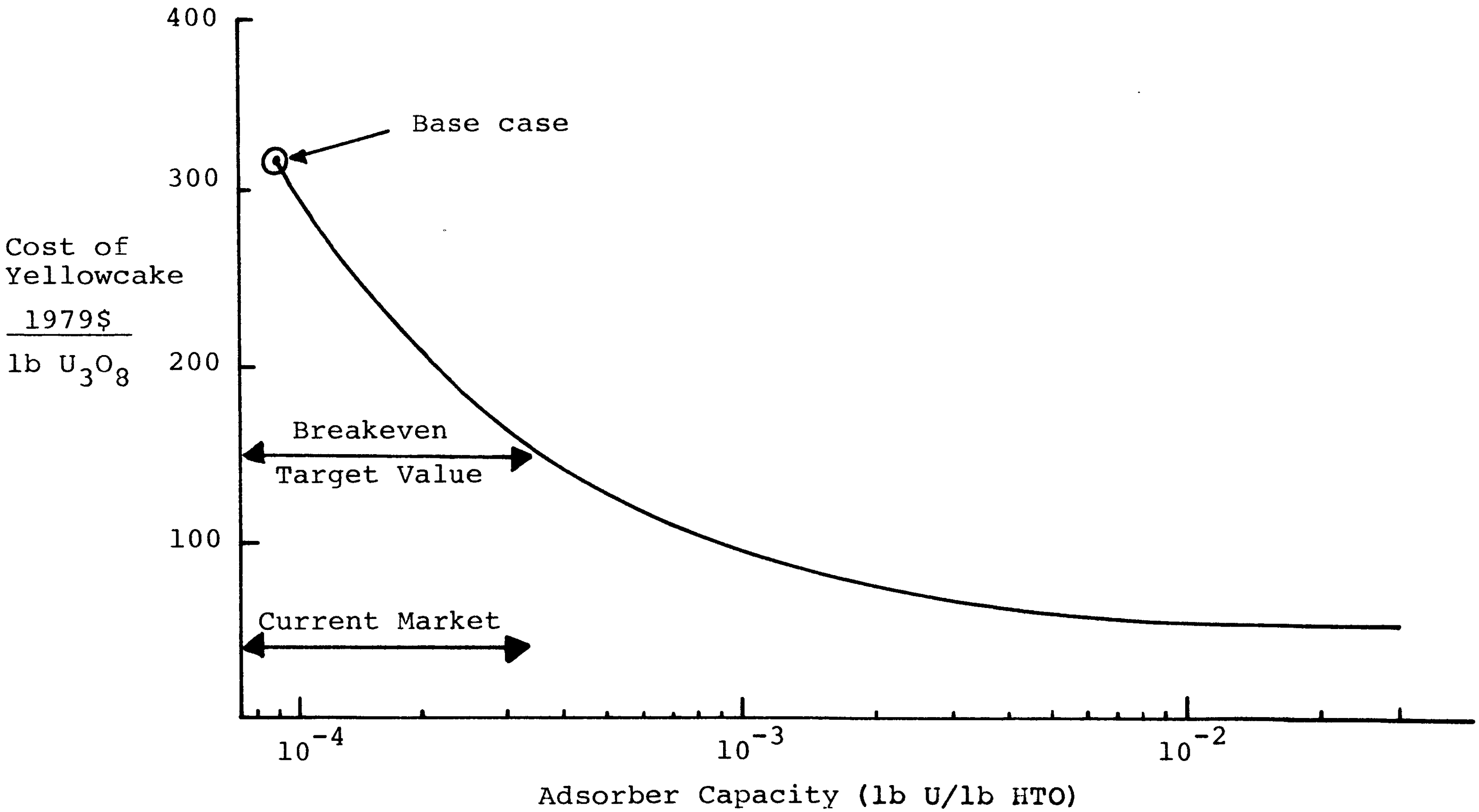


Fig. 3.7 Optimized U_3O_8 Cost as a Function of Adsorber Capacity

The pumping power was varied from the base case value, to ten times the base case value. The data are shown in Appendix C and plotted in Figure 3.8. This figure shows that,as expected from the sensitivity studies, the cost of uranium production increases much less than one-to-one with increasing pumping power requirements. This indicates that increases in pumping power requirements (due for example to the need for augmented pre-filtering or excessive bed fouling) could be offset by relatively smaller increases in adsorber capacity.

3.7 Summary

As a result of running the URPE code over a wide range of bed operating conditions, it was found that U_3O_8 produced from seawater using current state-of-the-art materials could not cost less than about 316 \$/lb U_3O_8 (1979 \$). This result is also supported by a comparison of URPE performance and economics models with ORNL and Exxon analyses. Inclusion of interest on capital during construction would increase this value, but increases in sorber capacity would lead to offsetting cost reductions. The potential of higher capacity adsorbers for reducing costs, together with development of an effective method of reducing the costs of chemicals expended during elution, could bring the ultimate production cost below 150 \$/lb U_3O_8. Indeed, this goal would appear assured if capacities typical of ion exchange resins could be demonstrated for uranium in seawater.

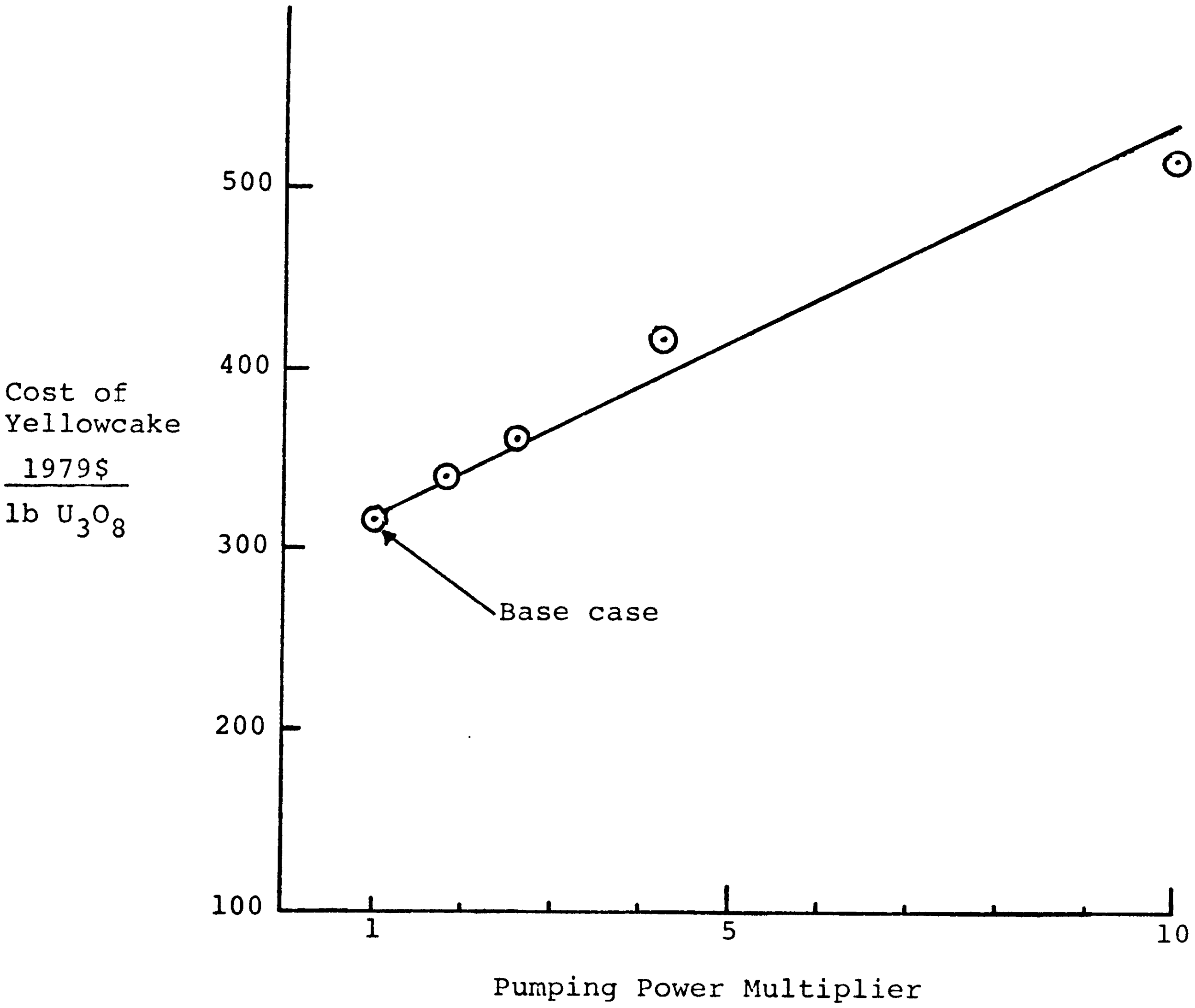


Fig. 3.8 Optimized U_3O_8 Cost as a Function of an Increase in Pumping Power Requirements

The importance of optimizing HTO coating thickness has been highlighted by determining the sensitivity of production cost to this variable. It has also been shown that, for now, actively pumped systems will produce uranium at a lower cost than passive systems.

Chapter Four discusses the overall conclusions of the present investigation and makes recommendations for future work.

CHAPTER IV

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 Introduction

Interest in the extraction of uranium from seawater has increased in recent years, due to concern over the future availability of moderate cost terrestrial resources, and the growing realization that alternative sources of energy will be more costly and available later in time than originally hoped. In addition, the development of an economic system for recovering uranium from seawater would obviate the need for the breeder, reprocessing, and the widespread use of plutonium. Recognizing these facts, Japan, Great Britain and the Federal Republic of Germany all have uranium from seawater programs very much larger than the efforts in this area underway in the United States.

The Energy Laboratory of the Massachusetts Institute of Technology, under a block grant from the United States Department of Energy, has funded a small project whose objectives were to perform an assessment of the state-of-the-art of the technology of uranium recovery from seawater, to define conditions under which uranium recovery from seawater would be economically attractive, and to set objectives for research and development in this area. A computer simulation program, URPE, was developed to meet these objectives by modeling the performance and economics of a state-of-the-art system for the recovery of uranium from seawater. The URPE code was then used to study and optimize the uranium recovery system, and to determine minimum expected production costs, to examine methods to reduce production costs, and to identify areas for future research and development efforts.

4.2 Summary of the URPE Model

The URPE uranium recovery system is based on an adsorption process in which hydrous titanium oxide (HTO) is used to adsorb uranium from seawater. The system, shown in Fig. 4.1, consists of a deep-water moored oil-rig type platform which supports a pump-diffuser (or for passive systems, a diffuser only) supplying seawater at very low velocity to an adsorbing system. The recovery cycle consists of a uranium loading period, during which seawater passes through the bed, followed by a fresh water wash, followed by an ammonium carbonate elution to desorb the uranium, followed by a fresh water wash and return to a loading period. The uranium-rich ammonium carbonate solution is stripped of ammonia and carbon dioxide, which are recycled to produce fresh ammonium carbonate solution. The uranium is ultimately recovered by an ion exchange process.

A multi-product chemical plant, on board the platform, burns coal to produce steam for electrical generation, ammonium carbonate stripper operation and desalination. Part

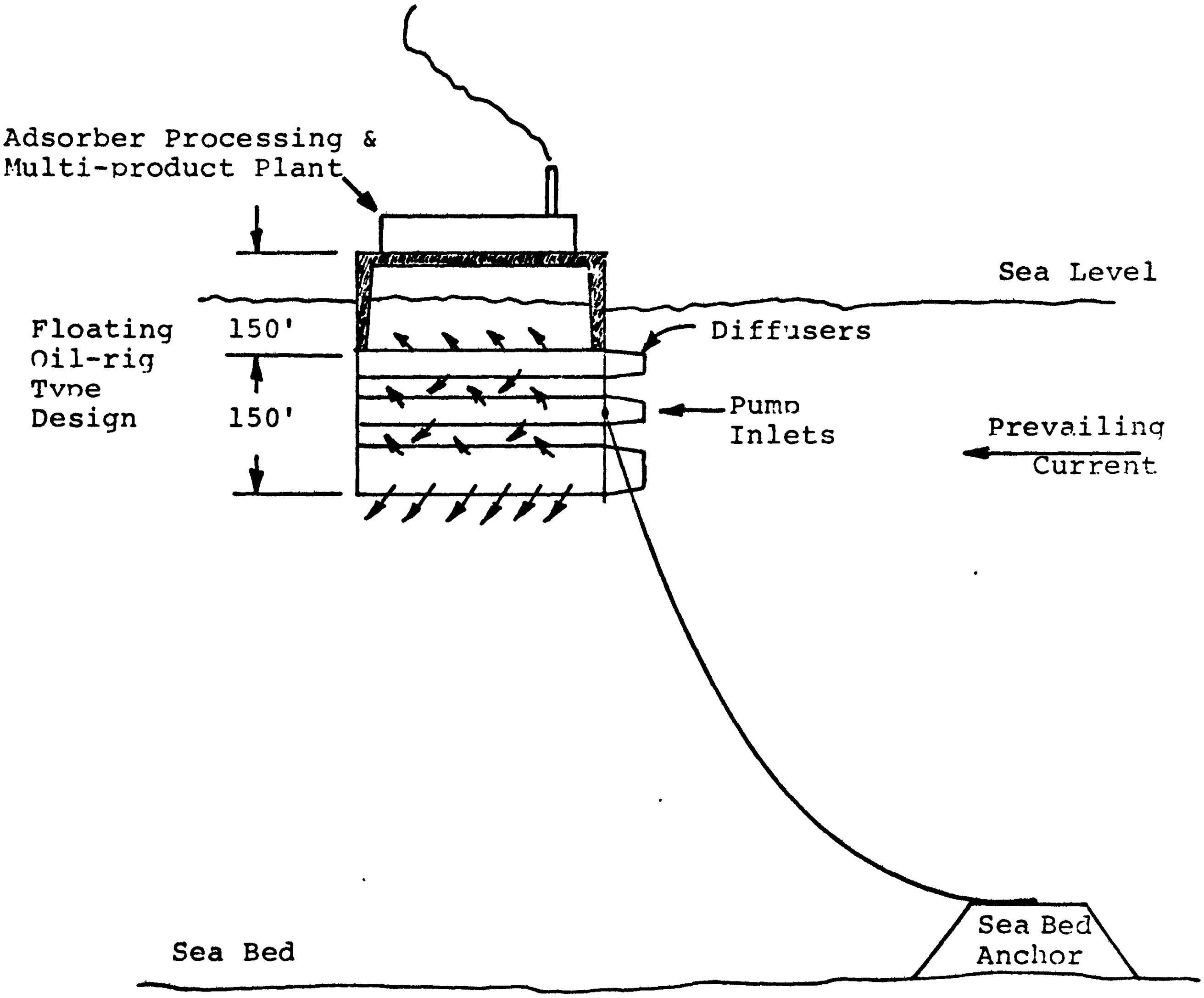


Figure 4.1

Uranium Recovery Plant Module (Side View) of the scrubbed stack gas is absorbed to supply make-up carbon dioxide. Coal and ammonia are brought to the plant by ship (although it would also be possible to synthesize ammonia (D3) on board).

The computer simulation calculates uranium production costs as a function of the physical properties of the adsorber system and the user-input bed operating conditions.

4.2.1 URPE Hydraulics Model

The hydraulic analysis of the uranium recovery system is based on a pump-diffuser arrangement supplying seawater to the adsorber bed. The hydraulic model includes consideration of the pump head, pump efficiency, the head loss in the diffuser, the head loss in pre-filtering mesh screens, the head losses on entering and leaving the bed, and the head loss in the bed itself. Equations 4.1 and 4.2 are the principal formulae used to calculate the system's pumping power requirements.

For packed beds,

$$P = 1.36\text{x}10^{-6} \frac{R\ A_2 V_2^3}{Q_7\ 2\ g} \left[k + 0.05\ A_7^2 + 0.12\ (A_7 - 1)^2 + \frac{27{,}600}{N^2} + 2 \left(\frac{1-v_1}{v_1^{\ 3}} \right) \frac{L_9}{D} \left(\frac{150(1-v_1)}{N} + 1.75 \right) \right] \tag{4.1}$$

For stacked tubes,

$$P = 1.36x10^{-6} \frac{R\ A_2V_2^3}{Q_7\ 2g} \left[0.05\ A_7^2 + 0.12\ (A_7-1)^2 + \frac{27,600}{N^2} + \frac{(2k + P_5 + F*L_9/D)}{v_1^2} \right] \qquad (4.2)$$

where,

P = Pumping power Mw(e),

R = Seawater density (lb/ft^3),

A_2= Bed frontal area (ft^2),

V_2= Superficial velocity (ft/sec),

Q_7= Pump efficiency,

A_7= Bed-area-to-intake area ratio,

N = Reynolds number,

k = Kinetic energy correction factor; equal to 2 for laminar flow conditions, 1 for turbulent flow

v_1= Bed void fraction,

L_9= Bed thickness (ft),

D = Characteristic dimension (ft),

F = Friction factor for tubes,

P_5= Tube entrance loss coefficient (a function of geometry and N),

g = Conversion factor (32.2 ft-lb$_m$/lb$_f$-sec^2), and $1.36x10^{-6}$ converts pumping power to Mw(e).

Auxiliary equations are used to calculate the friction factor and entrance loss coefficients for the stacked tube system.

Equations 4.1 and 4.2, with the pump head set equal to zero, are used to calculate the flow when the plant is designed to operate as a passive ocean current interceptor system.

4.2.2 Adsorption Kinetics Model

An adsorption process was selected as the most attractive method for the recovery of uranium from seawater. Hydrous titanium oxide (HTO) is the adsorber of choice, in concurrence with the recommendations of all research organizations active in this field. Equation 4.3, taken from Thomas' solution (S3) gives the uranium concentration in the adsorber as a function of time and position in the bed,

$$\frac{q}{q_o} = \frac{1-J(nT,\ n/K)}{J(n/K,nT) + [1-J(n,nT/K)]\ \exp\ [(1-K^{-1})(n-nT)]} \qquad (4.3)$$

where, J(x,y) is the integral of a modified Bessel function. J(x,y) was expanded and then integrated to get a series approximation which could be used to evaluate J(x,y). This expression is given by,

$$\begin{aligned} J(x,y) = 1 - e^{-x-y} \Bigg[& e^{x} - 1 \\ & + \frac{y}{1!} \left(\frac{-x}{1!} + \frac{1(e^{x}-1)}{1!} \right) \\ & + \frac{y^{2}}{2!} \left(\frac{-x^{2}}{2!} + \frac{2}{2!} \left(\frac{-x}{1!} + \frac{1(e^{x}-1)}{1!} \right) \right) \\ & + \frac{y^{3}}{3!} \left(\frac{-x^{3}}{3!} + \frac{3}{3!} \left(\frac{-x^{2}}{2!} + \frac{2}{2!} \left(\frac{-x}{1!} + \frac{1(e^{x}-1)}{1!} \right) \right) \right) \\ & + \dots \qquad (4.4) \\ & + \dots \\ & + \dots \Bigg] \end{aligned}$$

Where in Eqs. 4.3 and 4.4,

$$n = \frac{K_4 \ a \ z}{V_2} \qquad (4.5)$$

$$nT = \frac{K_4 \ a \ C_o}{R \ q_o} \left(t - \frac{z \ v_1}{V_2} \right) \qquad (4.6)$$

and,

K_4 = Bed kinetic rate constant (ft/sec),

a = Bed surface area per unit volume,

C_o = Inlet uranium concentration (moles/ft^3),

R = Bulk density of adsorber (lb/ft^3),

t = Time from start of flow (sec),

z = Distance into bed (ft),
v_1 = Bed void fraction,
V_2 = Fluid superficial velocity (ft/sec)
K = Uranium-HTO equilibrium constant.

The terms in Eq. 4.4 are specifically arranged so that during evaluation, when <u>hundreds</u> of terms may be necessary, out of range conditions do not occur in the computer. Note that Eq. 4.3 must be integrated over the volume of the adsorber bed to determine the total uranium being held at any instant of time. In addition, the equilibrium constant, K, and the kinetic rate constant, K_4, must be known or calculated for each set of bed operating conditions.

K is a physical property of the uranyl-HTO adsorption system. Prior to the present work, no one had published a value for this property. Figure 4.2 shows the equilibrium isotherm which was calculated for the uranyl-HTO system based on an analysis of published experimental data (O4) gathered for a different purpose. The equilibrium constant was found to have a value of 2.28. The triangle-enclosed points on the figure are from (O5).

K_4, the bed kinetic rate constant, is a function of the equilibrium constant, K, the fluid phase and solid phase mass transfer coefficients, and the bulk bed operating conditions. Prior to the present work, the kinetic rate constant was either estimated by assuming proportionate-pattern bed behavior, or measured for every bed operating condition.

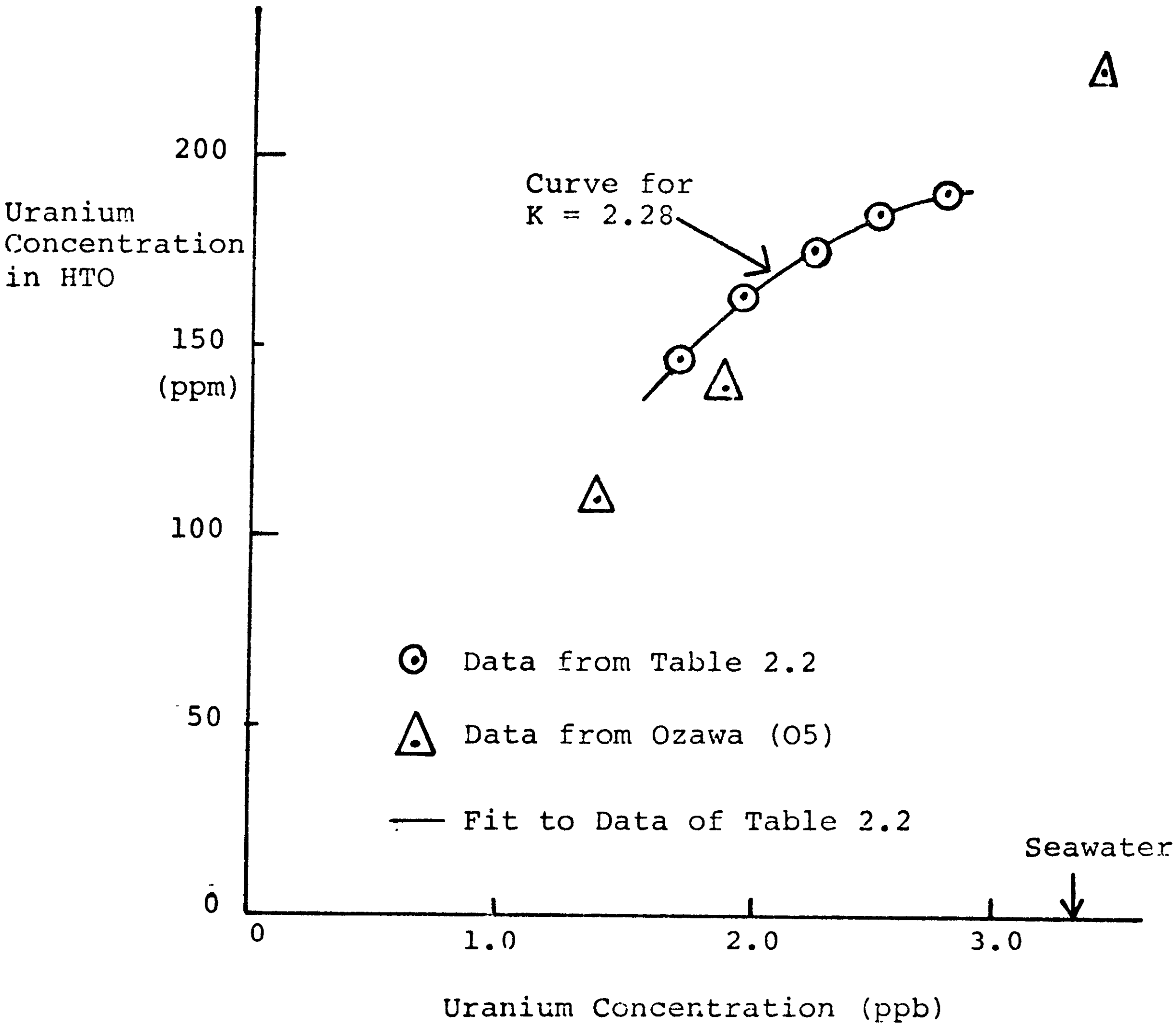


Fig. 4.2 Uranium - HTO Adsorption Isotherm

A new generalized formula for calculating the kinetic rate constant was derived by using the boundary conditions of the problem and the equilibrium expression relating the uranium concentration in the fluid at the particle's surface to the uranium concentration in the solid at the particle's surface. Equation 4.7 (shown below) allows one to calculate the rate constant for any bed operating condition,

$$K_4 = K_f \left[1 - \frac{-b + \sqrt{b^2 + 4(K-1)}}{2(K-1)} \right] \tag{4.7}$$

where,

$$b = 2 + \left[\frac{K_p \; R \; q_o}{K_f \; C_o} - 1 \right] K \tag{4.8}$$

K_p, K_f = Solid and fluid side mass transfer coefficients (ft/sec),

R = Adsorber bulk density (lb/ft^3),

q_o = Uranium concentration in adsorber (moles/lb),

C_o = Uranium concentration in seawater (moles/ft^3),

K = Equilibrium constant.

The forms of the solid and fluid phase mass transfer expressions are taken from standard correlations. However, the diffusivity of the uranyl species in HTO must be known in order to calculate the solid phase mass transfer coefficient. The diffusivity had not been published in the open literature prior to the present work. The diffusivity was estimated to be $4.73\text{x}10^{-15}$ ft^2/sec based on an analysis of two separate sets of experiments (K1, K2).

Equations 4.3 through 4.8, with auxiliary expressions for the void fraction and surface area per unit volume of bed, together with the equilibrium constant and diffusivity, form the basis for the calculation of the time and space dependent uranium concentration in the bed.

4.2.3 Chemical Consumption Model

The uranium-HTO adsorption process requires that the uranium be desorbed from the HTO for ultimate recovery. Ammonium carbonate was selected as the eluting agent, principally because it is easily recycled. Ammonium carbonate is lost or consumed in the bed and in the recycling process. Equations 4.9 and 4.10 were derived to give the ammonia and carbon dioxide loss rates, respectively:

$$C_6 = \frac{A_2\ L_9}{V_8+V_9}\left[0.08(0.4133)R_2(1-v_1)v_2+4(2.12\text{x}10^{-2})\right]\ \frac{\text{lb NH}_3}{\text{hr}} \tag{4.9}$$

and

$$C_7 = \frac{A_2L_9}{V_8+V_9}\left[0.94(0.04)0.4133\ R_2(1-v_1)v_2+0.06(4)0.274\right]\ \frac{\text{lb CO}_2}{\text{hr}} \tag{4.10}$$

where,

C_6 = Average ammonia consumption rate,

C_7 = Average carbon dioxide consumption rate,

A_2 = Bed area (ft^2),

L_9 = Bed thickness (ft),

V_8 = Elution time (hr),

V_9 = Loading time (hr),

R_2 = HTO density (lb/ft^3 adsorber), (not bulk density),

v_1 = Bed void fraction,

v_2 = Volume of active adsorber ÷ total particle volume.

4.2.4 Economics Models

The cost of producing uranium is calculated by using a levelized cost model,

$$U_2 = \frac{H_1\ (1+H_2)\ \sum [\text{Capital Costs}] + \begin{array}{c}\text{Annualized Operation}\\ \text{\& Maintenance Costs}\end{array}}{M_8\ 2204} \tag{4.11}$$

where,

U_2 = Levelized cost of producing U_3O_8 (\$/lb U_3O_8),

H_1 = Annual fixed charge rate (1/yr),

H_2 = Lang factor relating total plant cost to component capital cost

Capital Cost = The summation of all major capital costs, present worthed to the start of plant operation,

Annualized O&M = All consumable and service charges,

M_8 = Actual annual U_3O_8 production rate (MT U_3O_8/yr).

Based on current market conditions, the annual fixed charge rate for private investment was estimated to be 25%/yr. For government ownership, H_1 was set equal to 10%/yr. The Lang factor, relating total installed cost to major capital costs is estimated to be 4.46 based on a review of analogous chemical process systems (B7).

The annualized capital cost of the pumps and motors is given by,

$$B_9 = \frac{H_1 \; W_9 \; P \; Q_7 \quad 1000(1.1)}{M_8 \; 2204} \qquad \frac{\$}{\text{lb } U_3O_8} \qquad (4.12)$$

where,

W_9 = The unit cost of the pumps (\$/kw-shaft),

P = Total pumping power (Mw(e)),

Q_7 = Pump efficiency,

1.1 = Factor to include spares and allow for breakdowns.

The annualized capital cost of the initial HTO inventory and bed support structure is given by

$$B_8 = \frac{H_1 \; A_2 \; L_9[(1-v_1)v_2 \; R_2 \; W_6 + 0.5]}{M_8 \; 2204} \qquad \frac{\$}{\text{lb } U_3O_8} \qquad (4.13)$$

where,

W_6 = Installed bed cost (\$/lb HTO).

The annualized capital cost of the oil-rig platform and mooring is given by,

$$B_2 = \frac{H_1[(0.02T_m+522)A_2/A_7+1265T_p\ e^{0.006\ T_p}}{M_8\ 2204} \tag{4.14}$$

where,

T_m = Depth of water (ft),

T_p = Platform height (ft),

B_2 = Annualized capital cost of the platform-mooring system (\$/lb U_3O_8).

The cost of electricity is given by a parametric equation:

$$W_7 = \frac{1000}{8766\ F_9}\left[H_1\ 1348\left(\frac{P_8}{50}\right)^{-0.425} + 31.42\left(\frac{P_8}{50}\right)^{-0.321}\right] + \frac{0.142\ W_3}{Q_8} \tag{4.15}$$

where,

W_7 = Cost of electricity (mills/kw-hr),

P_8 = Effective plant rating (Mw(e)),

F_9 = Plant capacity factor,

W_3 = Cost of coal (\$/ton delivered),

Q_8 = Thermal efficiency,

and

$$P_8 = \left[\frac{3.33(1000)}{p-1.03} + 4(79)\right]\frac{62.4(0.1167)}{3413(1000)}\ \frac{A_2L_9}{V_8+V_9} + P \tag{4.16}$$

where,

P = Seawater pumping power (Mw(e)),

p = Desalination plant performance ratio (lb water/1000 BTU),

and the first term in Eq. 4.16 is used to calculate the power requirement of the desalination and stripper process heat loads.

The unit cost of desalinated water is given by the parametric expression,

$$W_8 = \frac{1000}{365.25\ F_9}\left[H_1\ 3.64\ S^{-0.2} + 0.07\ S^{-0.31}\right] + \frac{0.284\ W_7}{p} \tag{4.17}$$

where,

$$S = \frac{1.19\times10^{-5}}{1 - \frac{1.03}{p}}\ \frac{A_2 L_9}{V_8 + V_9} \tag{4.18}$$

W_8 = Unit cost of water (\$/kgal).

The unit cost for carbon dioxide is given by,

$$W_4 = \frac{1}{F_9}\left[H_1 (0.346)(C_7)^{-0.2606} + \left(\frac{3.42\ W_7}{218}\right) 0.00865\ (C_7)^{-0.0872}\right] \tag{4.19}$$

where,

W_4 = Unit cost of carbon dioxide (\$/lb CO_2).

The pumping power cost is given by,

$$B_7 = \frac{P\ 8766\ F_9\ W_7}{M_8\ 2204} \qquad \frac{\$}{\text{lb } U_3O_8} \qquad (4.20)$$

The cost of carbon dioxide consumption is given by,

$$B_4 = \frac{C_7\ 8766\ F_9\ W_4}{M_8\ 2204} \qquad \frac{\$}{\text{lb } U_3O_8} \qquad (4.21)$$

The cost of ammonia consumed is,

$$B_3 = \frac{C_6\ 8766\ F_9\ W_5}{M_8\ 2204} \qquad \frac{\$}{\text{lb } U_3O_8} \qquad (4.22)$$

The cost of water consumed is,

$$B_5 = \frac{3\ A_2L_9\ 7.48(8766)F_9W_8}{1000(V_8+V_9)\ 2204\ M_8} \qquad \frac{\$}{\text{lb } U_3O_8} \qquad (4.23)$$

The cost of HTO lost is given by,

$$B_6 = \frac{R\ V_2\ A_2\ 3600(8766)\ F_9\ z_5\ A_8\ v_2\ R_2\ W_6}{M_8\ 2204} \qquad \frac{\$}{\text{lb } U_3O_8} \qquad (4.24)$$

where,

z_5 = Seawater flow duration ÷ total cycle time,

A_8 = Volumetric material loss rate (ft^3/lb seawater),

and all other terms are as defined previously.

Equations 4.12 through 4.24 are substituted into Eq. 4.11 to obtain the levelized cost of U_3O_8 production.

Equations 4.1 through 4.10 constitute the set of equations used to describe the engineering performance of the uranium recovery system. Equations 4.11 through 4.24 constitute the set of equations used in URPE to calculate the cost of U_3O_8 production.

4.3 Summary of URPE Results

4.3.1 Comparison with other Designs

The URPE code performance and economics models were tested by performing sensitivity studies and by running the code using the physical properties, parameters, and economic ground rules used in the two major design studies prior to the present work - the ORNL (H1) and Exxon studies (B5,B6).

Table 4.1 lists the Oak Ridge and URPE results all in 1979 \$/lb U_3O_8. The URPE[a] and URPE[b] cases are for active pumping and current-interceptor systems respectively, both calculated using ORNL adsorber properties, bed operating conditions and economic ground rules. The difference in the results is due to the difference in uranium recovery efficiency. The recovery efficiency used by ORNL was not calculated directly from adsorber properties, but rather extrapolated from a reported recovery efficiency for different bed conditions. The URPE[c] case is based on the same bed operating conditions as the ORNL study, but using the URPE standard adsorber properties and economic ground rules. From the results of Table 4.1 it is clear that URPE performance and economics models are more conservative than the ORNL assumptions, with the exception of adsorbent and elution losses. The URPE adsorbent and elution loss models are based on data not available at the time of the ORNL study.

Table 4.2 lists the Exxon and URPE results in 1978-79 \$/lb U_3O_8. The Exxon design is based on an actively pumped system. The URPE[a] case shown was run using Exxon's input

Table 4.1

Comparison of Oak Ridge and URPE Results

	Oak Ridge	URPE[a]	URPE[b]	URPE[c]
Performance:				
Uranium Recovery	80%	10%	10%	9%
Bed Area (ft^2)	$1.1x10^7$	$9.0x10^7$	$9.0x10^7$	$9.4x10^7$
Attrition (lb HTO/lb U_3O_8)	140	37	37	42
Ammonia (lb/lb U_3O_8)	263	3574	3574	2459
Carbon Dioxide (lb/lb U_3O_8)	704	8464	8464	4035
Economics (all costs in 1979 \$/lb U_3O_8)				
Adsorbent losses	139	31	31	35
Chemicals	82	633	633	296
Water	2	17	17	282
Pumping Power	0	82	0	71
Annualized capital, maintenance, and labor	404	677	624	638
Total 1979\$/ lb U_3O_8	627	1440	1305	1322

---

[a] URPE, active pumping, ORNL unit costs and bed operating conditions.

[b] URPE, current interceptor, ORNL unit costs and bed operating conditions.

[c] URPE, active pumping, data of Tables 3.1 and 3.2, ORNL bed operating conditions.

Table 4.2

Comparison of Exxon and URPE Results

	Exxon	URPE[a]	URPE[b]	URPE[c]
Performance:				
Uranium Recovery (in bed)	80%	83%	57%	82%
Bed Area (ft^2)	2.1×10^7	1.9×10^7	2.1×10^8	1.7×10^7
Attrition (lb HTO/lb U_3O_8)	56	22	12	37
Ammonia (lb/lb U_3O_8)	518	448	458	457
Carbon dioxide (lb/lb U_3O_8)	533	586	1060	279
Economics[d]				
Adsorbent losses	28	11	6	19
Chemicals	91	37	48	38
Water		25	53	27
Pumping Power	58	70	6	85
Annualized capital, maintenance, and labor	1260(563)[e]	414	220	481
Total 1978-79 \$/lb U_3O_8	1437(740)[e]	557	333	650

---

[a] URPE, run using all Exxon ground rules Table 3.6.

[b] URPE, run using Exxon economic ground rules Table 3.6 and optimized bed conditions.

[c] URPE, run using Exxon bed conditions and plant capacity Table 3.6 and URPE ground rules, Tables 3.1 and 3.2 for government ownership.

[d] All costs are shown in 1978-1979 \$/lb U_3O_8.

[e] No interest on capital during construction.

for physical properties, bed operating conditions, and economic groundrules. URPE^b was run with the same physical properties and economic ground rules as URPE^a, but with optimized bed operating conditions. URPE^c was run with the Exxon bed conditions, but normal URPE physical properties and economic ground rules for government ownership.

Comparing the performance results of the Exxon study with URPE^a shows that the two analyses give very similar results. However, the annualized capital cost terms are different: the Lang factor inferred from the Exxon study is larger and their results include a large allowance for interest on capital during construction. Subtracting the interest on capital during construction from the Exxon total (shown in parentheses) gives results which are in much closer agreement. Qualitatively, the interest on capital during construction is not expected to be as important for the URPE system as it is for the Exxon design, because the URPE system is based on modular shipyard style construction rather than on the use of large terrestrial civil works constructed over a long period of time as in the Exxon design.

URPE^b is based on the same physical properties and economic ground rules as the Exxon study and URPE^a, but with optimized bed operating conditions. This analysis shows the potential for cost reduction possible through optimization of bed conditions. The most significant changes between URPE^a and URPE^b are due to reductions in fluid velocity, bed thickness, and active adsorber coating thickness.

$URPE^C$ was run using normal URPE physical properties and economic ground rules, but with Exxon bed operating conditions. Comparison of $URPE^C$ with the Exxon results provides a benchmark for evaluating other URPE analyses.

4.3.2 Optimized URPE Designs

Tables 4.3 and 4.4 list the physical properties and economic ground rules which were used in the subsequent URPE analyses. Tables 4.5 and 4.6 list the performance and economic results calculated for optimized active and passive, packed bed and stacked tube adsorbing systems. The results show that packed bed systems give performance superior to stacked tube systems, and that actively pumped systems are presently superior to passive ocean current interceptor designs.

Packed particle beds are seen to be superior to stacked tube designs due, in part, to the more effective use of adsorbing material in packed beds, but principally due to increased fresh water and chemical costs in stacked tube systems. Actively pumped systems are presently superior to passive systems due to their more compact and less costly bed designs, made possible by using the higher heads available in pumped systems. As shown, the minimum expected cost is 316 (1979 \$)/lb U_3O_8 for an actively pumped packed particle bed system, and 451 (1979 \$)/lb U_3O_8 for a passive current interceptor packed particle bed design.

Two sensitivity studies were conducted to determine the effect of bed operating conditions on production cost. For the

Table 4.3

Physical Properties Used in the URPE Analysis

Adsorber Properties:

Uranium Capacity, $Q_9 = 8.68 \times 10^{-5}$ lb U/lb HTO
(210 mgU/Kg Ti)

Uranium-HTO Equilibrium Constant, $K = 2.28$

Diffusivity of Uranium in HTO, $S_1 = 4.73 \times 10^{-15}$ ft^2/sec

Schmidt number for the uranyl species in seawater, $S = 7030$

Attrition Rate, $A_8 = 9.95 \times 10^{-10}$ $\dfrac{\text{ft}^3\text{ adsorber}}{\text{lb seawater}}$

Density of HTO coating, $R_2 = 93.6$ lb/ft^3 of coating

Bulk Void Fraction, (outside volume ÷ total bed volume) $v_1 = 0.40$ for particles; a function of diameter for tubes

Seawater Properties:

Uranium Concentration, $C_9 = 3.34 \times 10^{-9}$ lb U/lb seawater

Seawater Density, $R = 63.7$ lb/ft^3

Viscosity, $V = 3.74$ $\text{lb}_m\text{/ft-hr}$

System Operating Characteristics:

Pre-elution fresh water wash (lost to sea) = 3 bed volumes

Ammonium carbonate elution = 4 bed volumes

Post-elution freshwater wash (recovered for further use) = 4 bed volumes

Table 4.3 (Continued)

Physical Properties Used in the URPE Analysis

System Operating Characteristics:

Ammonium Carbonate eluting solution concentration = 0.1 M

Table 4.4

Economic Factors Used in the URPE Analysis

Annual Fixed Charge Rate,	H_1	= 25% per year for private ownership = 10% per year for government ownership
Uranium Production rate,	M_8	= 200 MT U_3O_8 per year
Lang Factor,	H_2	= 4.46
Plant Capacity Factor,	F_9	= 0.80
Pump Capital Cost,	W_9	= 150 \$/kw-shaft
Hydrous Titanium Oxide Cost,	W_6	= 0.83 \$/lb HTO
Ammonia Cost,	W_5	= 0.10 \$/lb ammonia
Coal Cost,	W_3	= 40 \$/Ton at the port (12,000 BTU/lb)
Bed Support Material		= 0.50 \$/ft^2 of bed
Round Trip Distance from plant-to-port,	N_9	= 3000 nautical miles

Table 4.5

Optimized Packed Bed and Stacked Tube Systems with Active Pumping

	Packed Bed	Stacked Tube
A. Bed Operating Conditions:		
Superficial Velocity (ft/sec)	0.00355	0.00816
Characteristic Dimension (ft)	0.000212	0.000344
Bed Thickness (ft)	0.0387	0.339
Loading Time (hr)	32	69
Area Ratio	2200	982
Coating Thickness (ft)	1.74×10^{-5}	2.15×10^{-5}
B. Calculated Performance:		
Uranium Recovery	74%	40%
Bed Area (ft^2)	3.34×10^{7}	2.44×10^{7}
Loading Fraction	82%	76%
Pumping Power (Mw(e))	48	38
Effective Plant Size (Mw(e))	90	178
C. Calculated Unit Costs:		
Water ($/kgal)	5.5	4.3
Electricity (mills/kw-hr)	61	51
Carbon Dioxide ($/lb CO_2)	0.014	0.012
Ammonia ($/lb NH_3)	0.10	0.10

Table 4.5 (Continued)

Optimized Bed and Stacked Tube Systems with Active Pumping

	Packed Bed	Stacked Tube
D. Economics:*		
Adsorbent Losses	11	8
Chemical Make-up	39	52
Water	63	164
Pumping Power	46	31
Annualized Capital, Maintenance and Labor	156	227
Total \$/lb U_3O_8	315	482

*All costs are in 1979 \$/lb U_3O_8

Table 4.6

Optimized Packed Bed and Stacked Tube Systems of the Passive Ocean Interceptor Type

		Packed Bed	Stacked Tube
A.	Bed Operating Conditions:		
	Superficial Velocity (ft/sec)	0.00207	0.00189
	Characteristic Dimension (ft)	0.000591	0.000505
	Bed Thickness (ft)	0.0543	0.0880
	Loading Time (hr)	51.0	73.2
	Area Ratio	2830	3110
	Coating Thickness (ft)	2.14×10^{-5}	2.78×10^{-5}
B.	Calculated Performance:		
	Uranium Recovery	48%	40%
	Bed Area (ft^2)	8.19×10^{7}	10.2×10^{7}
	Loading Fraction	72%	69%
	Pumping Power	NA	NA
	Effective Plant Size (Mw(e))	99.2	145
C.	Calculated Unit Costs:		
	Water ($/kgal)	4.71	4.46
	Electricity (mills/kw-hr)	56.7	56.7
	Carbon Dioxide ($/lb CO_2)	0.012	0.012
	Ammonia ($/lb NH_3)	0.10	0.10

Table 4.6 (Continued)

	Packed Bed	Stacked Bed
D. Economics:[b]		
Adsorbent Losses	8.3	9.8
Chemical Make-up	49.6	56.6
Water	126	174.6
Pumping Power	NA	NA
Annualized Capital, Maintenance and Labor	267	357
Total \$/lb U_3O_8	451	598

[a] Calculations based on a 4 mph current.

[b] All costs are in 1979 \$/lb U_3O_8.

first study, each bed operating parameter was increased (and decreased), and the resulting U_3O_8 production cost calculated. Table 4.7 shows the sensitivity of total production cost to changes in bed operating conditions. The sensitivities are positive for both increases and decreases in the bed parameters, because the sensitivity study was performed using the optimum bed parameters as the base case. The sensitivity shown was calculated by dividing the percent change in total cost by the percent change in the bed parameter.

Overall, the sensitivities show a strong resistance to further decreases in the values of bed operating parameters. As velocity is decreased, bed capital and consumable chemical costs rise sharply. As the characteristic dimension is decreased, pump related costs rise sharply. As bed thickness decreases, pump and bed related costs rise. As loading time decreases, consumable chemical costs rise. As coating thickness decreases, pump, bed and water costs rise.

Total production cost may vary due to changes in the performance model as well as changes in the bed operating parameters. Table 4.8 lists the sensitivity of production cost to changes in the sub-models. The sensitivities show that on a relative basis cost is most strongly dependent on the fixed charge rate, the plant capacity factor, and the Lang factor. The high sensitivity of total cost to the solid phase resistance to mass transfer emphasizes the importance of accurately modeling and improving bed performance in this area.

Table 4.7

Sensitivity of Total Cost to Bed Operating Conditions

Parameter	Sensitivity % Change in Cost per % Change in Parameter
Superficial Velocity	
Decrease	3.2
Increase	0.54
Characteristic Dimension	
Decrease	2.6
Increase	0.67
Bed Thickness	
Decrease	2.4
Increase	0.37
Loading Time	
Decrease	4.0
Increase	0.39
Area Ratio	
Decrease	0.16
Increase	0.14
Coating Thickness	
Decrease	5.2
Increase	1.0

Table 4.8

Sensitivity of Total Cost ($/lb U_3O_8) to Modeling Accuracy

Case No.	Assumed Change in the Model	% Change in Cost / % Change in Model
1.	Base Case	
	Pumping Head	
2.	+20%	0.18
3.	-20%	-0.19
	Fluid Side Mass Transfer	
4.	+20%	-0.01
5.	-20%	0.02
	Solid Side Mass Transfer	
6.	+20%	-0.14
7.	-20%	0.21
8.*	Eliminating Solid Side Resistance	-0.80
	Ammonia Consumption	
9.	+20%	0.12
10.	-20%	-0.12
	CO_2 Consumption	
11.	+20%	0.01
12.	-20%	-0.01
	Balance of Plant Cost	
13.	+20%	0.39
14.	-20%	-0.39

*Case 8 sensitivity = % Change in Cost ÷ 20%

Table 4.8 (Continued)

Sensitivity of Total Cost ($/lb U_3O_8) to

Modeling Accuracy

Case No.	Assumed Change in the Model	% Change in Cost / % Change in Model
	Attrition Rate	
15.	+20%	0.04%
16.	-20%	-0.04%
	Water Consumption	
17.	+20%	0.17
18.	-20%	-0.17
	Fixed Charge Rate	
19.	+20%	0.75
20.	-20%	-0.75
	Plant Capacity Factor	
21.	+20%	-0.50
22.	-20%	0.75
	Bed Void Fraction	
23.	+20%	+0.04
24.	-20%	+0.29

4.3.3 The Effect of Large Changes in Pumping Requirements and Adsorption Capacity

The adsorption capacity and pumping power requirements were studied in more detail than the sensitivity analysis discussed in Sec 4.3.2, because of their importance in the overall system model. The study was performed by starting from the optimized base case, increasing the item of interest, and reoptimizing the entire uranium recovery system design. The adsorption capacity was varied from the generally accepted minimum value of 8.68×10^{-5} lb U/lb HTO (210 mg U/kg Ti), to a maximum of 3×10^{-2} lb U/lb HTO (72,600 mg U/kg Ti). This includes the entire range of reported values of capacity, concluding with a capacity which might be typical of an ion exchange resin. The pumping power was varied from the base case value to ten times the base case value. Figs 4.3 and 4.4 show the results of these calculations.

Figure 4.3 shows that very large (but not physically impossible) increases in sorber capacity would be required to bring production cost down to the 1979 spot market price for U_3O_8, 40 \$/lb U_3O_8.

However, the capacity need only be increased to four times its present value, or 847 mg U/kg Ti, in order to produce uranium at the 150 \$/lb U_3O_8 breakeven price (for U_3O_8 used in LWR's in competition with breeder reactors or coal-fired units). Figure 4.4 indicates that increases in pumping power requirements (due for example to increased pre-filtering requirements or excessive bed fouling) could be offset by relatively smaller increases in adsorber capacity.

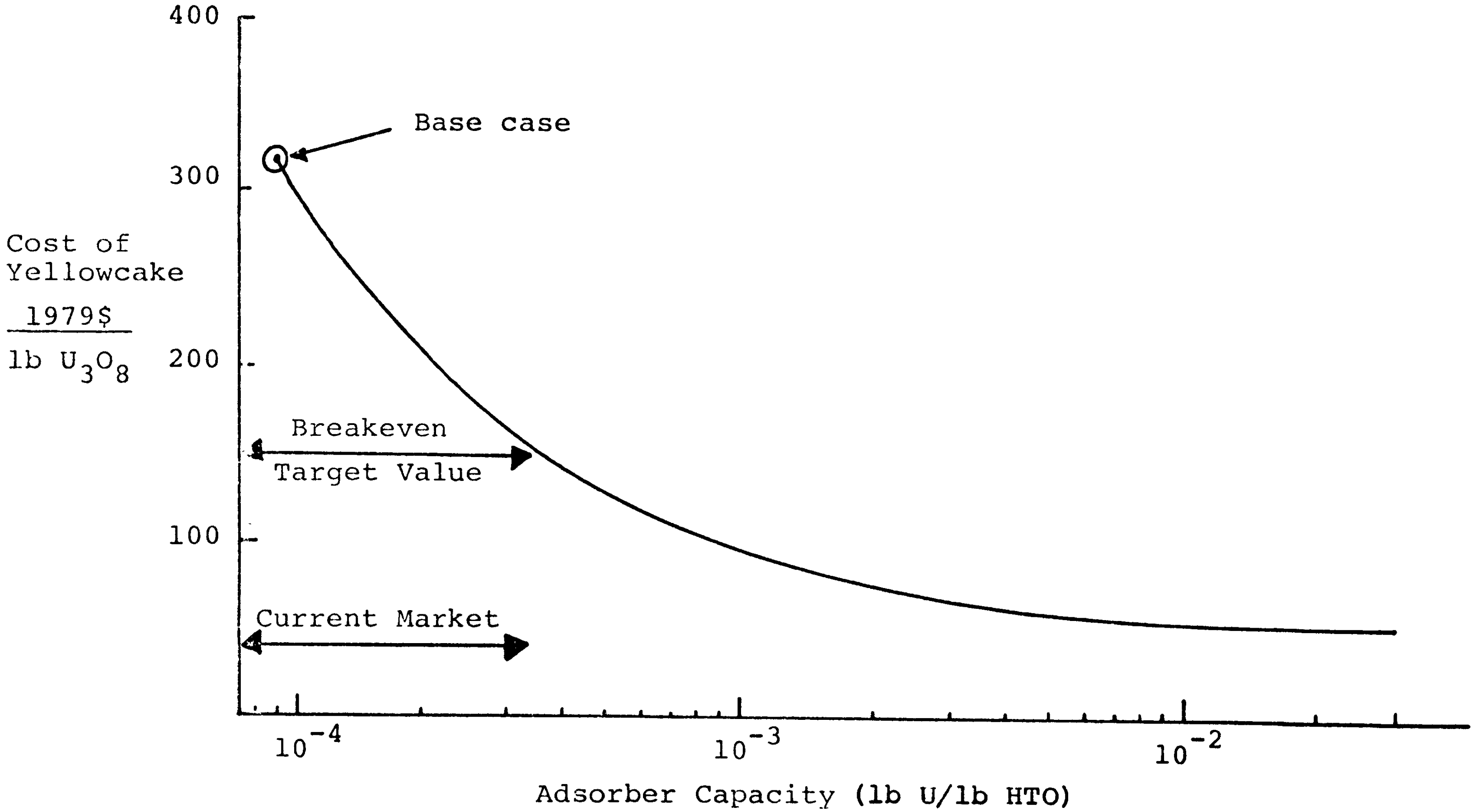


Fig. 4.3 Optimized U_3O_8 Cost as a Function of Adsorber Capacity

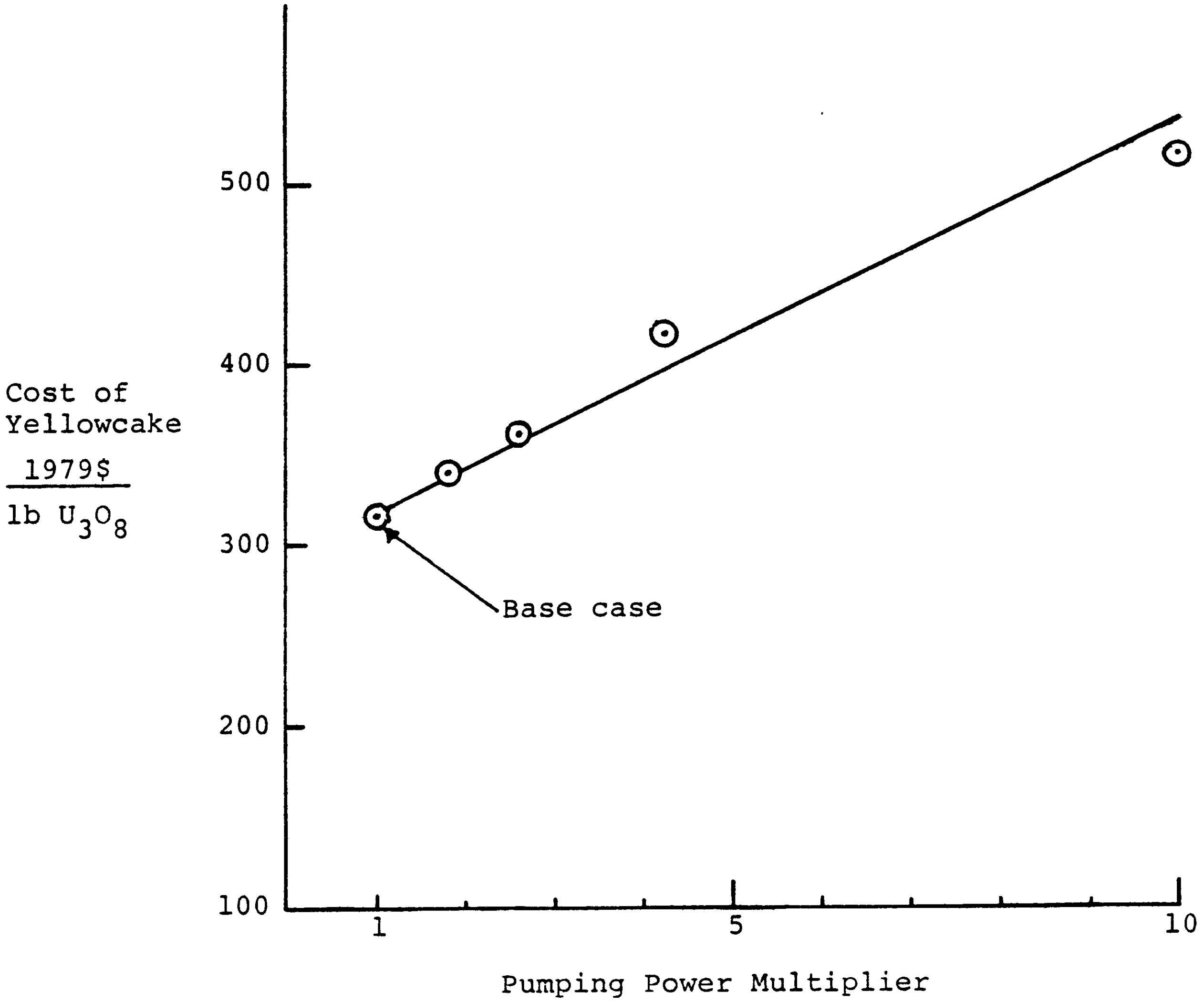


Fig. 4.4 Optimized U_3O_8 Cost as a Function of the Increase in Pumping Power Requirements

4.4 Conclusions and Recommendations

4.4.1 Assessment of the State-of-the Art

One major conclusion to be drawn from the present work is that the current state-of-the-art is insufficiently advanced to allow economic recovery of uranium from seawater, but that there are no intrinsic reasons why an economic recovery system could not be developed in the longer term.

Basic experimental information on the physical properties of the adsorber of choice, currently hydrous titanium oxide, must still be determined. However, based on the existing data certain trends can be discerned.

The equilibrium isotherm for the uranium-HTO system seems to be of the favorable equilibrium type. The equilibrium constant was estimated to be 2.28. The diffusion constant for the uranium species in HTO is estimated to be 4.73×10^{-15} ft^2/sec. A new generalized technique for calculating the kinetic rate constant for a fixed bed adsorption system was developed. Using this technique, an overall performance/economics model, URPE, was assembled to describe actively pumped and passive ocean interceptor systems. The performance and economic results have been compared with the results of prior studies at the Oak Ridge National Laboratory and Exxon Nuclear. It was found that the URPE-generated performance characteristics compare reasonably well, or are conservative, with respect to these prior results. The three studies use different economic ground rules, but when they are adjusted to a common basis, the URPE code is seen to be conservative with respect to the ORNL study, and slightly optimistic with respect to the Exxon study.

The results of a sensitivity analysis using the URPE code disclose a strong dependence on active adsorber coating thickness, bed loading time, fluid velocity and particle size. It was observed that by optimizing bed operating conditions, even using Exxon's ground rules, significant decreases in production cost can be achieved. Using the URPE code ground rules, the minimum production cost is calculated to be 316 (1979 \$)/lb U_3O_8 for an actively-pumped packed particle bed system, and 451 (1979 \$)/lb U_3O_8 for a passive ocean current interceptor system. These values are the basis for the conclusion that a system relying only upon currently available technology is not competitive.

4.4.2 Conditions for Economic Uranium Recovery

It was found that the dependence of recovery cost on adsorber capacity is such that an increase in capacity by a factor of four (to $\sim 3.5 \times 10^{-4}$ lb U/lb HTO) would reduce production costs to about 150 (1979 \$)/lb U_3O_8 which is the break-even cost of yellowcake for LWR use in competition with breeder reactors (U1). Uranium production cost would be reduced to about 47 (1979 \$)/lb U_3O_8 if adsorption capacities typical of ion exchange resins could be achieved ($\sim 3 \times 10^{-2}$ lb U/lb HTO). Failing the achievement of increased adsoprtion capacity, the overall production cost may still be lowered by developing porous adsorbing particles. These would allow uranium to move into the interior of the particles in the fluid phase where diffusion is considerably more rapid than in the solid phase. Further, Tables 4.5 and 4.6 show that the cost of chemicals and water, even expensive desalinated water, are not limiting factors in the overall production cost. Rather, it is the cost of the pumps, bed material, and bed structural supports which dominate in the proposed design. This can be overcome somewhat by use of more frequent elution cycles, if the chemical costs can be reduced. The ideal solution, however, would be to develop a material having an increased adsorption capacity, since this directly reduces adsorber inventory and bed structure, as well as reducing chemical consumption.

4.4.3 Recommendation of Objectives for Research and Development

The objectives for research and development identified during the course of this evaluation are grouped according to whether they concern the adsorber, the overall system design, or economics.

Research objectives dealing with the adsorber category are:

1. Efforts should be made to develop an adsorber with a capacity at least four times the present state-of-the-art value of 210 mg U/kg Ti.

2. The true mechanism by which the uranyl species is removed from seawater should be identified.

3. The equilibrium isotherm, the diffusivity, the kinetic constant, and their temperature dependence should be measured for candidate adsorber materials in the range of 0-3 ppb U in seawater.

4. The adsorber loss from a bed should be measured under realistic operating conditions, and the loss mechanism determined.

5. Elution and fresh water wash kinetics experiments should be carried out as the basis for development of an accurate elution model.

6. As one approach to realization of objective (1), a method for producing a thin porous coating of activated HTO on an inexpensive substrate should be developed.

7. Investigators should continue to search for materials which are superior to HTO; in particular ion exchange resins may be attractive alternatives.

Research objectives involving the overall system are:

1. An at-sea design for an actively pumped uranium recovery system must be developed and fully costed out. In particular,

   a) a technique for fabricating thin, inexpensive sorber beds must be worked out. The use of fluidized beds may be an alternative course of action.

   b) a technique for wash-elution of the sorber with reduced water and chemical consumption should be developed. For example, wash water requirements may be reduced if the bed could be drained of seawater before washing.

2. The impact on the local biota, and the ocean circulation patterns around the plant must be evaluated.

3. The legal implications of this form of sea mining must be assessed.

Finally, suggested objectives for follow-on economic analyses are:

1. Incorporate a generalized model which deals with cash flows during plant construction.

2. Up-date component costs as new cost data become available.

4.5 Concluding Comments

The recovery of uranium from seawater has been a subject of interest for at least the last twenty years. The technology is still in its infancy, if, indeed, it can be said to have been born. The successful development of this technology, which would do away with the need for reprocessing, the breeder reactor and commerce in plutonium could have a significant impact on reducing the conflict between nations for the earth's dwindling resources, and the level of technology needed to acquire access to a ubiquitous and inexhaustible energy supply. This achievement would hopefully also reduce the reluctance by some to concur in the wider deployment of nuclear power. Since the benefits are so great, and since our findings hold out hope for eventual success, we recommend the continuation of efforts, along the lines suggested herein.

APPENDIX A

User's Manual for URPE

(Uranium Recovery Performance and Economics)

A.1 Introduction

The purpose of this appendix is to provide the documentation necessary to execute the URPE program. The development of the models used in URPE is detailed in Chapter Two.

URPE is an interactive program written in the BASIC programming language for use on the Tektronix 4051 computer. The program requires 24 Kbytes of core and is routinely stored on a tape cartridge between uses. The program is available through Professor Michael J. Driscoll of the Nuclear Engineering Department of the Massachusetts Institute of Technology. The program is written using English Engineering Units, and all costs built into the program are in 1979 dollars.

Figure A.1 is a simplified schematic of the program. Section A.2 of this appendix provides a list of program variables. Upon execution, the program initializes certain variables to values taken from its data file. Section A.3 of this appendix describes how to change the value of variables in the data file. Section A.4 describes program execution. During execution (after initialization), the

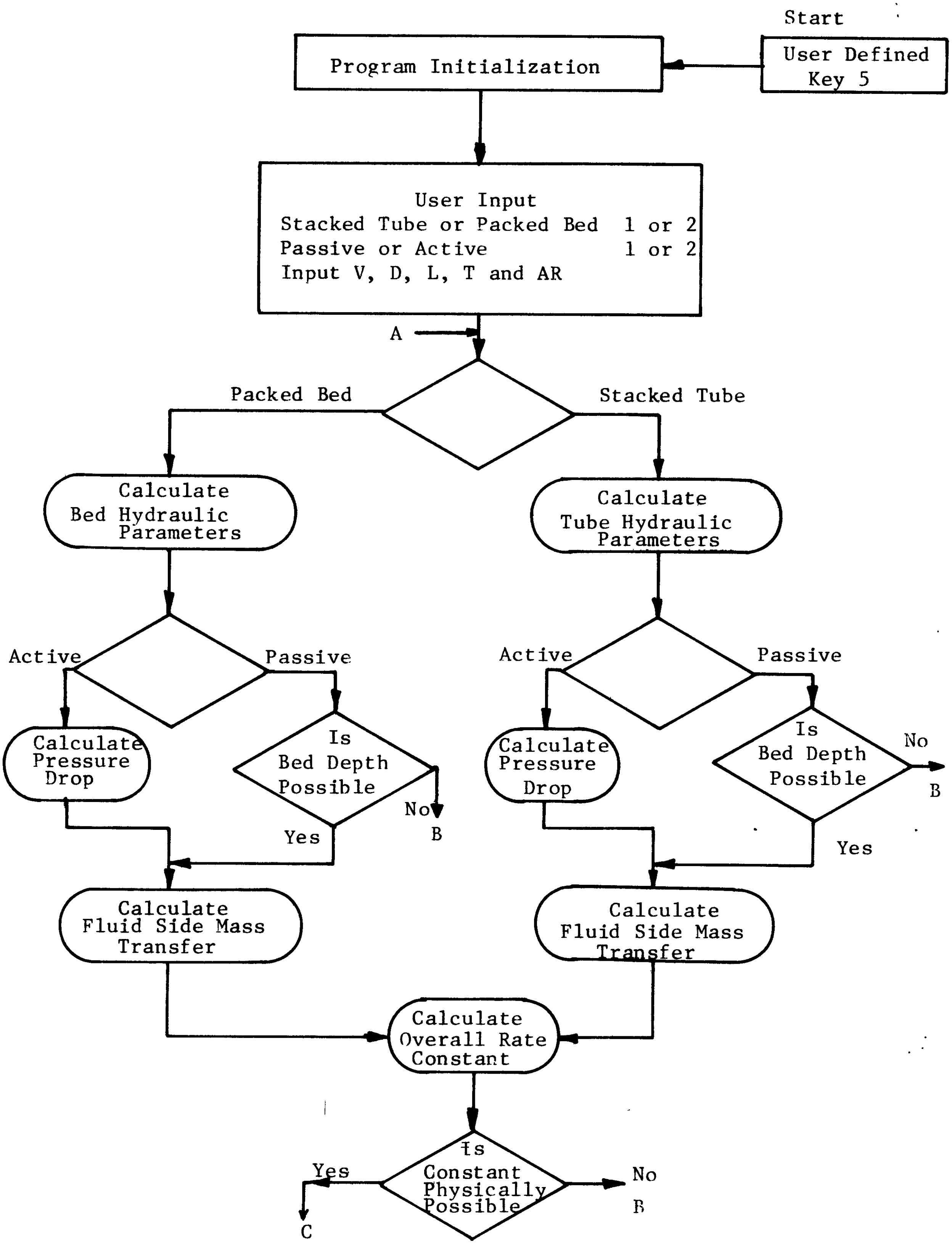


Figure A.1 Schematic of Program URPE

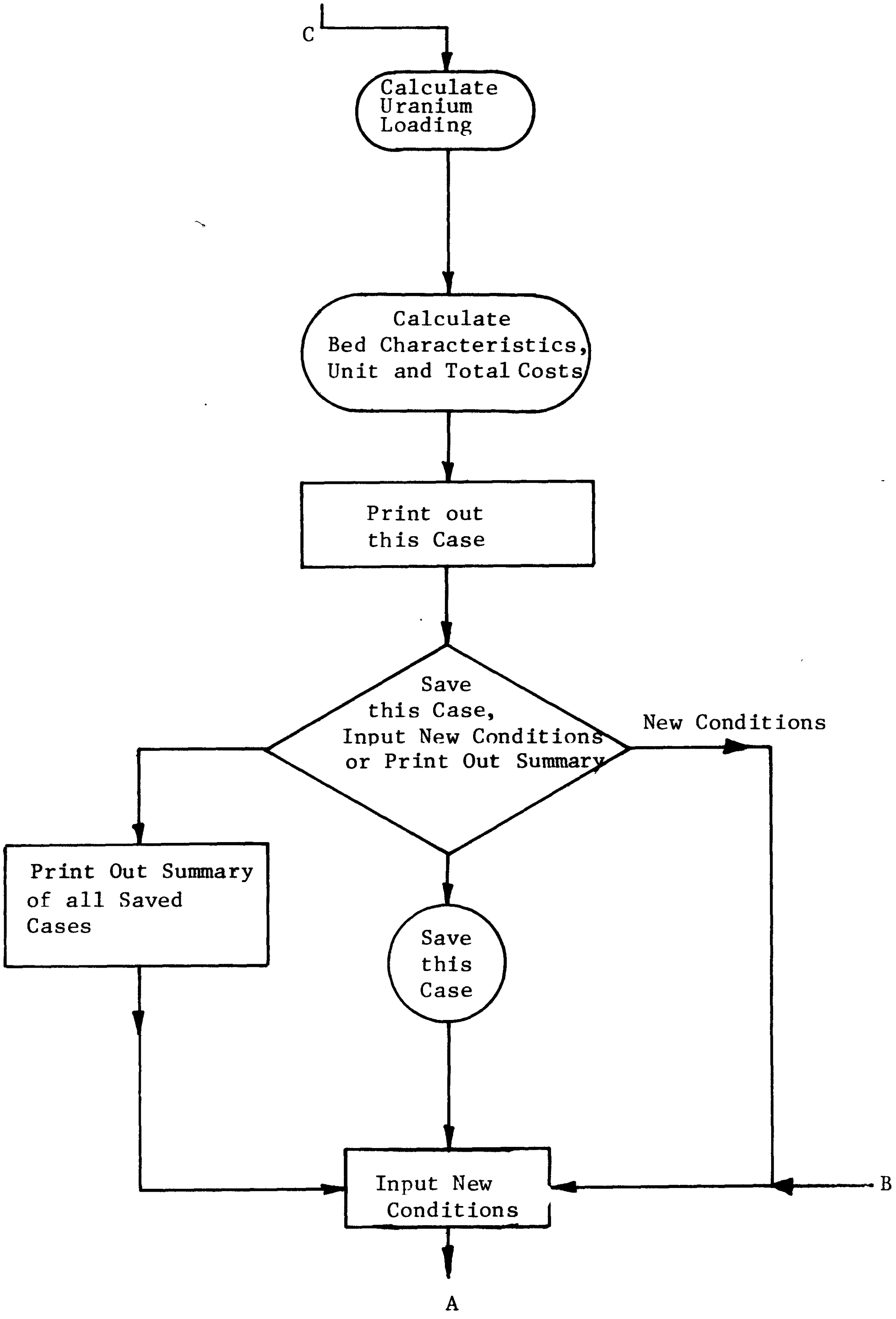


Figure A.1 (Continued)

program requests the user to select the type of system being analyzed; packed particle bed or stacked tube bed, and the values of key system operating parameters, such as fluid superficial velocity, bed characteristic dimension (particle diameter or tube inner diameter), bed depth, bed loading time and the ratio of bed frontal area to system inlet frontal area. The program calculates hydraulic conditions in the bed based on the user-selected pumping system. If a passive pumping scheme has been selected, the program checks pressure drops to insure that flow is hydraulically possible. If the user input conditions do not result in an allowable flow, the program prints an error message and requests new input data. Once an acceptable hydraulic configuration has been achieved, the program calculates the system mass transfer coefficient (kinetic). The program checks to be sure that the calculated kinetic constant is physically possible (i.e., non-negative), printing an error message and request for new data if necessary.

The program calculates and prints out system performance characteristics and uranium production costs. The user may then terminate the program, save the results of this calculation in memory, input new run data, or print out a summary from memory of all retained cases.

Section A.5 of this appendix contains a listing of the program. Section A.6 is a sample problem.

A.2 Program Variables

The following is a list of variables, with associated units, as used in URPE. Some variables are initialized to a certain value and retain this value throughout the program. Some variables are initialized to a certain value but change during program execution. Other variables are dummy variables whose value and dimension depend on their location in the program.

Variable	Unit(s)	Initial Value	Comments
A	*	0	number of retained cases analyzed
A2	FT^2	**	total bed frontal area
A5	*	**	tube flow region indicator
A6	*	**	average uranium recovery efficiency
A7	*	**	user input; ratio of bed frontal area to system intake area
A8	FT^3/LB seawater	2.21×10^{-10}	volumetric attrition loss rate
A9	*	**	dummy variable
B2	$/LB U308	**	allocated cost of moored oil-rig type platform
B3	$/LB U308	**	allocated cost of ammonia consumption
B4	$/LB U308	**	allocated cost of carbon dioxide consumption
B5	$/LB U308	**	allocated cost of water consumption
B6	$/LB U308	**	allocated cost of bed attrition
B7	$/LB U308	**	allocated cost of electricity consumed
B8	$/LB U308	**	allocated cost of adsorber bed
B9	$/LB U308	**	allocated cost of pumps and motors
C6	$/LB U308	**	average ammonia consumption rate
C7	LB CO2/HR	**	average carbon dioxide consumption rate
C9	LB U/LB seawater	3.34×10^{-9}	uranium concentration in seawater
D	FT	**	user input; particle diameter or tube inner diameter
F	*	**	tube friction factor

Variable	Unit(s)	Initial Value	Comments
F1	*	**	dummy variable
F2	*	**	dummy variable
F9	*	0.8	plant capacity factor
G	FT-LBm/ LBf-SEC^2	32.2	conversion factor
H1	1/YR	0.25	annual fixed charge rate
H2	*	4.46	Lang Factor relating partial capital cost to total plant cost
I	*	**	dummy variable
I1	*	10	number of bed intervals for averaging calculations
I5	*	**	dummy variable
I6	*	**	dummy variable
I7	*	**	dummy variable
I8	*	**	dummy variable
J	*	**	dummy variable used in averaging calculations
K1	FT/SEC	**	stacked tube turbulent mass transfer coefficient
K3	*	2.28	Uranium-$Ti(OH)_4$ equilibrium constant
K4	FT/SEC	**	dummy variable which becomes rate constant
L5	FT	**	passive operation stacked tube maximum length
L8	FT	**	passive operation packed particle bed maximum thickness
L9	FT	**	user input; bed thickness
M	*	**	array used for storage of case data
M8	MT U308	200	plant U308 production capacity
M9	LB U/HR	**	plant uranium production rate

Variable	Unit(s)	Initial Value	Comments
N	*	**	bed Reynolds number
N9	thousands of nautical miles	3	total nautical miles round-trip from port to plant
O1	MW(E)	**	electricity producible from uranium recovered
O2	$\frac{\text{MW(E)-SEC}^3}{\text{FT}^2\text{-LBm}}$	**	conversion factor
O8	FT	**	dummy variable
O7	**	**	dummy variable
P	MW(E)	**	bed pumping power consumption
P5	*	**	dummy variable
P8	MW	**	power plant effective size
Q	*	**	volume-average fractional uranium loading
Q2	*	**	average fractional uranium loading
Q7	*	0.86	pump efficiency
Q8	*	0.30	small power plant overall efficiency
Q9	LB U/LB adsorber	8.68×10^{-5}	uranium capacity per mass of active adsorber
R	LBm/FT^3	63.7	seawater density
R2	LBm/FT^3	97.6	active adsorber density
S	*	7030	initially Schmidt number; then $S^{-2/3}$
S1	$\text{FT}^2\text{/SEC}$	4.17×10^{-15}	diffusivity of uranium in titanium hydroxide
S6	*	**	dummy variable
S7	*	**	dummy variable
S8	*	**	variable controlling active or passive operation
S9	*	**	variable controlling active or passive operation

Variable	Unit(s)	Initial Value	Comments
T2	*	**	Energy Amplification Factor
T3	FT	9.84×10^{-5}	active adsorber coating thickness
T4	FT	**	tube wall total thickness
U1	FT/SEC	**	user input; superficial fluid velocity
U2	$/LB U308	**	total uranium production cost
V	LBm/FT-HR	3.74	seawater viscosity
V1	*	**	bed void fraction
V2	*	**	active material volume/ total material volume
V3	FT^2/FT^3	**	surface area/ unit volume
V8	HR	**	bed wash-elution-wash time
V9	HR	**	user input; bed loading time
W2			
W3	$/TON	40	initial cost of coal at harbor; recalculated to include shipping charges
W4	$/LB	**	calculated unit cost of carbon dioxide
W5	$/LB	0.1	unit cost of ammonia
W6	$/LB	0.827	unit cost of active adsorber
W7	Mills/KW-HR	**	calculated unit cost of electricity
W8	$/KGAL	**	calculated unit cost of water
W9	$/KW	214	pump capital cost per unit shaft KW
X7	*	**	dummy variable
X8	*	**	dummy variable
X9	*	**	dummy variable

Variable	Unit(s)	Initial Value	Comments
Y3	*	**	dummy variable
Y5	*	**	dummy variable
Y6	*	**	dummy variable
Y7	SEC	**	calculated time to fill bed with seawater
Y8	*	**	dummy variable
Y9	*	**	dummy variable
Z5	*	**	calculated ratio of loading time to total cycle time

---

*Dimensionless

**Not initialized

A.3 Data File Revision

In the analysis of uranium recovery from seawater, certain variables are not routinely changed. Seawater properties such as density and viscosity are examples of this type of variable. Variables (for which an initial value is shown in Section A.2, and which are not revised, as noted in the "comment" entry) constitute the entirety of this category. It is relatively easy to change these values prior to program execution by following the procedure outlined below.

Refer to the Tektronix User's Manual for general instructions on loading a program into the Tektronix core from a tape cassette. With the program in core memory, execute a "LIST" command and locate the statement number which contains the value of the variable to be changed. Call this statement into the Tektronix buffer and change the value of interest. Press "RETURN" to compile the new value into the program. The code is now ready for execution.

A.4 Program Execution

Refer to the Tektronix User's Manual for general instructions on loading a program into the Tektronix core from a tape cassette. The descriptive material which follows assumes that a satisfactory program exists in-core. Section A.2 provides a list of program variables. See Section A.3 for instructions on changing values in the program data file.

The program is started by pressing User Defined Key Number 5. As seen on Fig. A.1, this initializes the value of certain variables in the program. The program will then ask the user whether a stacked tube or packed bed system is to be analyzed. The program also displays the number codes for stacked tube and packed bed systems. The user should enter a "1" and depress "RETURN" for stacked tube operation or a "2" and depress "RETURN" for packed bed operation.

The program next asks whether an active or passive pumping system is to be used. The user should enter a "1" and depress "RETURN" for passive operation or a "2" and depress "RETURN" for active pumping.

The program will then print "INPUT VALUES OF U, D, L, T, AR." This is a request by the code for the operating conditions in the uranium recovery system. "U" is the superficial fluid velocity in the adsorber bed expressed in feet per second. "D" is the characteristic dimension of the adsorber in the bed expressed in feet. For a particle bed, the characteristic dimension is particle diamter. For a stacked tube bed, the characteristic dimension is tube inner diameter. "L" is bed thickness expressed in feet. "T" is bed loading time expressed in hours. Bed loading time is the number of hours per load-wash-elute-wash cycle during which seawater is moved through the bed. "AR" is the ratio of the bed frontal area to the seawater intake area.

The user should type the desired fluid velocity "U", then a comma "," ; the desired characteristic dimension "D", then a comma ","; the desired bed thickness "L", then a comma ","; the desired loading time "T", then a comma ","; finally, the desired area ratio "AR" then "RETURN". The code automatically begins program execution at this point.

The code checks the user input characteristic dimension "D" in comparison with the data file thickness of the active adsorber coating to insure that the configuration so described is physically possible. For particle beds, the code checks that the particle diameter is at least twice as large as the adsorber coating thickness. If the data file coating thickness is too large for the particle diameter, the coating thickness is set equal to approximately half the particle diameter. In effect, the particles become solid adsorbing material, rather than an active coating on an inert core. For tube beds, the code checks to insure that the tube wall is at least twice as thick as the adsorber coating thickness. If the coating thickness is too large for the characteristic dimension chosen, the code prints a message saying that this is the case, and waits for new input data. The user should realize that only fluid superficial velocity, characteristic dimension, bed thickness, loading time and area ratio are potential input data. Of these, only the characteristic dimension can affect the coating thickness error message condition. If the user wishes to change the coating thickness, the program data file will have to be changed. See Section A.3 for further discussion on data file changes. The code waits for a new input datum by printing the message "INPUT NEXT VALUE OR SEARCH TYPE: (-) U=1, D=2, L=3, T=4, AR=5". If this is the first time this message has been encountered in this execution of the program, or if the wrong "SEARCH TYPE" has been established, (see below for further discussion of "SEARCH TYPE") the user will have to select the variable to be changed. The characteristic dimension "D" is changed by entering "-2" and executing "RETURN". The new value of "D" is then entered (in feet) and "RETURN" executed. The code restarts program execution.

If a passive system is being studied, the code next checks system hydraulics to insure that flow exists under the user input conditions. If the fluid velocity or area ratio are too small, the fluid head may be insufficient to force seawater through the system. If this is the case, the code prints an error message stating "AREA RATIO OR CURRENT TOO LOW FOR PASSIVE OPERATION," and also prints the maximum possible bed thickness (in feet) which the system could have under the user input conditions. The code then waits for a new input datum. As in the case of the coating thickness versus characteristic dimension check, the code prints out the message "INPUT NEXT VALUE OR SEARCH TYPE: (-) U=1, D=2, L=3, T=4, AR=5". The user may correct the no-flow condition by increasing bed superficial velocity, characteristic dimension or area ratio, or by decreasing the bed thickness. Changing the loading time has no effect on a no-flow condition. The variable to be changed (typically L) is identified to the code by typing either 1,2,3,4 or 5 preceded by a minus "-" sign, and executing "RETURN". The code then reprints "INPUT NEXT VALUE OR SEARCH TYPE: (-) U=1, D=2, L=3, T=4,AR=5". The user should then type the value of the variable in the appropriate units and execute "RETURN". The code then restarts program execution.

Having rechecked both the characteristic dimension versus coating thickness and that flow exists in the system, the program calculates the kinetic reaction rate constant for the adsorber bed. The code checks to insure that the kinetic reaction rate constant is physically possible and prints an error message if it is negative. If negative, the code then prints the "INPUT NEXT VALUE..." message and awaits a corrected input datum. The user selects the variable to be changed and enters the new datum as described above. The program then restarts program execution.

Assuming that all comparison checks are met satisfactorily, the program calculates a variety of system performance and economic characteristics resulting from the user-input operating conditions. See Section A.6 for a sample of the single case printout summary. The variables printed are:

1. EAF - Energy Amplification Factor, the amount of thermal energy recoverable from the uranium in a LWR divided by the "effective" amount of thermal energy consumed in extracting the uranium from seawater. "Effective" thermal energy includes the thermal energy used to generate electrical power consumed by the seawater pumps (if an active pumping system is used) plus the thermal power used in the desalination and ammonium carbonate stripper units.
2. Bed Depth - sorber bed thickness in feet.
3. Area Ratio - the ratio of bed frontal area to seawater intake area.
4. "S9" code identifying the type of system being analyzed; stacked tube or particle bed.
5. Load Time - the number of hours per overall cycle during which seawater flows through the system.
6. "#" - the number of cases already stored in program memory.
7. Current Speed - printed only for passive systems; the open ocean seawater speed in miles per hour.
8. "U" - fluid superficial velocity in the bed in feet per second.
9. "D" - characteristic adsorber dimension in feet; for particle beds, "D" is particle diameter; for tube beds, "D" is tube inner diameter.

10. "R EFF" - this is the average uranium recovery efficiency during the loading cycle.

11. "A" - bed frontal area in square feet.

12. REGIME - the Reynolds number for flow in the tubes of stacked tube systems; for particle bed systems, "REGIME" is either the Reynolds number for flow in the bed or a code number indicating an out-of-range condition on the pressure drop correlation. For particle bed systems, a Reynolds number out of specification low results in a "-1" being printed out under the "REGIME" heading. A "-2" printed out under "REGIME" indicates a Reynolds number out of specification high. In practice, these error conditions occur very infrequently. If an out of specification condition does occur, the user will have to investigate further to determine the acceptability of the results.

13. "$/LB U308" - the total allocated cost of U_3O_8 recovery in 1979 dollars.

14. "CHEM COST" - the allocated cost of chemical consumption.

15. "PMP CPTL" - the allocated cost of pump capital cost.

16. "BED CPTL" - the allocated cost of bed capital cost.

17. "BOP" - the allocated cost of the balance of the plant exclusive of pump and bed capital cost.

18. "PWR CST" - the allocated cost of electricity supplied to seawater pumps.

19. "BED ATRN" - the allocated cost of replacement adsorber for adsorbing material lost from the bed due to attrition.

20. "WATER" - the allocated cost of fresh water consumed in uranium recovery from seawater.

21. "MRNG CST" - the allocated cost of a moored oil-rig type platform.

At the end of the single case print-out summary, the program prints the standard message "INPUT NEXT VALUE. . .". The user may then select several follow-on options:

1. Typing "0" (zero) and executing "RETURN" causes the program to store the results of this case in program memory for later output. The code then prints the standard request for input datum message.

2. Typing "-9" and executing "RETURN" causes the program to print out a summary of all cases saved by the "0" (zero) command discussed above. The code then prints the standard request for input message.

3. Typing "-1", "-2", "-3", "-4" or "-5" causes the program to set up to receive a particular piece of input datum. "-1" establishes a superficial fluid velocity input condition; "-2" a characteristic dimension input condition; "-3" a bed depth input condition; "-4" a loading time input condition; "-5" an area ratio input condition.

Upon typing any one of the above codes and executing "RETURN" the program prints the standard request for input message and awaits the new input datum. The user should then type in, in appropriate units, the new input datum. Executing "RETURN" will cause the program to restart.

"-1", "-2", "-3", "-4" and "-5" are referred to as "Search Types" because they are used to establish a search in a particular variable space (velocity, characteristic dimension, bed depth, loading time, or area ratio). The Search Type need not be specified each time the standard request for input data message is encountered. The Search Type must be specified only when the standard request for input data message is first encountered or when the Search Type is to be changed. For example, if"-1" is typed and "RETURN" executed the first time the "INPUT NEXT VALUE OR SEARCH TYPE: (-) U=1, D=2, L=3, F=4, AR=5" message is encountered, the next and all following times this message is encountered the user need only type in the new value of the superficial velocity and execute "RETURN" to cause the program to calculate a new case based on the new superficial velocity. The Search Type will remain in the superficial velocity domain until a different "-" (minus) 2 through 5 code is executed in reponse to a standard request for input datum message. The Search Type is not altered by "0" (zero) or "-9" code executions. The program is terminated by typing a "-99" and executing "RETURN" in response to a standard request for input datum message.

Note that "0" and "-9" codes may be used in any order but that calculating a new case before executing a "0" code causes the current case data to be lost. This may or may not be desirable based on the outcome of a particular calculation. In practice, several cases are run with a "0" code storing the results of each calculation prior to running a print-out summary. The print-out run may then be followed by further case studies.

As a final comment on program execution, the code cannot shift bed design or pumping system configuration once these have been chosen in the initial input statements. The program must be terminated and restarted if the user wishes to change the basic system configuration.

Section A.5 presents a listing of the complete program, and Section A.6 displays a sample problem.

A.5 Program Listing

The following pages show the program listing for the URPE code.

```
20 RUN 100
100 INIT
110 REM .....**  PROGRAM URPE  **.........BED AND TUBE  U3O8 COST.......
120 DIM M(27,20)
130 READ R,V,S,F9,G,C9,S1,N9,A
140 DATA 63.7,3.74,7030,0.8,32.2,3.34E-9,4.73E-15,3,0
150 READ H1,H2,W9,W6,W5,W3,Q9,A8,Q8
160 DATA 0.25,4.46,150,0.83,0.1,40,8.68E-5,9.95E-10,0.3
170 READ Q7,M8,K3,I1,T3
180 DATA 0.86,200,2.28,10,9.8425E-5
190 S=S↑-0.6666666
200 O1=M8*0.848*2204*60000*0.32/8766/F9/1000
210 O2=0.001356/(Q7*2000*G)
220 R2=1.5*62.4
230 PAGE
240 M9=M8*0.848*2204/(8766*F9)
250 W3=W3+0.87+0.5752*N9
260 PRINT "STACKED TUBE - 1   OR   PACKED BED - 2  ??"
270 INPUT S9
280 PRINT "ACTIVE OR PASSIVE?   PASSIVE= 1,  ACTIVE=2"
290 INPUT S8
300 PRINT "INPUT VALUES OF V,D,L,T,AR    "
310 INPUT U1,D,L9,V9,A7
320 GO TO S9 OF 580,330
330 N=R*U1*D*3600/V
340 F2=N
343 IF T3<D/2 THEN 350
344 T3=0.99*D/2
350 V1=0.4
360 V2=1-(1-2*T3/D)↑3
370 V3=6*(1-V1)/D
410 GO TO S8 OF 420,490
420 P=0
430 O8=(A7↑2*(1-0.01)-1-(A7-1)↑2*0.12-27611/N↑2)*D*V1↑3
```

```
432 IF O8>0 THEN 435
433 D=D*1.1
434 GO TO 330
435 L8=O8/(2*(1-V1)*(150*(1-V1)/N+1.75))
436 IF L9<L8*1.000001 THEN 510
437 L9=L8
438 GO TO 510
440 IF O8<0 THEN 2300
450 L8=O8/(2*(1-V1)*(150*(1-V1)/N+1.75))
460 IF L9<L8*1.000001 THEN 510
470 PRINT " AREA RATIO OR VELOCITY TOO SMALL FOR PASSIVE OPERATION";L8
475 PRINT "GGGGGGGGGGGGGGGGGGG"
480 GO TO 2100
490 P=(150*(1-V1)/N+1.75)*2*(1-V1)*L9/(D*V1↑3)+0.12*(A7-1)↑2+1
500 P=P+0.05*A7↑2+27611/N↑2
510 IF N>1.0E-3 THEN 540
520 F2=-1
530 GO TO 560
540 IF N<2500*(1-V1) THEN 560
550 F2=-2
560 K4=2.09*U1*N↑-0.585*S
570 GO TO 1070
580 T4=0.047882*D+1.667E-4
581 IF T3<T4/2 THEN 590
582 T4=1.01*2*T3
590 V1=D/(D+2*T4)
600 V2=T3*(6*D+4*T4+3*T3)/(4*T4*(D+T4))
610 V3=(3*D+2*T4)/((D+2*T4)*(D+T4))
620 IF T4>2*T3 THEN 650
630 PRINT "TUBE DIAMETER TOO SMALL FOR COATING THICKNESS"
640 GO TO 2100
650 U1=U1/V1
660 N=R*U1*D*3600/V
670 A5=1
680 IF N>2000 THEN 720
```

```
690 F=64/N
700 A5=2
710 GO TO 810
720 F1=0.07
730 F2=F1
740 F1=1/(0.86*LOG(N*F1)-0.8)
750 IF F2/F1<1.0E-4 THEN 770
760 GO TO 730
770 F=F1↑2
780 IF N>10000 THEN 810
790 A5=1.5
800 F=(64/N+F)/2
810 IF N<10 THEN 870
820 IF N<50 THEN 890
830 P5=3.2486-0.3524*LOG(N)-0.7*V1
840 IF P5>0.2 THEN 900
850 P5=0.2
860 GO TO 900
870 P5=3.455+24.44/N-V1
880 GO TO 900
890 P5=12.032-2.5847*LOG(N)-1.2*V1
900 P=0.05*A7↑2+0.12*(A7-1)↑2+(2*A5+P5+27611/N↑2+F*L9/D)/V1↑2
910 F2=N
920 GO TO S8 OF 930,1020
930 P=0
940 O7=1-(1/(U1*A7))↑2*(P5+27611/N↑2+2*A5)-0.01-0.12*(1-1/A7)↑2
941 IF Z9=0 THEN 950
942 IF O7>0 THEN 946
943 D=1.1*D
944 U1=U1*V1
945 GO TO 580
946 L5=O7*D*(A7*V1)↑2/F
947 IF L9<L5*1.000001 THEN 949
948 L9=L5
949 GO TO 1020
```

```
950 IF O7>0 THEN 980
960 PRINT "AREA RATIO OR CURRENT TOO LOW FOR PASSIVE OPERATION"
965 PRINT "GGGGGGGGGGGGGGG"
970 GO TO 2100
980 L5=O7*D*(A7*V1)↑2/F
990 IF L9<L5*1.000001 THEN 1020
1000 PRINT " AREA RATIO OR CURRENT TOO LOW FOR PASSIVE OPERATION";L5
1010 GO TO 2100
1020 K1=0.0149*U1*S/N↑0.12
1030 K4=8*U1*S/N
1040 IF K4>K1 THEN 1060
1050 K4=K1
1060 U1=U1*V1
1070 Y6=2+K3*(10*S1*Q9*V2*R2/K4/C9/R/(2*T3)-1)
1080 K4=K4*(1-(SQR(Y6↑2+4*(K3-1))-Y6)/2/(K3-1))
1090 IF K4>0 THEN 1120
1100 PRINT " ERROR****   RATE CONSTANT  NEGATIVE"
1110 GO TO 2100
1120 Y9=K4*V3*L9/U1/I1
1130 Y8=K4*V3*R*C9/Q9/R2/(1-V1)/V2
1140 Y7=L9*V1/U1
1150 IF V9*3600>Y7 THEN 1180
1160 PRINT "LOADING TIME TOO SHORT"
1170 GO TO 2100
1180 Y7=Y7/I1
1190 Q=0
1200 J=1
1210 FOR I=0 TO I1
1220 IF I<I1 THEN 1240
1230 J=1
1240 Y6=Y8*(V9*3600-Y7*I)
1250 Y5=Y9*I/K3
1260 GOSUB 2340
1270 X9=EXP(-Y6-Y5)*I8
1280 Y3=Y5
```

```
1290 Y5=Y6
1300 Y6=Y3
1310 GOSUB 2340
1320 X8=1-EXP(-Y6-Y5)*I8
1330 Y6=Y9*I
1340 Y5=Y5/K3
1350 GOSUB 2340
1360 X7=EXP(-Y6-Y5)*I8
1370 Q2=X9/(X8+X7*EXP((Y9*I-Y5*K3)*(1-1/K3)))
1380 Q=Q+J*Q2
1400 IF Q2<1.0E-5 THEN 1460
1410 IF -1↑(I+1)<0 THEN 1440
1420 J=2
1430 GO TO 1450
1440 J=4
1450 NEXT I
1460 Q=Q/3/I1
1470 REM  Q IS THE VOLUME AVERAGE URANIUM UPTAKE
1490 V8=4.64*L9+8
1500 Z5=V9/(V9+V8)
1510 A2=M9*(V8+V9)/Q/Q9/R2/L9/(1-V1)/V2
1515 A6=M8*0.848*2204/(3600*8766*U1*F9*Z5*A2*R*C9)
1520 P=P*R*U1↑3*A2*O2
1530 P8=(3.33*1000/(12-1.03)+4*79)*62.4*0.1167*A2*L9/3413/1000/(V8+V9)
1550 P8=P+P8
1560 T2=O1/P8
1570 W8=H1*3.64*(A2*L9*1.19E-5/((V8+V9)*(1-1.03/12)))↑-0.2*1000
1580 W8=W8+0.07*(A2*L9*1.19E-5/((V8+V9)*(1-1.03/12)))↑-0.31*1000
1590 W8=W8/(365.25*F9)
1600 GO TO S8 OF 1610,1630
1610 W7=1.33*W3
1620 GO TO 1650
1630 W7=1000*(H1*1348*(P8/50)↑-0.425+31.42*(P8/50)↑-0.321)/(8766*F9)
1640 W7=W7+0.14*W3/Q8
1650 W8=W8+0.284*W7/12
```

```
1660 IF W8<2.14*N9+3.24 THEN 1680
1670 W8=2.14*N9+3.24
1680 C7=0.04*0.41329*R2*(1-V1)*V2
1690 C6=(2*C7*F9+0.0848)*A2*L9/(V8+V9)
1700 C7=(C7*0.94+0.06*1.1)*A2*L9/(V8+V9)
1710 W4=0.3855*C7↑-0.0872*3.42*W7/218
1720 W4=(W4+H1*(15.4*C7↑-0.2606))*8.2/F9/365.25
1730 IF W4<0.06 THEN 1750
1740 W4=0.06
1750 B9=H1*N9*P*Q7*1000*1.1/M8/2204
1760 B8=H1*A2*(0.5+L9*(1-V1)*V2*R2*W6)/M8/2204
1770 B7=P*8766*F9*W7/M8/2204
1780 B6=R*U1*A2*3600*8766*A8*Z5*F9*V2*R2*W6/M8/2204
1790 B5=3*A2*L9*7.48*W8*8766*F9/1000/(V8+V9)/M8/2204
1800 B4=C7*8766*F9*W4/M8/2204
1810 B3=C6*8766*F9*W5/M8/2204
1820 B2=H1*((8.19E-4*1500+22.5)*23.2*A2/A7+1150*300*EXP(0.006*300)*1.1)
1830 B2=B2/M8/2204
1840 U2=(1+H2)*(B9+B8)+B7+B6+B5+B4+B3+B2
1850 PAGE
1860 PRINT USING 1865:"EAF=";T2;"BED DEPTH=";L9;"AR=";A7
1865 IMAGE 4A,X,2D.2D,3X,10A,X,2D.5D,2X,3A, X,6D,2X
1870 PRINT
1880 PRINT "TUBE=1 BED=2  ";S9,"LOAD TIME=";V9,"#=";A
1890 PRINT
1900 GO TO S8 OF 1910,1930
1910 PRINT "CURRENT SPEED (MPH) =";U1*0.681818*A7
1920 PRINT
1930 PRINT USING "3(10A,2X),S":"U(FT/SEC)","    D(FT)","    R EFF"
1940 PRINT USING "3(10A)":"    A(FT2)","    REGIME"," $/LBU308"
1950 PRINT
1960 PRINT USING 1970:U1,D,A6,A2,F2,U2
1970 IMAGE 3E,4X,D.7D,6D.3D,2X,3E,5X,2D.D,2X,9D.D
1980 PRINT
1990 PRINT USING 2000:"CHEM  COST"," PMP CPTL"," BED CPTL","    BOP"
```

```
2000 IMAGE 2X,4(10A),S
2010 PRINT USING "3(10A)":" PWR CST"," BED ATRN","    WATER"
2020 PRINT
2030 PRINT USING "X,9D,X,6D.D,X9D,S":B4+B3,B9,B8
2040 PRINT USING "X9D,7D.D,X9D,S":H2*(B9+B8),B7,B6
2050 PRINT USING "X,9D":B5
2060 PRINT
2070 PRINT "MRNG CST"
2080 PRINT
2090 PRINT USING "   4D.D":B2
2095 PRINT "GG"
2100 PRI "INPUT NEXT VALUE OR SEARCH TYPE(-) U=1,D=2,L=3,T=4,AR=5      "
2110 INPUT S7
2120 IF S7=0 THEN 2510
2130 IF S7=-9 THEN 2790
2140 IF S7=-8 THEN 3300
2145 IF S7=-7 THEN 5000
2150 IF S7=-99 THEN 2320
2160 IF S7>0 THEN 2190
2170 S6=ABS(S7)
2180 GO TO 2100
2190 GO TO S6 OF 2200,2220,2240,2260,2280,2295
2200 U1=S7
2210 GO TO 320
2220 D=S7
2230 GO TO 320
2240 L9=S7
2250 GO TO 320
2260 V9=S7
2270 GO TO 320
2280 A7=S7
2290 GO TO 320
2295 T3=S7
2296 GO TO 320
2300 PRINT "AREA RATIO TOO SMALL FOR PASSIVE OPERATION"
```

```
2305 PRINT "GGGGGGGGGGGGGGGG"
2310 GO TO 2100
2320 END
2330 REM J(X,Y) SUBROUTINE
2340 I8=EXP(Y6)-1
2350 I7=I8
2360 I5=1
2370 I6=1
2380 IF Y6=0 THEN 2480
2390 FOR J2=1 TO 500
2400 I5=I5*Y5/J2
2410 I6=I6*Y6/J2
2420 I7=-I6+I7
2430 I9=I5*I7
2440 I8=I8+I9
2450 IF ABS(I9/I8)<1.0E-6 THEN 2480
2460 NEXT J2
2470 PRINT "BESSEL FUNCTION LOOP EXCEEDED";I,Y6,Y5
2480 IF ABS(EXP(-Y6-Y5)*I8)>1.0E-7 THEN 2500
2490 I8=0
2500 RETURN
2510 A=A+1
2520 M(1,A)=U1
2530 M(2,A)=D
2540 M(3,A)=L9
2550 M(4,A)=V9
2560 M(5,A)=A7
2570 M(6,A)=T3
2580 M(7,A)=T2
2590 M(8,A)=Q
2600 M(9,A)=A6
2610 M(10,A)=A2
2620 M(11,A)=F2
2630 M(12,A)=P
2640 M(13,A)=P8
```

```
2650 M(14,A)=W8
2660 M(15,A)=W7
2670 M(16,A)=W4
2680 M(17,A)=W5
2690 M(18,A)=W3
2700 M(19,A)=B9
2710 M(20,A)=B8
2720 M(21,A)=H2*(B9+B8)
2730 M(22,A)=B7
2740 M(23,A)=B6
2750 M(24,A)=B5
2760 M(25,A)=B4+B3
2770 M(26,A)=B2
2775 M(27,A)=U2
2780 GO TO 2100
2790 REM        PRINTOUT SUBROUTINE
2800 A9=A
2810 PAGE
2820 GO TO S8 OF 2880,2830
2830 GO TO S9 OF 2840,2860
2840 PRINT "    STACKED TUBE ACTIVE PUMPING",Q9;" LB U/LB TI(OH)4"
2850 GO TO 2920
2860 PRINT "    PACKED BED ACTIVE PUMPING",Q9;" LB U/LB TI(OH)4"
2870 GO TO 2920
2880 GO TO S9 OF 2890,2910
2890 PRINT "    STACKED TUBE PASSIVE SYSTEM",Q9;" LB U/LB TI(OH)4"
2900 GO TO 2920
2910 PRINT "    PACKED BED PASSIVE SYSTEM",Q9;" LB U/LB TI(OH)4"
2920 PRI USI 2930:" #","CRNT MPH","U FT/SEC","D FT","L FT","T HR","AR"
2930 IMAGE 2A,X,3(10A),4A,4X,4A,4X,2A,S
2932 PRINT USING "3X,6A,2X,10A":"      ","$/LBU308"
2940 FOR A=1 TO A9
2950 PRINT USING 2960:A,M(1,A)*0.68*M(5,A),M(1,A),M(2,A),M(3,A),M(4,A)
2960 IMAGE 2D,4D.2D,3X,D.5D,2X,D.7D,2X,D.5D,4D.D,X,S
2965 PRINT USING "6D,11X                     ,6D.D":M(5,A),M(27,A)
```

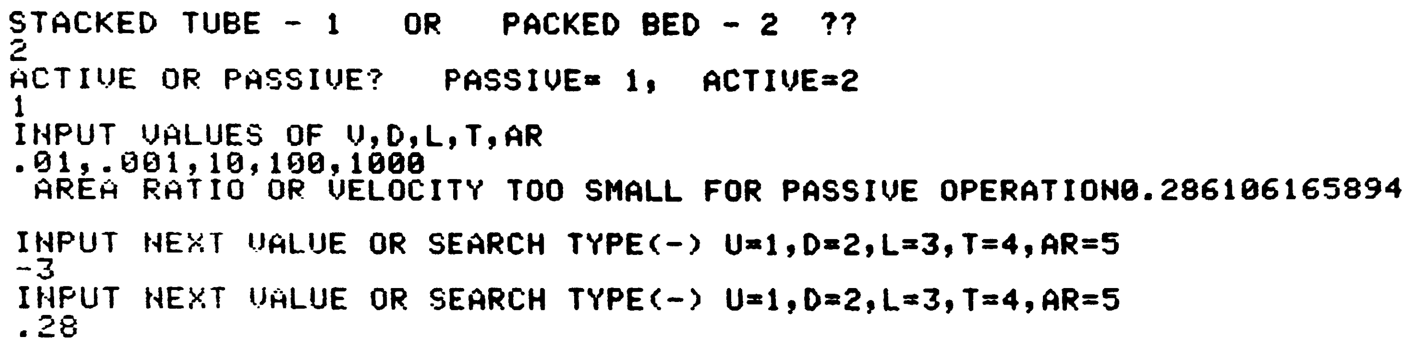
```
2970 NEXT A
2980 PRINT
2990 PRINT USING 3020:" #","   EAF","AVG LD","RCV","AREA FT","REG"
3000 PRINT USING 3010:"PMP PWR MW"," TOTAL PWR"
3010 IMAGE 2(10A)
3020 IMAGE 2A,5(10A),S
3030 FOR A=1 TO A9
3040 PRI USI 3050:A,M(7,A),M(8,A),M(9,A),M(10,A),M(11,A),M(12,A),M(13,A)
3050 IMAGE 2D,3(2D.3D,4X),2E,3D.2D,4X,7D.2D,7D.2D
3060 NEXT A
3070 PRINT
3080 PRI USI 3090:" #"," $/KGAL","MILL/KWHR","$/LBCO2","$/LBNH3","$/TON"
3090 IMAGE 2A,5(10A),S
3100 PRINT USING 3110:"MRNG CST"
3110 IMAGE 8A
3120 FOR A=1 TO A9
3130 PRINT USING 3140:A,M(14,A),M(15,A),M(16,A),M(17,A),M(18,A),M(26,A)
3140 IMAGE 2D,5(3D.3D,3X),4D.D
3150 NEXT A
3160 PRINT
3170 PRI USI 3180:" #","  P CPTL"," B CPTL","  BOP","  PWR","  ATTRN"
3180 IMAGE 2A,5( 8A),S
3190 PRINT USING 3200:"  WATER","  CHEM","T$/LBU308"
3200 IMAGE 2(8A),10A
3210 FOR A=1 TO A9
3220 PRINT USING 3230:A,M(19,A),M(20,A),M(21,A),M(22,A),M(23,A),M(24,A)
3230 IMAGE 2D,6(4D.D,2X),S
3240 PRINT USING 3250:M(25,A),M(27,A)
3250 IMAGE 4D.D,2X,5D.D
3260 NEXT A
3270 A=A9
3280 GO TO 2100
3290 REM
```

A.6 Sample Problem

The following set of instructions set in motion the analysis of a particle bed system operating in the passive ocean interceptor mode. The program listing and data file are those of Section A.5. This discussion commences assuming that the program has been loaded into the computer. (Refer to the Tektronix User's Manual for general instructions on loading a program into the Tektronix core from a tape cassette.) Figures A.2, A.3 and A.4 are copies of the Tektronix screen for this sample problem.

Begin program execution by depressing user defined key number 5. This will automatically clear the screen and print line 1 of Figure A.2. For a particle bed system, the user should type in "2" and execute "RETURN". The computer will then print line 3. For a passive system operation, the user should type in "1" and execute "RETURN". The computer will then print line 5. The user should then type line 6 as shown and execute "RETURN".

The input data have been chosen such that input bed thickness exceeds the allowable bed thickness for the given conditions. The program prints lines 7 and 8, including the maximum allowable bed thickness. Deciding to change bed thickness to overcome this problem, the user types in "-3" and executes "RETURN". The program prints line 10. The user then types line 11 and executes "RETURN". The program computes the performance and economic results for the given

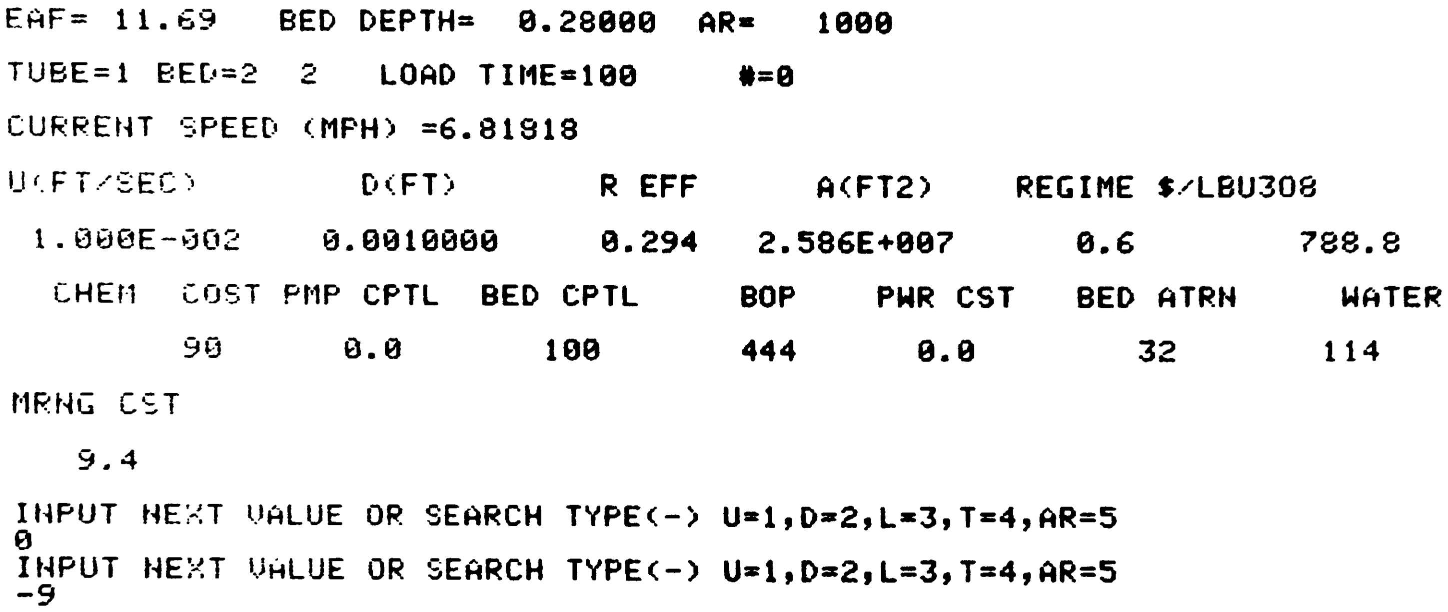


```
STACKED TUBE - 1   OR   PACKED BED - 2  ??
2
ACTIVE OR PASSIVE?   PASSIVE= 1,  ACTIVE=2
1
INPUT VALUES OF V,D,L,T,AR
.01,.001,10,100,1000
 AREA RATIO OR VELOCITY TOO SMALL FOR PASSIVE OPERATION0.286106165894

INPUT NEXT VALUE OR SEARCH TYPE(-) V=1,D=2,L=3,T=4,AR=5
-3
INPUT NEXT VALUE OR SEARCH TYPE(-) V=1,D=2,L=3,T=4,AR=5
.28
```

Fig. A.2 Page 1 of Sample Problem

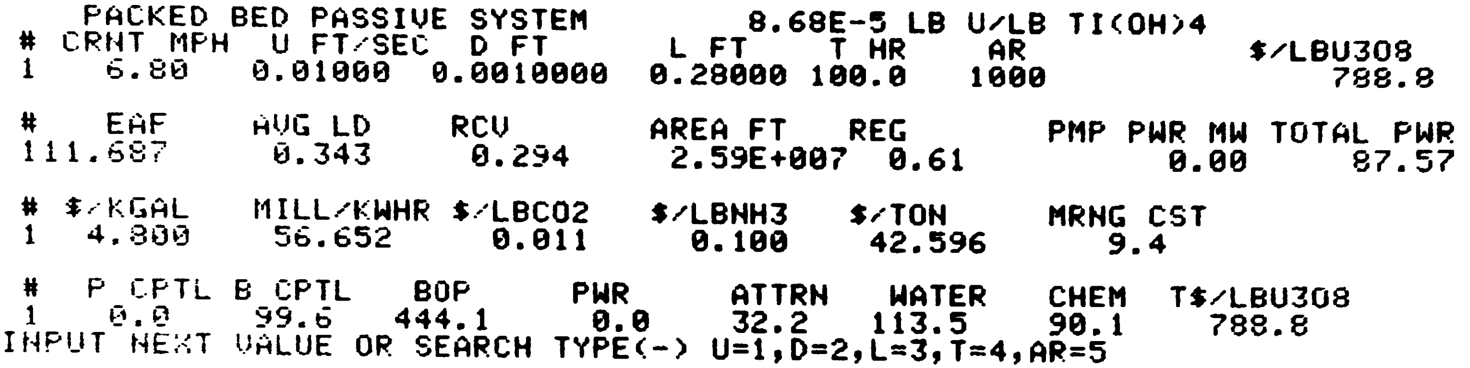
input data, erases the Tektronix screen and prints out the single case summary, Figure A.3, and standard request for input data message.

Store this case in memory by entering "0" and executing "RETURN". The code stores the data and prints out a standard request for input data. The user would then normally enter a new value for some variable and run another case as explained in "changes of run variables" discussed above. Since this sample problem has no further cases to run, the user should type "-9" and execute "RETURN". This will clear the screen and cause the program to display the cases stored in memory (in this instance only one case). The output should appear as shown in Fig. A.4. The user may analyze further cases as desired or terminate the program by typing "-99" and executing "RETURN". The program may be restarted by depressing User Defined Key Number 5. The number of possible permutations of the use of store, print-out and variable change codes is large, allowing the code to be flexible in meeting the user's needs. The user will perceive still further possibilities as his experience with the program and the TEKTRONIX computer increases.



```
EAF= 11.69   BED DEPTH=  0.28000  AR=   1000

TUBE=1 BED=2  2   LOAD TIME=100     #=0

CURRENT SPEED (MPH) =6.81818

U(FT/SEC)         D(FT)        R EFF      A(FT2)    REGIME $/LBU308

 1.000E-002    0.0010000     0.294   2.586E+007      0.6         788.8

  CHEM   COST PMP CPTL  BED CPTL     BOP    PWR CST   BED ATRN     WATER

         90      0.0        100       444      0.0        32        114

MRNG CST

   9.4

INPUT NEXT VALUE OR SEARCH TYPE(-) U=1,D=2,L=3,T=4,AR=5
0
INPUT NEXT VALUE OR SEARCH TYPE(-) U=1,D=2,L=3,T=4,AR=5
-9
```

Fig. A.3 Page 2 of Sample Problem
Single Case Summary



```
    PACKED BED PASSIVE SYSTEM        8.68E-5 LB U/LB TI(OH)4
 # CRNT MPH  U FT/SEC  D FT      L FT    T HR    AR           $/LBU308
 1   6.80   0.01000  0.0010000  0.28000 100.0   1000              788.8

 #   EAF     AVG LD    RCV       AREA FT   REG       PMP PWR MW TOTAL PWR
 111.687     0.343     0.294     2.59E+007  0.61          0.00      87.57

 # $/KGAL    MILL/KWHR $/LBCO2   $/LBNH3   $/TON     MRNG CST
 1  4.800    56.652     0.011     0.100    42.596      9.4

 #  P CPTL B CPTL   BOP     PWR     ATTRN   WATER   CHEM  T$/LBU308
 1   0.0    99.6   444.1     0.0    32.2   113.5   90.1    788.8
INPUT NEXT VALUE OR SEARCH TYPE(-) U=1,D=2,L=3,T=4,AR=5
```

Fig. A.4 Page 3 of Sample Problem

Output Data Summary

APPENDIX B

Energy Recovery Considerations

An elementary energy balance can be employed to put the question of allowable adsorber bed pressure drop into proper perspective.

Suppose that fuel is consumed in a heat engine to produce electricity or shaft work to drive a pump which moves water through a filter.

$$W = N_1N_2Q \qquad (B.1)$$

where,

W = pump work
N_1 = efficiency of heat engine (0.35)
N_2 = efficiency of pump (0.8)
Q = thermal energy use rate, kwhr/hr

But

$$W = K_1LG\Delta P, \qquad (B.2)$$

with

K_1 = conversion factor = 3.77×10^{-7} kwhr/ft lb.
G = rated flow rate, lb/hr
ΔP = required filter head, measured in ft of H_2O

We also have:

$$U = N_3LCG \times 10^{-9} \qquad (B.3)$$

in which

U = uranium recovery rate, lb/hr
C = concentration of U in sea water, 3.3 ppb
N_3 = filter efficiency, fraction of uranium recovered from water passing through the plant (0.8)
L = extraction plant capacity factor (0.85)

Finally, for a once-through LWR fuel cycle:

B = burnup, MWD/MTHM (30,000)

$(\frac{F}{P})$ = lbs natural U feed per lb slightly enriched U charged to the reactor (6)

Thus

$$E = (\frac{24}{2.205})\ B(\frac{P}{F}) \cdot U \text{ energy delivered, kwhr/hr} \qquad (B.4)$$

The energy amplification factor, EAF, is then given by

$$EAF = (\frac{E}{Q}) = \frac{0.0289\ N_1 N_2 N_3 CB}{\Delta P(F/P)} \qquad (B.5)$$

Substituting the representative values shown in parentheses in the preceding development, we find:

$$EAF = (\frac{E}{Q}) \simeq \frac{100}{\Delta P} \qquad (B.6)$$

Thus only extraction units requiring heads, ΔP, on the order of 10 ft H_2O (5 psi), and preferably less, are of practical interest, for unless the uranium yields substantially more energy than consumed to produce it, the entire enterprise is fruitless.

It should be noted that Eq. (B.6) is optimistic in the sense that no allowance is made for other energy consumption in the system, in particular in the chemical plant, which, as shown in Chapter 3, can itself be appreciable.

APPENDIX C

URPE Output Data

This appendix summarizes data generated by the URPE code when used to analyze the various sytems detailed in Chapter 3. The URPE output data format is discussed in detail in Appendix A, and summarized here for convenience.

The URPE output is arranged into four sections: first, a summary of input bed operating conditions and total cost; second a summary of calculated system performance data; third, a summary of calculated unit costs; and fourth, a summary of allocated costs and total cost. Each column heading includes the name of the variable and the units of the value shown.

Starting with the input data summary, the variables are:

1. "#" - case number, used to identify results; repeated for each section.
2. CRNT MPH - the superficial velocity at the diffuser entrance in miles per hour. For passive systems this gives the total available head; for active systems, the pumps supply the total head. The current shown for actively pumped systems is the superficial velocity, <u>not</u> the current required to achieve the same head as the pumps.

3. U - the superficial velocity in the bed.
4. D - the characteristic dimension of the adsorber; particle diameter, or tube inner diameter.
5. L - bed thickness.
6. T - uranium loading time.
7. AR - area ratio; ratio of bed area to intake area.
8. CTG - active adsorber coating thickness.
9. \$/LB U3O8 - total U_3O_8 production cost.

The calculated performance output summary section consists of the following:

1. "#" - case number
2. EAF - Energy Application Factor, the ratio of the thermal energy recoverable from the uranium, divided by the thermal energy consumed in recovering the uranium.
3. AVG LD - the fraction of its' ultimate capacity to which the adsorber is loaded at the conclusion of a load cycle.
4. RCV - the fraction of the total uranium passing through the system which is recovered.
5. AREA - the total bed frontal area.
6. REG - the Reynolds number in the bed.
7. PMP PWR MW - the required electrical pumping power in Mw(e).
8. TOTAL PWR - the effective capacity of the multi-product plant in Mw(e).

The third section summarizes the calculated unit costs:

1. "#" - the case number

2. \$/KGAL - the unit cost of desalinated water.
3. MILL/KWHR - the unit cost of electricity.
4. \$/LBCO2 - the unit cost of carbon dioxide.
5. \$/LBNH3 - the unit cost of ammonia.
6. \$/TON - the unit cost of coal at the plant.
7. MRNG CST - the allocated cost of the mooring system and oil rig platform in \$/lb U_3O_8.

The fourth section summarizes the allocated production costs as follows:

1. "#" - case number.
2. P CPTL - the allocated capital cost of the pumps and motors, \$/lb U_3O_8.
3. B CPTL - the allocated capital cost of the HTO bed inventory and structural supports, \$/lb U_3O_8.
4. BOP - the balance of the plant, \$/lb U_3O_8.
5. PWR - the cost of electricity consumed in seawater pumping, \$/lb U_3O_8.
6. ATTRN - the cost of HTO lost due to attrition and elution, \$/lb U_3O_8.
7. WATER - the cost of water consumed, \$/lb U_3O_8.
8. CHEM - the cost of chemicals consumed, \$/lb U_3O_8.
9. T\$/lb U_3O_8 - total U_3O_8 production cost.

Table C.1 is a summary of the URPE code output data which results from 20 percent variations in the performance of the URPE sub-models. The case numbers referred to in the table are explained in detail in Chapter 3, and also listed at the end of Table C.1.

Table C.2 is a summary of the output data for the URPE a, b, and c cases run for comparison with the Exxon study discussed in Chapter 3. The column headings are the same as those described above.

Table C.3 is a summary of the output data of the URPE results for optimized packed bed and stacked tube systems using active pumping by propeller-type pumps. Table C.4 is similar to the preceding table, but using a passive current interceptor system and current speeds of 2 and 4 miles per hour.

Table C.5 lists the URPE output used to determine the sensitivity of total uranium production cost to the variation of bed operating conditions around the optimum. The optimum bed operating conditions are those of the optimized packed bed actively pumped system. The data of Table C.5 have been used to plot Figs. 3.1 through 3.6 and to prepare Table 3.3.

Tables C.6 and C.7 list the output data for the URPE system, optimized for increasing values of adsorber capacity and pumping power requirements. These effects are discussed in Section 3.6

Table C.1 Output Data on the Sensitivity of Total Cost to 20% Variations in the Sub-models

```
   PACKED BED ACTIVE PUMPING          8.68E-5 LB U/LB TI(OH)4
#  CRNT MPH   U FT/SEC  D FT          L FT      T HR      AR    CTG FT   $/LBU3O8
1    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    315.5
2    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    326.9
3    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    303.8
4    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    314.7
5    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    316.6
6    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    306.7
7    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    328.5
8    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    266.2
9    5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    322.7
10   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    308.3
11   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    315.9
12   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    315.0
13   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    340.0
14   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    290.9
15   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    317.7
16   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    313.3
17   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    326.0
18   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    304.7
19   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    363.5
20   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    267.5
21   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    285.0
22   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    363.4
23   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    317.7
24   5.31     0.00355   0.0002121   0.03874   32.0     2200  1.74E-005    333.6
```

Table C.1 (Continued)

#	EAF	AVG LD	RCV	AREA FT	REG	PMP PWR MW	TOTAL PWR
1	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
2	10.256	0.816	0.737	3.34E+007	0.05	57.22	99.79
3	12.679	0.816	0.737	3.34E+007	0.05	38.14	80.72
4	11.369	0.819	0.739	3.33E+007	0.05	47.56	90.02
5	11.294	0.813	0.734	3.35E+007	0.05	47.87	90.62
6	11.699	0.842	0.760	3.24E+007	0.05	46.21	87.48
7	10.844	0.781	0.705	3.49E+007	0.05	49.86	94.37
8	13.684	0.985	0.889	2.77E+007	0.05	39.51	74.79
9	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
10	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
11	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
12	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
13	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
14	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
15	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
16	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
17	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
18	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
19	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
20	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
21	11.340	0.816	0.737	3.34E+007	0.05	47.68	90.25
22	11.340	0.816	0.737	2.78E+007	0.05	39.73	75.21
23	11.353	0.851	0.666	4.18E+007	0.05	59.60	112.81
24	9.730	0.779	0.797	3.70E+007	0.05	43.03	90.14
				3.09E+007	0.05	65.81	105.18

Table C.1 (Continued)

#	$/KGAL	MILL/KWHR	$/LBCO2	$/LBNH3	$/TON	MRNG CST
1	5.462	60.973	0.014	0.100	42.596	6.0
2	5.423	59.293	0.013	0.100	42.596	6.0
3	5.509	62.925	0.014	0.100	42.596	6.0
4	5.466	61.017	0.014	0.100	42.596	6.0
5	5.457	60.904	0.013	0.100	42.596	6.1
6	5.501	61.510	0.014	0.100	42.596	5.9
7	5.407	60.217	0.013	0.100	42.596	6.3
8	5.702	64.311	0.014	0.100	42.596	5.2
9	5.462	60.973	0.014	0.100	42.596	6.0
10	5.462	60.973	0.014	0.100	42.596	6.0
11	5.462	60.973	0.013	0.100	42.596	6.0
12	5.462	60.973	0.014	0.100	42.596	6.0
13	5.462	60.973	0.014	0.100	42.596	6.0
14	5.462	60.973	0.014	0.100	42.596	6.0
15	5.462	60.973	0.014	0.100	42.596	6.0
16	5.462	60.973	0.014	0.100	42.596	6.0
17	5.312	60.973	0.014	0.100	42.596	6.0
18	5.654	60.973	0.014	0.100	42.596	6.0
19	6.381	68.450	0.016	0.100	42.596	7.3
20	4.544	53.495	0.011	0.100	42.596	4.8
21	4.824	56.820	0.011	0.100	42.596	5.3
22	6.374	66.698	0.017	0.100	42.596	7.2
23	5.379	60.994	0.014	0.100	42.596	6.5
24	5.469	58.440	0.013	0.100	42.596	5.7

Table C.1 (Continued)

#	P CPTL	B CPTL	BOP	PWR	ATTRN	WATER	CHEM	T$/LBU3O8
1	3.8	23.7	122.8	46.3	11.1	62.8	39.0	315.5
2	4.6	23.7	126.2	54.0	11.1	62.3	38.9	326.9
3	3.1	23.7	119.4	38.2	11.1	63.3	39.0	303.8
4	3.8	23.6	122.5	46.2	11.0	62.7	38.9	314.7
5	3.9	23.8	123.3	46.4	11.1	63.0	39.1	316.6
6	3.7	23.0	119.0	45.2	10.7	61.3	37.8	306.7
7	4.0	24.8	128.4	47.8	11.6	65.0	40.7	328.5
8	3.2	19.6	101.8	40.4	9.2	54.3	32.4	266.2
9	3.8	23.7	122.8	46.3	11.1	62.8	46.2	322.7
10	3.8	23.7	122.8	46.3	11.1	62.8	31.8	308.3
11	3.8	23.7	122.8	46.3	11.1	62.8	39.4	315.9
12	3.8	23.7	122.8	46.3	11.1	62.8	38.5	315.0
13	3.8	23.7	147.4	46.3	11.1	62.8	39.0	340.0
14	3.8	23.7	98.2	46.3	11.1	62.8	39.0	290.9
15	3.8	23.7	122.8	46.3	13.3	62.8	39.0	317.7
16	3.8	23.7	122.8	46.3	8.9	62.8	39.0	313.3
17	3.8	23.7	122.8	46.3	11.1	73.3	39.0	326.0
18	3.8	23.7	122.8	46.3	11.1	52.0	39.0	304.7
19	4.6	28.4	147.4	51.9	11.1	73.4	39.5	363.5
20	3.1	19.0	98.2	40.6	11.1	52.2	38.4	267.5
21	3.2	19.7	102.3	43.1	11.1	55.5	44.8	285.0
22	4.8	29.6	153.5	50.6	11.1	73.3	33.3	363.4
23	3.5	24.1	123.1	41.8	12.3	68.4	38.1	317.7
24	5.3	23.7	129.2	61.2	10.2	58.1	40.2	333.6

Table C.1 (Continued)

Case No.	Sub-model Variation	Case No.	Sub-model Variation
1	Base Case	13	Balance of Plant Cost +20%
2	Pumping Head +20%	14	Balance of Plant Cost -20%
3	Pumping Head -20%	15	Attrition Rate +20%
4	Fluid Side Mass Transfer +20%	16	Attrition Rate -20%
5	Fluid Side Mass Transfer -20%	17	Water Consumption +20%
6	Solid Side Mass Transfer +20%	18	Water Consumption -20%
7	Solid Side Mass Transfer -20%	19	Fixed Charge Rate +20%
8	Solid Side Resistance Eliminated	20	Fixed Charge Rate -20%
9	Ammonia Consumption +20%	21	Plant Capacity Factor +20%
10	Ammonia Consumption -20%	22	Plant Capacity Factor -20%
11	CO_2 Consumption +20%	23	Bed Void Fraction +20%
12	CO_2 Consumption -20%	24	Bed Void Fraction -20%

Table C.2 The URPE Code as Run for Comparison with the Exxon Study

```
    PACKED BED ACTIVE PUMPING          8.68E-5 LB U/LB TI(OH)4
   CRNT MPH  U FT/SEC  D FT        L FT     T HR     AR    CTG FT   $/LBU308
a   50.17    0.01300  0.0004920  2.46000 490.0    5675 9.84E-005    556.8
b    8.37    0.00217  0.0005974  0.29917 221.0    5675 3.22E-005    333.3
c   54.01    0.01300  0.0004920  2.46000 490.0    6110 9.84E-005    649.0

     EAF      AVG LD     RCV       AREA FT    REG        PMP PWR MW TOTAL PWR
a  4.164      0.807      0.829      1.90E+007  0.39         450.98     546.18
b  8.820      0.935      0.574      2.14E+008  0.08          35.68     257.85
c  4.581      0.802      0.824      1.69E+007  0.39         450.67     558.47

   $/KGAL     MILL/KWHR $/LBCO2    $/LBNH3    $/TON       MRNG CST
a   2.126      21.800     0.025      0.059     42.596       0.4
b   1.956      21.800     0.025      0.059     42.596       2.3
c   2.288      29.525     0.005      0.100     42.596       0.4

    P CPTL B CPTL   BOP       PWR       ATTRN      WATER     CHEM   T$/LBU308
a   19.8    55.8    337.5     70.4      11.2       24.6      37.1     556.8
b    1.6    38.4    178.4      5.6       6.0       52.8      48.3     333.3
c    6.4    81.7    392.8     84.7      18.7       26.6      37.8     649.0
```

Key: a. Exxon ground rules Table 3.6

b. Exxon ground rules Table 3.6 and optimized bed conditions

c. URPE ground rules Tables 3.1 and 3.2, with Exxon bed conditions and plant capacity

Table C.3 Optimized Bed Conditions for Actively Pumped Packed Bed and Stacked Tube Systems

```
                  ACTIVE PUMPING         8.68E-4 LB U/LB TI(OH)4
# CRNT MPH   U FT/SEC   D FT        L FT      T HR     AR    CTG FT   $/LBU308
1    5.31   0.00355  0.0002121  0.03874   32.0   2200 1.74E-005   315.5
2    5.45   0.00816  0.0003443  0.33863   68.7    982 2.15E-005   482.4

#    EAF       AVG LD     RCV         AREA FT    REG        PMP PWR MW TOTAL PWR
111.340      0.816      0.737        3.34E+007  0.05             47.68      90.25
2 5.747      0.755      0.393        2.44E+007  0.36             38.26     178.09

# $/KGAL     MILL/KWHR $/LBCO2      $/LBNH3    $/TON       MRNG CST
1  5.462      60.973     0.014       0.100      42.596        6.0
2  4.342      50.866     0.012       0.100      42.596        9.1

#   P CPTL B CPTL    BOP      PWR      ATTRN    WATER     CHEM   T$/LBU308
1    3.8     23.7   122.8     46.3      11.1     62.8     39.0     315.5
2    3.1     36.9   178.3     31.0       7.9    164.0     52.2     482.4
```

Key: 1 - Packed Bed System

2 - Stacked Tube System

Table C.4 Optimized Bed Conditions for Passive Ocean Interceptor Systems of Packed Beds and Stacked Tubes

```
                     PASSIVE SYSTEM        8.68E-5 LB U/LB TI(OH)4
# CRNT MPH  U FT/SEC  D FT         L FT     T HR    AR   CTG FT   $/LBU308
1    1.99   0.00173  0.0012709  0.09972  88.4    1699 2.55E-005   774.7
2    3.99   0.00207  0.0005905  0.05430  51.0    2834 2.14E-005   450.9
3    3.99   0.00189  0.0005054  0.08799  73.2    3110 2.78E-005   598.1

#   EHF     AVG LD     RCV         AREA FT    REG        PMP PWR MW TOTAL PWR
1 5.317      0.650      0.312       1.41E+008  0.13            0.00     192.48
210.319      0.721      0.477       8.19E+007  0.07            0.00      99.17
3 7.053      0.685      0.404       1.02E+008  0.10            0.00     145.11

# $/KGAL    MILL/KWHR $/LBCO2     $/LBNH3    $/TON      MRNG CST
1  4.278     56.652      0.012      0.100     42.596      27.3
2  4.711     56.652      0.012      0.100     42.596      10.3
3  4.455     56.652      0.012      0.100     42.596      11.5

#   P CPTL B CPTL   BOP       PWR       ATTRN   WATER     CHEM  T$/LBU308
1    0.0    83.1   370.7      0.0        7.3   222.4     63.9    774.7
2    0.0    47.0   209.5      0.0        8.3   126.2     49.6    450.9
3    0.0    63.3   282.3      0.0        9.8   174.6     56.6    598.1
```

Key: 1 - Packed Bed with 2 mph current

2 - Packed Bed with 4 mph current

3 - Stacked Tube with 4 mph current

Table C.5.1 Total Cost as a Function of Superficial Velocity

```
   PACKED BED ACTIVE PUMPING        8.68E-5 LB U/LB TI(OH)4
#  CRNT MPH  U FT/SEC   D FT        L FT      T HR      AR   CTG FT    $/LBU308
1    0.75    0.00050  0.0002121  0.03874    32.0     2200 1.74E-005  1170.4
2    1.20    0.00080  0.0002121  0.03874    32.0     2200 1.74E-005   768.9
3    1.50    0.00100  0.0002121  0.03874    32.0     2200 1.74E-005   632.1
4    2.99    0.00200  0.0002121  0.03874    32.0     2200 1.74E-005   373.5
5    4.49    0.00300  0.0002121  0.03874    32.0     2200 1.74E-005   320.5
6    5.31    0.00355  0.0002121  0.03874    32.0     2200 1.74E-005   315.5
7    5.98    0.00400  0.0002121  0.03874    32.0     2200 1.74E-005   316.9
8    7.48    0.00500  0.0002121  0.03874    32.0     2200 1.74E-005   330.1
9    8.98    0.00600  0.0002121  0.03874    32.0     2200 1.74E-005   351.4
10  11.97    0.00800  0.0002121  0.03874    32.0     2200 1.74E-005   409.3
11  14.96    0.01000  0.0002121  0.03874    32.0     2200 1.74E-005   483.3
12  29.92    0.02000  0.0002121  0.03874    32.0     2200 1.74E-005  1102.3

#    EAF       AVG LD      RCV         AREA FT    REG         PMP PWR MW TOTAL PWR
1  4.172       0.157      1.005        1.74E+008  0.01            23.76     245.32
2  6.235       0.250      1.000        1.09E+008  0.01            24.91     164.13
3  7.468       0.312      0.999        8.74E+007  0.01            25.61     137.04
411.469        0.593      0.951        4.60E+007  0.03            30.67      89.23
511.912        0.764      0.816        3.57E+007  0.04            40.40      85.91
611.340        0.816      0.737        3.34E+007  0.05            47.68      90.25
710.708        0.847      0.678        3.22E+007  0.05            54.52      95.57
8  9.185       0.889      0.570        3.07E+007  0.07            72.33     111.42
9  7.771       0.914      0.488        2.98E+007  0.08            93.64     131.69
10 5.561       0.939      0.376        2.90E+007  0.10           147.02     184.02
11 4.057       0.952      0.305        2.86E+007  0.13           215.77     252.27
12 1.159       0.973      0.156        2.80E+007  0.26           846.94     882.67
```

Table C.5.1 (Continued)

#	$/KGAL	MILL/KWHR	$/LBCO2	$/LBNH3	$/TON	MRNG CST
1	3.965	47.011	0.009	0.100	42.596	26.0
2	4.370	51.934	0.010	0.100	42.596	16.8
3	4.578	54.426	0.011	0.100	42.596	13.7
4	5.208	61.167	0.013	0.100	42.596	7.8
5	5.427	61.823	0.013	0.100	42.596	6.4
6	5.462	60.973	0.014	0.100	42.596	6.0
7	5.470	60.006	0.014	0.100	42.596	5.9
8	5.453	57.528	0.013	0.100	42.596	5.7
9	5.417	55.003	0.013	0.100	42.596	5.5
10	5.333	50.448	0.013	0.100	42.596	5.4
11	5.256	46.698	0.013	0.100	42.596	5.4
12	5.017	35.846	0.012	0.100	42.596	5.3

#	P CPTL	B CPTL	BOP	PWR	ATTRN	WATER	CHEM	T$/LBU308
1	1.9	123.3	558.6	17.8	8.1	237.2	197.5	1170.4
2	2.0	77.5	354.6	20.6	8.2	164.3	125.0	768.9
3	2.1	62.0	285.9	22.2	8.2	137.8	100.4	632.1
4	2.5	32.6	156.4	29.8	8.6	82.4	53.4	373.5
5	3.3	25.3	127.5	39.7	10.0	66.7	41.6	320.5
6	3.8	23.7	122.8	46.3	11.1	62.8	39.0	315.5
7	4.4	22.9	121.5	52.0	12.0	60.6	37.6	316.9
8	5.8	21.8	123.0	66.2	14.3	57.6	35.8	330.1
9	7.5	21.2	128.1	81.9	16.7	55.7	34.8	351.4
10	11.8	20.6	144.6	118.0	21.7	53.3	33.8	409.3
11	17.4	20.3	168.1	160.3	26.8	51.8	33.3	483.3
12	68.2	19.9	392.7	483.0	52.4	48.4	32.4	1102.3

Table C.5.2 Total Cost as a Function of Particle Diameter

```
     PACKED BED ACTIVE PUMPING          8.68E-5 LB U/LB TI(OH)4
 #  CRNT MPH   U FT/SEC   D FT         L FT      T HR      AR    CTG FT  $/LBU308
 1     5.31    0.00355  0.0000500   0.03874   32.0     2200 1.74E-005    940.4
 2     5.31    0.00355  0.0001000   0.03874   32.0     2200 1.74E-005    442.8
 3     5.31    0.00355  0.0001500   0.03874   32.0     2200 1.74E-005    337.2
 4     5.31    0.00355  0.0002000   0.03874   32.0     2200 1.74E-005    315.9
 5     5.31    0.00355  0.0002121   0.03874   32.0     2200 1.74E-005    315.5
 6     5.31    0.00355  0.0002500   0.03874   32.0     2200 1.74E-005    319.9
 7     5.31    0.00355  0.0003000   0.03874   32.0     2200 1.74E-005    334.3
 8     5.31    0.00355  0.0004000   0.03874   32.0     2200 1.74E-005    378.4
 9     5.31    0.00355  0.0006000   0.03874   32.0     2200 1.74E-005    500.6
10     5.31    0.00355  0.0008000   0.03874   32.0     2200 1.74E-005    654.3
11     5.31    0.00355  0.0010000   0.03874   32.0     2200 1.74E-005    834.7
12     5.31    0.00355  0.0020000   0.03874   32.0     2200 1.74E-005   2098.7

 #    EAF       AVG LD      RCV          AREA FT    REG          PMP PWR MW TOTAL PWR
 1  1.594       0.472      0.996        2.47E+007  0.01             610.47     641.96
 2  5.510       0.633      0.993        2.48E+007  0.02             154.16     185.75
 3  9.266       0.764      0.907        2.71E+007  0.03              75.87     110.44
 411.130        0.812      0.769        3.20E+007  0.04              51.16      91.95
 511.340        0.816      0.737        3.34E+007  0.05              47.68      90.25
 611.585        0.822      0.646        3.81E+007  0.05              39.77      88.34
 711.293        0.816      0.548        4.49E+007  0.07              33.35      90.62
 8  9.885       0.787      0.408        6.03E+007  0.09              26.69     103.53
 9  6.980       0.708      0.252        9.75E+007  0.13              22.31     146.63
10  4.984       0.632      0.171        1.44E+008  0.17              22.11     205.34
11  3.687       0.565      0.124        1.99E+008  0.22              23.72     277.58
12  1.233       0.359      0.040        6.16E+008  0.44              44.87     830.13
```

Table C.5.2 (Continued)

#	$/KGAL	MILL/KWHR	$/LBCO2	$/LBNH3	$/TON	MRNG CST
1	5.182	38.093	0.011	0.100	42.596	4.8
2	5.469	50.329	0.012	0.100	42.596	4.8
3	5.562	57.666	0.013	0.100	42.596	5.2
4	5.491	60.655	0.013	0.100	42.596	5.8
5	5.462	60.973	0.014	0.100	42.596	6.0
6	5.362	61.340	0.013	0.100	42.596	6.7
7	5.220	60.903	0.013	0.100	42.596	7.7
8	4.943	58.694	0.013	0.100	42.596	9.9
9	4.481	53.470	0.012	0.100	42.596	15.1
10	4.129	49.088	0.011	0.100	42.596	21.7
11	3.854	45.656	0.011	0.100	42.596	29.6
12	3.054	36.256	0.008	0.100	42.596	88.7

#	P CPTL	B CPTL	BOP	PWR	ATTRN	WATER	CHEM	T$/LBU308
1	49.1	31.6	360.1	370.0	19.1	44.1	61.6	940.4
2	12.4	25.4	168.5	123.4	14.3	46.7	47.3	442.8
3	6.1	22.9	129.3	69.6	11.8	51.9	40.3	337.2
4	4.1	23.4	122.7	49.4	11.1	60.5	39.0	315.9
5	3.8	23.7	122.8	46.3	11.1	62.8	39.0	315.5
6	3.2	24.9	125.5	38.8	11.0	70.3	39.4	319.9
7	2.7	27.0	132.3	32.3	11.1	80.7	40.6	334.3
8	2.1	31.9	151.6	24.9	11.5	102.6	44.0	378.4
9	1.9	44.1	204.5	19.0	12.8	150.5	52.9	500.6
10	1.8	59.2	271.8	17.3	14.3	204.3	64.0	654.3
11	1.9	77.0	352.1	17.2	16.0	264.2	76.6	834.7
12	3.6	207.1	939.7	25.9	25.2	647.6	160.9	2098.7

Table C.5.3 Total Cost as a Function of Bed Thickness

```
   PACKED BED ACTIVE PUMPING         8.68E-5 LB U/LB TI(OH)4
 # CRNT MPH   U FT/SEC   D FT        L FT      T HR     AR   CTG FT    $/LBU308
 1    5.31   0.00355   0.0002121   0.00400    32.0     2200 1.74E-005   1006.7
 2    5.31   0.00355   0.0002121   0.00800    32.0     2200 1.74E-005    606.7
 3    5.31   0.00355   0.0002121   0.01000    32.0     2200 1.74E-005    526.2
 4    5.31   0.00355   0.0002121   0.02000    32.0     2200 1.74E-005    369.0
 5    5.31   0.00355   0.0002121   0.03000    32.0     2200 1.74E-005    325.6
 6    5.31   0.00355   0.0002121   0.03874    32.0     2200 1.74E-005    315.5
 7    5.31   0.00355   0.0002121   0.04500    32.0     2200 1.74E-005    316.8
 8    5.31   0.00355   0.0002121   0.06000    32.0     2200 1.74E-005    338.3
 9    5.31   0.00355   0.0002121   0.08000    32.0     2200 1.74E-005    389.4
10    5.31   0.00355   0.0002121   0.10000    32.0     2200 1.74E-005    451.3
11    5.31   0.00355   0.0002121   0.30000    32.0     2200 1.74E-005   1094.8
12    5.31   0.00355   0.0002121   0.35000    32.0     2200 1.74E-005   1255.4

 #   EAF      AVG LD      RCV        AREA FT    REG          PMP PWR MW  TOTAL PWR
 1 3.326      0.976      0.091       2.70E+008  0.05            272.10     307.71
 2 5.686      0.966      0.180       1.36E+008  0.05            144.02     179.99
 3 6.615      0.961      0.224       1.10E+008  0.05            118.54     154.72
 4 9.645      0.925      0.431       5.70E+007  0.05             68.51     106.10
510.996       0.873      0.610       4.03E+007  0.05             53.27      93.07
611.340       0.816      0.737       3.34E+007  0.05             47.68      90.25
711.260       0.771      0.808       3.05E+007  0.05             45.80      90.89
810.431       0.657      0.919       2.69E+007  0.05             45.22      98.11
 9 8.902      0.524      0.977       2.53E+007  0.05             48.68     114.96
10 7.557      0.427      0.994       2.49E+007  0.05             53.97     135.42
11 2.882      0.145      1.011       2.51E+007  0.05            114.69     355.05
12 2.491      0.124      1.011       2.52E+007  0.05            130.49     410.84
```

Table C.5.3 (Continued)

#	$/KGAL	MILL/KWHR	$/LBCO2	$/LBNH3	$/TON	MRNG CST
1	5.227	44.577	0.013	0.100	42.596	39.6
2	5.364	50.730	0.013	0.100	42.596	20.6
3	5.406	52.729	0.013	0.100	42.596	16.9
4	5.505	58.300	0.014	0.100	42.596	9.4
5	5.507	60.450	0.014	0.100	42.596	7.0
6	5.462	60.973	0.014	0.100	42.596	6.0
7	5.412	60.852	0.013	0.100	42.596	5.6
8	5.251	59.571	0.013	0.100	42.596	5.1
9	5.015	57.042	0.012	0.100	42.596	4.9
10	4.803	54.597	0.011	0.100	42.596	4.8
11	3.826	43.155	0.009	0.100	42.596	4.9
12	3.706	41.790	0.008	0.100	42.596	4.9

#	P CPTL	B CPTL	BOP	PWR	ATTRN	WATER	CHEM	T$/LBU3O8
1	21.9	88.3	491.5	193.0	89.7	50.3	32.5	1006.7
2	11.6	50.6	277.4	116.2	45.3	52.1	32.9	606.7
3	9.5	43.1	234.9	99.4	36.5	52.8	33.1	526.2
4	5.5	28.7	152.6	63.5	18.9	55.9	34.4	369.0
5	4.3	24.7	129.3	51.2	13.4	59.2	36.5	325.6
6	3.8	23.7	122.8	46.3	11.1	62.8	39.0	315.5
7	3.7	23.7	122.2	44.3	10.1	65.9	41.2	316.8
8	3.6	25.3	129.2	42.9	8.9	75.0	48.2	338.3
9	3.9	29.4	148.7	44.2	8.4	89.8	60.2	389.4
10	4.3	34.5	173.2	46.9	8.2	105.7	73.7	451.3
11	9.2	89.9	441.9	78.7	8.1	248.4	213.8	1094.8
12	10.5	104.2	511.6	86.8	8.1	280.6	248.8	1255.4

Table C.5.4 Total Cost as a Function of Loading Time

```
    PACKED BED ACTIVE PUMPING         8.68E-5 LB U/LB TI(OH)4
#  CRNT MPH   U FT/SEC   D FT         L FT      T HR     AR    CTG FT   $/LBU308
1     5.31    0.00355  0.0002121   0.03874    2.0    2200 1.74E-005  1493.6
2     5.31    0.00355  0.0002121   0.03874   10.0    2200 1.74E-005   462.7
3     5.31    0.00355  0.0002121   0.03874   16.0    2200 1.74E-005   366.2
4     5.31    0.00355  0.0002121   0.03874   24.0    2200 1.74E-005   323.0
5     5.31    0.00355  0.0002121   0.03874   28.0    2200 1.74E-005   316.4
6     5.31    0.00355  0.0002121   0.03874   32.0    2200 1.74E-005   315.5
7     5.31    0.00355  0.0002121   0.03874   35.0    2200 1.74E-005   317.7
8     5.31    0.00355  0.0002121   0.03874   39.0    2200 1.74E-005   323.5
9     5.31    0.00355  0.0002121   0.03874   43.0    2200 1.74E-005   332.0
10    5.31    0.00355  0.0002121   0.03874   50.0    2200 1.74E-005   351.5
11    5.31    0.00355  0.0002121   0.03874   70.0    2200 1.74E-005   423.6
12    5.31    0.00355  0.0002121   0.03874  100.0    2200 1.74E-005   544.2
13    5.31    0.00355  0.0002121   0.03874  150.0    2200 1.74E-005   746.8
14    5.31    0.00355  0.0002121   0.03874  200.0    2200 1.74E-005   947.6
15    5.31    0.00355  0.0002121   0.03874  250.0    2200 1.74E-005  1147.2

#    EAF       AVG LD     RCV         AREA FT    REG            PMP PWR MW  TOTAL PWR
 1  1.539      0.067      0.968       1.03E+008  0.05              147.07     665.36
 2  6.296      0.322      0.931       3.83E+007  0.05               54.67     162.54
 3  8.672      0.493      0.890       3.33E+007  0.05               47.51     118.01
 410.575       0.681      0.820       3.21E+007  0.05               45.76      96.78
 511.077       0.756      0.779       3.25E+007  0.05               46.39      92.39
 611.340       0.816      0.737       3.34E+007  0.05               47.68      90.25
 711.408       0.854      0.705       3.43E+007  0.05               49.00      89.71
 811.364       0.893      0.662       3.58E+007  0.05               51.16      90.06
 911.206       0.924      0.620       3.76E+007  0.05               53.69      91.32
1010.763       0.958      0.554       4.12E+007  0.05               58.82      95.09
11  9.200      0.993      0.410       5.34E+007  0.05               76.25     111.24
12  7.330      1.000      0.289       7.34E+007  0.05              104.85     139.62
13  5.443      1.000      0.193       1.07E+008  0.05              153.25     188.01
14  4.328      1.000      0.144       1.41E+008  0.05              201.69     236.45
15  3.592      1.000      0.116       1.75E+008  0.05              250.13     284.89
```

Table C.5.4 (Continued)

#	$/KGAL	MILL/KWHR	$/LBCO2	$/LBNH3	$/TON	MRNG CST
1	3.288	37.826	0.007	0.100	42.596	15.9
2	4.544	52.064	0.011	0.100	42.596	6.7
3	4.959	56.640	0.012	0.100	42.596	6.0
4	5.286	59.797	0.013	0.100	42.596	5.9
5	5.389	60.575	0.013	0.100	42.596	5.9
6	5.462	60.973	0.014	0.100	42.596	6.0
7	5.502	61.075	0.014	0.100	42.596	6.2
8	5.540	61.010	0.014	0.100	42.596	6.4
9	5.562	60.772	0.014	0.100	42.596	6.6
10	5.578	60.091	0.014	0.100	42.596	7.1
11	5.549	57.553	0.014	0.100	42.596	8.9
12	5.475	54.160	0.014	0.100	42.596	11.7
13	5.381	50.177	0.013	0.100	42.596	16.5
14	5.316	47.428	0.013	0.100	42.596	21.4
15	5.267	45.379	0.013	0.100	42.596	26.2

#	P CPTL	B CPTL	BOP	PWR	ATTRN	WATER	CHEM	T$/LBU308
1	11.8	73.1	378.8	88.5	8.4	460.2	456.8	1493.6
2	4.4	27.2	140.8	45.3	8.8	132.4	97.1	462.7
3	3.8	23.6	122.4	42.8	9.2	94.4	63.9	366.2
4	3.7	22.7	117.9	43.5	10.0	72.8	46.5	323.0
5	3.7	23.1	119.5	44.7	10.5	66.9	42.0	316.4
6	3.8	23.7	122.8	46.3	11.1	62.8	39.0	315.5
7	3.9	24.4	126.2	47.6	11.6	60.5	37.3	317.7
8	4.1	25.4	131.8	49.7	12.3	58.2	35.7	323.5
9	4.3	26.7	138.3	51.9	13.2	56.5	34.5	332.0
10	4.7	29.2	151.5	56.2	14.7	54.6	33.3	351.5
11	6.1	37.9	196.4	69.8	19.9	52.4	32.1	423.6
12	8.4	52.1	270.0	90.3	28.3	51.4	31.8	544.2
13	12.3	76.2	394.7	122.3	42.4	50.5	31.8	746.8
14	16.2	100.2	519.5	152.2	56.5	49.9	31.7	947.6
15	20.1	124.3	644.3	180.6	70.6	49.4	31.7	1147.2

Table C.5.5 Total Cost as a Function of Area Ratio

```
   PACKED BED ACTIVE PUMPING        8.68E-5 LB U/LB TI(OH)4
#  CRNT MPH   U FT/SEC   D FT        L FT     T HR      AR   CTG FT   $/LBU308
1     0.48   0.00355  0.0002121  0.03874   32.0     200 1.74E-005   360.6
2     1.45   0.00355  0.0002121  0.03874   32.0     600 1.74E-005   326.0
3     2.41   0.00355  0.0002121  0.03874   32.0    1000 1.74E-005   319.3
4     3.38   0.00355  0.0002121  0.03874   32.0    1400 1.74E-005   316.8
5     4.35   0.00355  0.0002121  0.03874   32.0    1800 1.74E-005   315.8
6     4.83   0.00355  0.0002121  0.03874   32.0    2000 1.74E-005   315.6
7     5.31   0.00355  0.0002121  0.03874   32.0    2200 1.74E-005   315.5
8     6.04   0.00355  0.0002121  0.03874   32.0    2500 1.74E-005   315.6
9     7.24   0.00355  0.0002121  0.03874   32.0    3000 1.74E-005   316.2
10   12.07   0.00355  0.0002121  0.03874   32.0    5000 1.74E-005   322.4
11   24.14   0.00355  0.0002121  0.03874   32.0   10000 1.74E-005   355.8
12   60.35   0.00355  0.0002121  0.03874   32.0   25000 1.74E-005   571.8
13  120.70   0.00355  0.0002121  0.03874   32.0   50000 1.74E-005  1261.5

 #    EAF      AVG LD     RCV       AREA FT    REG         PMP PWR MW  TOTAL PWR
 111.583     0.816      0.737      3.34E+007  0.05             45.78       88.35
 211.567     0.816      0.737      3.34E+007  0.05             45.91       88.48
 311.534     0.816      0.737      3.34E+007  0.05             46.16       88.73
 411.485     0.816      0.737      3.34E+007  0.05             46.54       89.11
 511.420     0.816      0.737      3.34E+007  0.05             47.05       89.62
 611.381     0.816      0.737      3.34E+007  0.05             47.35       89.92
 711.340     0.816      0.737      3.34E+007  0.05             47.68       90.25
 811.270     0.816      0.737      3.34E+007  0.05             48.24       90.81
 911.136     0.816      0.737      3.34E+007  0.05             49.33       91.90
1010.418     0.816      0.737      3.34E+007  0.05             55.67       98.24
11 7.999     0.816      0.737      3.34E+007  0.05             85.38      127.95
12 3.046     0.816      0.737      3.34E+007  0.05            293.37      335.94
13 0.949     0.816      0.737      3.34E+007  0.05           1036.23     1078.88
```

Table C.5.5 (Continued)

#	$/KGAL	MILL/KWHR	$/LBCO2	$/LBNH3	$/TON	MRNG CST
1	5.471	61.338	0.014	0.100	42.596	53.4
2	5.470	61.313	0.014	0.100	42.596	18.7
3	5.469	61.264	0.014	0.100	42.596	11.7
4	5.468	61.191	0.014	0.100	42.596	8.8
5	5.465	61.093	0.014	0.100	42.596	7.1
6	5.464	61.036	0.014	0.100	42.596	6.5
7	5.462	60.973	0.014	0.100	42.596	6.0
8	5.460	60.868	0.014	0.100	42.596	5.5
9	5.455	60.665	0.013	0.100	42.596	4.8
10	5.429	59.550	0.013	0.100	42.596	3.4
11	5.331	55.425	0.013	0.100	42.596	2.3
12	5.054	43.695	0.012	0.100	42.596	1.7
13	4.838	34.575	0.012	0.100	42.596	1.5

#	P CPTL	B CPTL	BOP	PWR	ATTRN	WATER	CHEM	T$/LBU3O8
1	3.7	23.7	122.1	44.7	11.1	62.9	39.0	360.6
2	3.7	23.7	122.2	44.8	11.1	62.9	39.0	326.0
3	3.7	23.7	122.3	45.0	11.1	62.9	39.0	319.3
4	3.7	23.7	122.4	45.3	11.1	62.9	39.0	316.8
5	3.8	23.7	122.6	45.7	11.1	62.8	39.0	315.8
6	3.8	23.7	122.7	46.0	11.1	62.8	39.0	315.6
7	3.8	23.7	122.8	46.3	11.1	62.8	39.0	315.5
8	3.9	23.7	123.0	46.7	11.1	62.8	39.0	315.6
9	4.0	23.7	123.4	47.6	11.1	62.7	39.0	316.2
10	4.5	23.7	125.7	52.7	11.1	62.4	38.9	322.4
11	6.9	23.7	136.3	75.3	11.1	61.3	38.9	355.8
12	23.6	23.7	211.0	203.9	11.1	58.1	38.7	571.8
13	83.4	23.7	477.6	570.0	11.1	55.6	38.5	1261.5

Table C.5.6 Total Cost as a Function of Coating Thickness

```
    PACKED BED ACTIVE PUMPING           8.68E-5 LB U/LB TI(OH)4
 # CRNT MPH   U FT/SEC  D FT          L FT      T HR     AR    CTG FT   $/LBU308
 1    5.31    0.00355  0.0002121   0.03874   32.0    2200 1.00E-006  1859.8
 2    5.31    0.00355  0.0002121   0.03874   32.0    2200 3.00E-006   762.4
 3    5,31    0.00355  0.0002121   0.03874   32.0    2200 6.00E-006   468.8
 4    5.31    0.00355  0.0002121   0.03874   32.0    2200 1.00E-005   354.4
 5    5.31    0.00355  0.0002121   0.03874   32.0    2200 1.40E-005   321.0
 6    5.31    0.00355  0.0002121   0.03874   32.0    2200 1.60E-005   316.3
 7    5.31    0.00355  0.0002121   0.03874   32.0    2200 1.74E-005   315.5
 8    5.31    0.00355  0.0002121   0.03874   32.0    2200 2.00E-005   317.4
 9    5.31    0.00355  0.0002121   0.03874   32.0    2200 2.20E-005   320.8
10    5.31    0.00355  0.0002121   0.03874   32.0    2200 2.60E-005   330.2
11    5.31    0.00355  0.0002121   0.03874   32.0    2200 3.00E-005   341.3
12    5.31    0.00355  0.0002121   0.03874   32.0    2200 4.00E-005   370.1
13    5.31    0.00355  0.0002121   0.03874   32.0    2200 5.00E-005   397.1
14    5.31    0.00355  0.0002121   0.03874   32.0    2200 7.00E-005   443.0
15    5.31    0.00355  0.0002121   0.03874   32.0    2200 1.00E-004   500.9
16    5.31    0.00355  0.0002121   0.03874   32.0    2200 1.05E-004   510.2

 #   EAF     AVG LD     RCV         AREA FT    REG        PMP PWR MW TOTAL PWR
 1 0.936     1.000      0.061      4.05E+008  0.05          577.71    1093.52
 2 2.755     1.000      0.179      1.37E+008  0.05          196.26     371.49
 3 5.348     0.999      0.348      7.88E+007  0.05          101.10     191.36
 4 8.325     0.970      0.541      4.55E+007  0.05           64.94     122.93
 510.323     0.893      0.671      3.67E+007  0.05           52.37      99.14
 610.981     0.848      0.714      3.45E+007  0.05           49.24      93.20
 711.340     0.816      0.737      3.34E+007  0.05           47.68      90.25
 811.841     0.761      0.770      3.20E+007  0.05           45.66      86.43
 912.119     0.723      0.788      3.13E+007  0.05           44.61      84.44
1012.489     0.656      0.812      3.03E+007  0.05           43.29      81.94
1112.701     0.602      0.825      2.98E+007  0.05           42.57      80.58
1212.870     0.508      0.836      2.94E+007  0.05           42.01      79.52
1312.780     0.449      0.831      2.96E+007  0.05           42.31      80.08
1412.234     0.381      0.795      3.10E+007  0.05           44.19      83.65
1511.007     0.330      0.715      3.44E+007  0.05           49.12      92.98
1610.794     0.323      0.702      3.51E+007  0.05           50.09      94.81
```

Table C.5.6 (Continued)

#	$/KGAL	MILL/KWHR	$/LBCO2	$/LBNH3	$/TON	MRNG CST
1	3.211	34.493	0.009	0.100	42.596	58.7
2	4.006	42.723	0.011	0.100	42.596	20.8
3	4.619	49.955	0.013	0.100	42.596	11.4
4	5.094	56.021	0.013	0.100	42.596	7.8
5	5.347	59.400	0.014	0.100	42.596	6.5
6	5.423	60.427	0.014	0.100	42.596	6.2
7	5.462	60.973	0.014	0.100	42.596	6.0
8	5.517	61.719	0.013	0.100	42.596	5.8
9	5.546	62.124	0.013	0.100	42.596	5.7
10	5.584	62.656	0.013	0.100	42.596	5.6
11	5.606	62.955	0.013	0.100	42.596	5.5
12	5.623	63.193	0.013	0.100	42.596	5.5
13	5.614	63.067	0.012	0.100	42.596	5.5
14	5.558	62.291	0.012	0.100	42.596	5.5
15	5.426	60.468	0.011	0.100	42.596	5.7
16	5.402	60.140	0.011	0.100	42.596	6.2
						6.3

#	P CPTL	E CPTL	BOP	PWR	ATTRN	WATER	CHEM	T$/LBU308
1	46.5	126.4	771.0	317.0	9.0	447.3	83.8	1859.8
2	15.8	50.6	296.1	133.4	9.0	189.6	47.1	762.4
3	8.1	31.7	177.7	80.3	9.1	112.6	37.9	468.8
4	5.2	24.9	134.3	57.9	9.3	79.8	35.3	354.4
5	4.2	23.4	123.2	49.5	10.1	67.5	36.5	321.0
6	4.0	23.5	122.4	47.3	10.7	64.4	37.9	316.3
7	3.8	23.7	122.8	46.3	11.1	62.8	39.0	315.5
8	3.7	24.3	124.9	44.8	11.9	60.7	41.2	317.4
9	3.6	24.9	127.2	44.1	12.5	59.7	43.1	320.8
10	3.5	26.3	132.8	43.2	13.8	58.3	46.8	330.2
11	3.4	27.7	139.0	42.6	15.0	57.5	50.4	341.3
12	3.4	31.2	154.3	42.2	17.8	57.0	58.8	370.1
13	3.4	34.3	168.1	42.4	20.1	57.3	66.0	397.1
14	3.6	39.2	190.9	43.8	23.7	59.2	76.9	443.0
15	4.0	45.0	218.3	47.3	27.4	64.3	88.5	500.9
16	4.0	45.9	222.6	47.9	28.0	65.2	90.3	510.2

Table C.6 The Effect of Increasing Sorber Capacity on Optimized, Actively Pumped, Packed Bed Designs

```
  PACKED BED ACTIVE PUMPING
# CRNT MPH  U FT/SEC  D FT         L FT      T HR      AR   CTG FT  $/LBU308
1   5.31   0.00355  0.0002121  0.03874   32.0    2200 1.74E-005   315.5
2   5.19   0.00451  0.0002566  0.04219   37.3    1693 1.57E-005   214.4
3   4.97   0.00693  0.0003766  0.03721   54.7    1055 1.57E-005   114.2
4   4.97   0.00770  0.0004350  0.04298   66.2     950 1.65E-005   102.2
5   4.65   0.01231  0.0007356  0.05058  188.9     557 6.68E-006    47.2

#    EAF      AVG LD     RCV          AREA FT    REG        PMP PWR MW  TOTAL PWR
111.340      0.816      0.737       3.34E+007  0.05             47.68       90.25
216.531      0.776      0.803       2.34E+007  0.07             33.16       61.91
334.968      0.713      0.780       1.48E+007  0.16             17.77       29.35
440.850      0.688      0.778       1.31E+007  0.21             15.08       25.05
599.334      0.306      0.783       7.54E+006  0.56              7.75       10.30

# $/KGAL     MILL/KWHR $/LBCO2     $/LBNH3     $/TON        MRNG CST
1  5.462      60.973     0.014      0.100      42.596         6.0
2  5.971      67.945     0.016      0.100      42.596         5.6
3  7.300      85.459     0.022      0.100      42.596         5.7
4  7.574      89.930     0.023      0.100      42.596         5.6
5  9.660     121.354     0.039      0.100      42.596         5.5

#   P CPTL B CPTL    BOP      PWR      ATTRN    WATER    CHEM   T$/LBU308
1    3.8    23.7    122.8    46.3     11.1     62.8     39.0    315.5
2    2.7    15.1     79.4    35.8      7.9     46.4     21.5    214.4
3    1.4     7.5     40.0    24.2      5.8     22.8      6.7    114.2
4    1.2     6.8     35.9    21.6      5.3     20.4      5.5    102.2
5    0.6     2.7     14.7     15.0     1.3      6.7      0.6     47.2
```

Key: 1 8.68×10^{-5} lb U/lb HTO
2 1.74×10^{-4} lb U/lb HTO
3 6.61×10^{-4} lb U/lb HTO
4 8.68×10^{-4} lb U/lb HTO
5 3.00×10^{-2} lb U/lb HTO

Table C.7 The Effect of Increasing Pumping Power Requirements on Optimized Packed Bed Designs

```
   PACKED BED ACTIVE PUMPING          8.68E-5 LB U/LB TI(OH)4
# CPHT MPH  U FT/SEC  D FT        L FT     T HR     AR   CTG FT   $/LBU308
1    5.31   0.00355  0.0002121  0.03874  32.0   2200 1.74E-005   315.5
2    4.79   0.00320  0.0002333  0.04068  32.0   2200 1.65E-005   341.0
3    4.09   0.00304  0.0002566  0.04474  33.6   1980 1.65E-005   360.9
4    3.48   0.00274  0.0003105  0.05414  38.8   1871 1.73E-005   417.5
5    2.97   0.00234  0.0003586  0.05955  44.8   1862 1.82E-005   456.5
6    2.53   0.00211  0.0004339  0.06878  47.0   1769 1.82E-005   512.5

#    EAF       AVG LD     RCU        AREA FT    REG        PMP PWR MW TOTAL PWR
1 11.340      0.816      0.737     3.34E+007  0.05              47.68      90.25
2  9.598      0.801      0.744     3.67E+007  0.05              57.50     106.63
3  8.712      0.799      0.744     3.83E+007  0.05              63.35     117.47
4  6.805      0.765      0.742     4.15E+007  0.05              87.20     150.39
5  6.247      0.752      0.743     4.73E+007  0.05              93.64     163.82
6  5.214      0.717      0.733     5.31E+007  0.06             109.09     196.28

#  $/KGAL     MILL/KWHR $/LBCO2    $/LBNH3    $/TON      MRNG CST
1   5.462     60.973     0.014      0.100    42.596      6.0
2   5.279     58.222     0.013      0.100    42.596      6.5
3   5.165     56.709     0.013      0.100    42.596      7.3
4   4.959     53.119     0.013      0.100    42.596      8.2
5   4.851     51.959     0.012      0.100    42.596      9.2
6   4.637     49.640     0.012      0.100    42.596     10.7

#   P CPTL B CPTL    BOP       PWR       ATTRN     WATER    CHEM   T$/LBU308
1     3.8    23.7   122.8     46.3       11.1     62.8     39.0     315.5
2     4.6    24.9   131.7     53.3        9.7     70.0     40.3     341.0
3     5.1    26.2   139.4     57.2        8.9     75.5     41.3     360.9
4     7.0    29.6   163.1     73.7        7.9     84.6     43.3     417.5
5     7.5    33.8   184.5     77.4        7.2     92.0     44.7     456.5
6     8.8    37.4   205.8     86.2        6.2    109.2     48.3     512.5
```

Key: 1 - Base Case
2 - 1.5 x Base Case Pumping Power
3 - 2 x Base Case Pumping Power
4 - 4 x Base Case Pumping Power
5 - 6 x Base Case Pumping Power
6 - 10 x Base Case Pumping Power

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