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EXTRACTION of URANIUM from SEAWATER: EVALUATION of URANIUM RESOURCES and PLANT SITING,

Volume I

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XN-RT-14

EXTRACTION OF URANIUM FROM SEAWATER: EVALUATION OF URANIUM RESOURCES AND PLANT SITING,
VOLUME I

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EXTRACTION OF URANIUM FROM SEAWATER
EVALUATION OF URANIUM RESOURCES AND PLANT SITING
VOLUME I

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EXECUTIVE SUMMARY

1 Objectives and Organization of the Study

The objectives for this study were: 1) to evaluate the territorial coastal waters of the United States of America as a uranium resource and 2) to select one or more sites for plants designed for the large scale extraction of uranium from these waters. The target production scale was to be on the order of 500-1000 metric tons (hereinafter noted as "tonnes") of uranium per year.

These objectives were the initial stages toward the further objectives of the overall study which were: to select a process for the extraction and to determine the technical, economic and environmental feasibility of such an operation aimed at meeting a significant part of the Nation's energy needs in the future. A multidisciplinary group was assembled under the project management of Exxon Nuclear Company (ENC) to attain these objectives. Oregon State University (OSU) under subcontract to ENC provided scientific and technical expertise in oceanography and nuclear engineering available in its School of Oceanography and Department of Nuclear Engineering. Expertise in the Departments of Chemistry and Chemical Engineering was utilized as well. Vitro Engineering Corporation (VEC) developed engineering flowsheets and architectural design. ENC provided overall project management and coordination and ability to transfer technology development to operating systems. Cost estimating, operating and environmental experience, as well as economic modelling were also specifically provided by Exxon Nuclear Company.

In an endeavor to assure the technical reliability of this report, a technical review committee composed of experts from the above mentioned fields who were not involved in this study was asked to review and comment on all aspects of the study three times during the course of the project. Technical Review Committee comments were taken very seriously and incorporated into the study.

In that much of the prior work on recovering uranium from seawater was reported by European and Japanese scientists and engineers, trips were taken to these locations to learn of the state-of-the-art. These visits were most helpful in providing a more substantial basis for the many decisions needed in arriving at sound conclusions and facility designs.

The results of the project have been recorded in two documents, each consisting of two volumes. The first document, of which this is Volume

I, treats the evaluation of U. S. coastal ocean waters as a uranium resource and the selection of a suitable site for a large-scale extraction plant, noted above as the first two objectives of this study. Volume II of this document contains the literature citations, located in this study, which are pertinent to the resource evaluation and site selection. 471 literature citations are presented there together with author, geographic and subject indices. Volume II will often be cited herein as "The Bibliography".

The companion document to this one treats, in Volume I, the selection of a chemical process suitable for large scale extraction of uranium from seawater, together with the technical, economic and environmental considerations involved in plant construction. It will often be referred to in this one as "the Feasibility Study." Volume II of that document contains an analogous bibliography and indices.

Before turning to the content of This Study, it should be noted that it was prepared in close collaboration with all the other components of the overall study, particularly with respect to site selection considerations.

2 Resource Evaluation

Examination of the marine and physical chemical literature revealed nothing to weaken the conception currently held by marine chemists that approximately 98% of the uranium in seawater occurs in the dissolved state as negatively charged uranyl-carbonate complex ions. Somewhat less than 2% occurs as negatively charged uranyl hydroxide complex ions. Other forms such as overall neutrally charged chemical forms may exist but probably in relative amounts much less than one percent.

Uranium behaves as what the oceanographer calls a conservative constituent of the oceans: It remains dissolved in the oceans on the average for periods of time which are very long compared to the circulation and mixing times of the deep waters of the oceans. This results from the annual supply and removal rates of uranium to and from the sea being very small fractions of the total amount contained therein. As a result, uranium is distributed much like sea salt in the oceans and to maximize the local resource, one should seek a location where the salinity is high.

Although the concentration of uranium is quite low, about 3.3 ppb (parts per billion) in seawater of average oceanic salinity, the amount present in the total volume of the oceans is very great, some 4.5 billion tonnes. Of this, perhaps only that uranium contained in the upper 100 meters or so of the surface well-mixed layer should be considered accessible for recovery, some 160 million tonnes. Practically speaking, the amount contained in the ocean surface layers is unlimited with respect to large scale extraction in the forseeable future. This results from the replenishment by continental weathering and river runoff being much larger than forseeable extraction rates.

Our study indicated that open ocean seawater acquired for the purpose of uranium extraction would be a more favorable resource than would rivers entering the sea, the cooling water of present or planned power plants (either fossil fuel or nuclear), or the feed or effluent streams of existing plants producing other products such as magnesium, bromine, or potable and/or agricultural water from seawater. The reasons for these conclusions are: 1) In the case of rivers and streams, production on the scale of a thousand tonnes of uranium per year would require total extraction of the uranium from a major fraction of even our largest river, the Mississippi. Further, the sediment load carried by any large river would incapacitate any known process for the extraction. 2) In the case of existing power or material production plants utilizing seawater as coolant or feed, the scales are simply too small.

Our conclusion relative to marine resources is that only seawater pumped or otherwise accessed for the purpose of uranium extraction would constitute a viable resource.

3 Plant Sites

To select suitable extraction plant sites, it was necessary to consult both our co-workers in this project and the scattered literature on coastal oceanography, geography, geology, and geophysics of coastal regions. Our co-workers were able to provide us with process and plant specific criteria for site selection. Literature information allowed us to evaluate various regions and local areas against these and resource considerations.

Process and plant specific criteria included relatively high temperature of the local seawater, topography, geological and geophysical suitability of the potential site, availability of sufficient fresh water and other process needs, accessibility to logistic and labor bases for plant construction and operation, etc. Resource specific considerations included ready access to a steady supply of relatively saline seawater with minimal biological or other fouling potential, and assurance that the uranium-stripped plant outflow stream would not mix back into the plant intake.

Process selection and plant design were intimately connected with certain aspects of resource evaluation concerning regional oceanographic conditions. Three basic plant configurations were considered: 1) an open ocean platform, either bottom supported, free floating with dynamic position control, or more or less loosely moored to the bottom, 2) a tidally driven seawater feed stream, and 3) a coastal plant with a pumped seawater feed stream.

It was found that the only U. S. site with a favorable tidal range to permit tidal energy as the seawater motive power was Cook Inlet, Alaska. Unfortunately the temperatures and salinities in that region are too low. Relatively high seawater temperatures are required because of the high temperature coefficients involved in the extraction processes considered. Low temperatures appear to adversely affect the amount of uranium which can be extracted by an absorber. (See the Feasibility Study.) Low salinity of the seawater feed stream may be equated with dilution of the uranium contained in it. (See Section 2.1.) This is an effect of about 10%. Finally, the regional circulation patterns of the waters in and around Cook Inlet are such that the stripped outflow of the plant would mix back into the feed stream, drastically reducing plant efficiency.

Offshore plants, either bottom mounted, or floating would offer several advantages in principle. These include accessibility to more steady surface currents than available close inshore, and typically lower sediment loads and biological fouling as well as potentially better separation of feed and out flow streams. However, it was found that a poor data base was accessible upon which to develop a technical, economic, and environmental feasibility study. (This subject has been treated more fully in the Feasibility Study.)

Such considerations led to the selection of a site for a pumped seawater coastal plant at a coastal location. Puerto Yabucoa, Puerto Rico was selected. This coastal site has a narrow continental shelf which allows the Antilles Current to bring a relatively constant supply of warm, saline seawater relatively close to the potential plant site and to assist in carrying away the plant outflow. More than six square kilometers of nearly level terrain less than three meters above sea level, suitable for a plant site abut the shoreline. An ample fresh water supply is available or could be economically developed. The present land use is of relatively low intensity, as is human habitation.

4 Further Research and Development Indicated

Lest a misconception be conveyed about the state of knowledge basic to this subject, we would make several points here. First, the basic chemistry background knowledge of exactly how uranium occurs in seawater needs to be improved. What is known is mainly inferred from data obtained for distilled water experiments at one or two temperatures and not from experiments on natural seawater over the ranges of oceanic temperature and salinity. The extraction process could be more "finely tuned" were this data base more firmly established.

More detailed oceanographic and other data should be obtained for any set of sites to be considered further. These data would include uranium concentration distributions and variations, more detailed chemical observations, as well as surface current, meteorological, climatic, geographic, geological, and geophysical data. The impact of large-scale process streams should be hydrologically modeled for all plant sites considered. Although some marine organisms do concentrate uranium from seawater, present or projected harvest levels and methods do not appear to lend themselves to large scale uranium extraction processes but study of the mechanisms of concentration by these organisms might lead to improved processes. Finally, although it appears from this study that current technology can mitigate societal and environmental impacts of large scale uranium extraction plants, the subject bears careful study.

5 Process Selection and Feasibility

The process selection, technical, economic and environmental feasibility of the extraction of uranium from seawater are treated in the Feasibility Study, to which the reader is directed.

6 Summary Statement

1) The surface waters of the oceans comprise a virtually inexhaustible uranium resource of some 160 million tonnes, extractible indefinitely at a rate of a few thousand tonnes per year.
2) The best site located in this study was Puerto Yabucoa, Puerto Rico. It is oceanographically and otherwise well suited for construction of a large scale uranium extraction plant.
3) Before actual plant construction is begun, further research must be conducted on the marine chemistry of uranium and its detailed oceanographic distribution and variability in the locale of the plant must be studied.

ABSTRACT

This report is one result of a U. S. Department of Energy (DOE) project sponsored through Bendix Field Engineering Corporation (BFEC). The project's objective was to examine the feasibility and economics of the extraction of uranium from territorial waters of the United States of America on a scale large enough to meet a significant fraction of projected national energy needs. It was a joint effort between Exxon Nuclear Company, Inc. (ENC) and Oregon State University (OSU).

This report deals with the evaluation of U. S. coastal waters as a uranium resource and with the selection of a suitable site for construction of a large-scale plant for uranium extraction.

A companion work to this report contains 471 literature citations relevant to the subject. It is:

> "SELECTED BIBLIOGRAPHY FOR THE EXTRACTION OF URANIUM FROM SEAWATER: EVALUATION OF URANIUM RESOURCES AND PLANT SITING" by Arthur C-T. Chen, Louis I. Gordon, Michael R. Rodman and Stephen E. Binney (Exxon Nuclear Company Publication Number XN-RT-14, Vol. I).

Both that document and the present bibliography are closely related to two other documents, which were also an important part of the same study:

> "EXTRACTION OF URANIUM FROM SEAWATER: CHEMICAL PROCESS AND PLANT DESIGN FEASIBILITY STUDY" by M. H. Campbell, J. M. Frame, N. D. Dudley, G. R. Kiel, V. Mesec, F. W. Woodfield, S. E. Binney, M. R. Jante, R. C. Anderson, and G. T. Clark.

and

> "SELECTED BIBLIOGRAPHY FOR THE EXTRACTION OF URANIUM FROM SEAWATER: CHEMICAL PROCESS AND PLANT DESIGN FEASIBILITY STUDY" by S. E. Binney, S. Polkinghorne, M. R. Jante, M. R. Rodman, A. C-T. Chen, and L. I. Gordon.

These documents are Exxon Nuclear Company Report Number XN-RT-15, Volumes I and II and Oregon State University Department of Nuclear Engineering Report Number OSU-NE-7901, Volumes I and II. Their titles indicate the remaining objectives of the overall study, selection of a suitable chemical process for the extraction, and a design and economic feasibility study of a large-scale extraction plant.

Evaluation of the resource revealed that although the concentration of uranium is quite low, about 3.3 ppb (parts per billion) in seawater of

average oceanic salinity, the amount present in the total volume of the oceans is very great, some 4.5 billion metric tons (hereinafter noted as "tonnes"). Of this, perhaps only that uranium contained in the upper 100 meters or so of the surface well-mixed layer should be considered accessible for recovery, some 160 million tonnes. Practically speaking the amount contained in the ocean surface layers is unlimited with respect to large scale extraction in the forseeable future. This results from the replenishment by continental weathering and river runoff being much larger than forseeable extraction rates.

Our study indicated that open ocean seawater acquired for the purpose of uranium extraction would be a more favorable resource than would rivers entering the sea, the cooling water of present or planned power plants (either fossil fuel or nuclear), or the feed or effluent streams of existing plants producing other products such as magnesium, bromine, or potable and/or agricultural water from seawater.

Various considerations led to the selection of a site for a pumped seawater coastal plant at a coastal location. Puerto Yabucoa, Puerto Rico was selected. This coastal site has a narrow continental shelf which allows the Antilles Current to bring a relatively constant supply of warm, saline seawater relatively close to the potential plant site and to assist in carrying away the plant outflow. More than six square kilometers of nearly level terrain less than three meters above sea level, suitable for a plant site abut the shoreline. An ample fresh water supply is available or could be economically developed. The present land use is of relatively low intensity as is human habitation. Several topics for further research and development were identified.

First, the basic chemistry background knowledge of exactly how uranium occurs in seawater needs to be improved. The extraction process could be more "finely tuned" were this data base more firmly established. More detailed oceanographic and other data should be obtained for any set of sites to be considered further. The impact of large-scale process streams upon local currents and related oceanographic and biological systems should be hydrologically modeled for all plant sites considered. Although some marine organisms do concentrate uranium from seawater, present or projected harvest levels and methods do not appear to lend themselves to large scale uranium extraction processes but study of the mechanisms of concentration by these organisms might lead to improved processes. Finally, although it appears from this study that current technology can mitigate societal and environmental impacts of large scale uranium extraction plants, the subject bears careful study.

EXTRACTION OF URANIUM FROM SEAWATER:
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Ms. Beverly Knapp, the School of Oceanography editor, Mr. George Shaw and Robert Lewis of the Oregon State University Department of Printing were most helpful and patient during the final preparation of copy for the press. Our most special thanks and gratitude are due Ms. Nancy Sarpola whose amazing patience, competence, and sense of humor carried us through this project, especially in its frantic last days of report preparation.

CHAPTER 1

INTRODUCTION

1.1 Background

This section gives a brief statement of the purpose of this report, its relation to other documents, a short background statement on the extraction of uranium from seawater and a general description of the production and organization of this report.

1.1.1 Objectives and Organization of the Study

The objectives for this study were: 1) to evaluate the territorial coastal waters of the United States of America as a uranium resource and 2) to select one or more sites for plants designed for the large scale extraction of uranium from these waters. The target production scale was to be on the order of 500-1000 tons of uranium per year.

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The results of the project have been recorded in two documents, each consisting of two volumes. The first document, of which this is Volume I, treats the evaluation of U. S. coastal ocean waters as a uranium resource and the selection of a suitable site for a large-scale extraction plant, noted above as the first two objectives of this study. Volume II of this document contains the literature citations, located in this study, which are pertinent to the resource evaluation and site selection. 471 literature citations are presented there together with author, geographic and subject indices. Volume II, often called herein "the Bibliography", may be cited as:

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These documents are Exxon Nuclear Company Report Number XN-RT-15, Volumes I and II and Oregon State University Department of Nuclear Engineering Report Number OSU-NE-7901, Volumes I and II. They constitute part of the low-level uranium resource study conducted by DOE/BFEC as part of the National Uranium Resource Evaluation (NURE) program.

Before turning to the content of This Study it should be noted that it was prepared in close collaboration with all the other components of the overall study, particularly with respect to site selection considerations. The specific individuals were chiefly the authors of the Feasibility Study.

1.1.2 Background for the extraction of uranium from seawater

The Department of Energy projections for low cost uranium resources in the United States range from 2.2 to 4.1 million tonnes [285] whereas, the oceans contain over 4 billion tonnes of uranium in the dissolved form. The possibility that this practically unlimited amount of uranium in seawater can be extracted has intrigued many investigators.

In the mid 1960's, British investigators considered a number of possibilities for uranium recovery from seawater as a consequence of their decision to begin a nuclear power program and their total lack of domestic reserves of uranium. Similar studies were soon undertaken in Russia, India, Germany, Pakistan and Japan. These foreign countries appear to be a few steps ahead of the United States in this aspect. The present project constitutes an increment in closing the gap.

1.1.3 Compilation of the Bibliography

The compilation of and access to key literature sources listed in the Bibliography were necessary first steps in this study. In the Bibliography, a total of 471 references from various countries have been collected. They are for the most part references related to uranium resources in seawater, river water, marine organisms, sediments and mineral deposits in the oceans; references dealing with the uranium resource available through treatment of seawater pumped in such operations as desalination and power plant cooling; and references concerning the site selection criteria for the construction of a large scale uranium extraction plant. Some other pertinent references, for example, the resource evaluation of potential co-products and consideration of the environmental and social impacts were also listed. Apparently outmoded data or data obtained by using apparently unreliable methodology have been excluded. The articles referenced in this report are all listed in the the Bibliography. The Bibliography lists many references that are not directly referenced in this report.

The bibliography was compiled using a machine literature retrieval system, a computerized bibliographic system, and a computer word processor system. These are described in the Bibliography and again here.

1.1.4 Literature retrieval system

In order to facilitate thorough and efficient retrieval of reference material dealing with the uranium resources and U.S coastal site characteristics, the Oregon State University Kerr Library Information Retrieval Service (LIRS) was used. LIRS provided on-line bibliographic searching through remote access terminals, which connect with data bases such as that of the Lockheed Information Systems and Systems Development Corporation. These data bases provided information from a number of indices and directories, e.g., Chemical Abstracts and Oceanic Abstracts, programmed for retrieval by computer. Although these data bases covered various subject areas, the searches focussed upon the relevant chemistry, engineering and earth sciences. The data bases accessed were the NTIS (1964-1978); Oceanic Abstracts (1964-1977); Nuclear Science Abstracts (1966-1976); Energy Data Base (1976-1978); Chemical Abstracts (1972-1978) and Dissertation Abstracts (1953-1976).

After searching these data bases and evaluating accessible background information, secondary references were developed and, experts contacted in the relevant fields to complete the data base.

1.1.5 Bibliographic data system

As bibliographic information and actual reprints and copies of articles were acquired, appropriate bibliographic data were entered into the FAMULUS bibliographic data management system available through the Oregon State University Computer Center. This system provided the capacity for entry and storage of the bibliographic data, editing capability, listing and numbering after sorting (in this case by alphabetical order of authors), indexing according to the authors's countries, geographical areas of study and subject keywords and finally printing out in useable format the data list.

1.1.6 Text processor system

When all bibliographic data were in order, the front matter and text of this report and the Bibliography were prepared using the RNF word processor system available at the Oregon State University Computer Center. This enabled text entry, storage and editing capability. RNF proved to be especially valuable in preparing the Bibliography and this report in the short time period available.

1.2 Organization of This Report

In the following chapters are presented the detailed findings and conclusions we obtained in this study. Several potential oceanic or ocean-related resources are evaluated in Chapter 2. This chapter begins with a discussion of the chemical forms, and concentrations in which uranium occurs in seawater. This knowledge is necessary in order to understand the distribution of uranium in the oceans as well as for an intelligent selection and design of an extraction process. The uranium resource potential of the oceans and ocean-related sources is also presented in this chapter. Examined were:

a) the oceans and their systems of currents,
b) rivers,
c) marine sediments and mineral deposits, organisms and their shells,
d) the feed or cooling streams of existing or planned chemical extraction or power plants in coastal regions,
e) and the value of potential byproducts or coproducts which might be produced together with uranium.

In Chapter 3 is presented a detailed discussion of the selection criteria employed by us in collaboration with our colleagues on this project (See the Feasibility Study.) to arrive at a suitable process and site for an extraction plant. Selection of a process and of a site proved to be quite interrelated. This is reflected in the discussion to be found in Chapter 3.

The regional characteristics of U. S. coastal environs as they relate to this project are then described in Chapter 4. This then allowed a comparison of the characteristics of the various regions with the selection criteria developed in Chapter 3. The set of generally qualified regions is then described and discussed in Chapter 5. Finally, with regard to site selection, there is a discussion of the specific sites chosen, in Chapter 6. Included there are treatments of how well they fit the selection criteria of Chapter 3 and the merits and faults of each site.

In Chapter 7 are considered very briefly some of the legal environmental and social considerations which have to be kept in mind for an extraction process of the kind and scale in this study. The Feasibility Study contains a more fully developed treatment of these topics.

Considerable further research and development will be required in order to further pursue large scale uranium recovery from the seas. Ideas on what is required as seen from our vantage point are presented in Chapter 8.

The conclusions which followed from this study are reviewed in Chapter 9. Lastly, the Appendix contains three sections, two of which may prove to be especially helpful to the reader. The first is a glossary of terms as we employ them in this report. In consideration of the wide range of readership anticipated there has been a serious attempt on our part to avoid chemical and oceanographic jargon. We apologize for the slips which may have occurred and hope that where specialized terms, mnemonics and symbols have been inevitable we have included all of them in the Glossary. Also in the Appendix is a report of a literature search and site visit trip made by two of us (A. C-T. C. and M. R. R.). The last item in the Appendix contains the citation and Abstract for the Bibliography, Volume II of this document as well as the citations and Executive Summaries for Volume I and Volume II of the companion document, the Feasibility Study.

CHAPTER 2

RESOURCE EVALUATION

It has been estimated that the U.S. uranium resources range from 2.2 to 4.1 million tonnes [285], whereas, the oceans contain over 4 billion tonnes of uranium in dissolved form. The possibility that this practically unlimited amount of uranium in seawater can be extracted economically has intrigued many investigators.

In this chapter, the resource potential for uranium from the oceans and their currents, as well as that of rivers, various marine sediments and deposits and of marine organisms is examined. The resource potential of the seawater currently being (and projected to be) pumped in industrial facilities such as desalination plants and power plants is examined and the possibility of co-and/or by-products is evaluated.

2.1 Uranium in Seawater, Forms and Concentration

The chemical states of uranium in seawater must be known before one can fully understand the adsorption mechanism and to manufacture proper adsorbents. Since most of the previous studies have been made only for fresh water environments [38; 258; S15], it is necessary to investigate the uranium speciation in the oceans as follows.

It has long been known that uranyl compounds [compounds containing UO_2^{2+}] show considerable solubility in sodium carbonate solution. Haldar [151], in 1947, observed discontinuities in the conductometric titration of uranyl nitrate with carbonate solutions. The discontinuities at points corresponding to carbonate: uranium mole ratios of 2:1 and 3:1 were indicative of the formation of stable complexes. Several authors have also shown [38; 63; 258; 373; S15] that uranyl ions in carbonate solution will form the complexes $UO_2(CO_3)_2^{-2}$ and $UO_2(CO_3)_3^{4-}$ when the carbonate ion is present in excess and the pH is greater than 7. The stability constants have been determined to be on the order of 10^{-14} and 10^{-18} respectively [38; 258; S8; S12]. By considering the elements found in seawater, Starik and Kolyadin [373] expected uranium to occur in the following forms in seawater:

1. In the colloidal state as a result of the solubility of some of its compounds

2. In the form of complexes with colloidal particles present in seawater.

3. In the form of carbonate complexes.

4. In the form of soluble products of hydrolyzed uranyl ion.

5. In the form of complexes with organic components of seawater.

From the results of experiments on seawater and carbonate solutions of uranium (ultrafiltration, adsorption on cation and anion ion exchangers, adsorption on glass powder), it was concluded [373] that at $pH < 7.5$ the uranium exists in seawater in the form of complexes with colloidal particles. The adsorption of uranium on cation and anion exchangers also indicated that, at lower pH (3 to 6), there occur strong shifts in the equilibrium between the uranyl ion hydrolysis products and the anion complex upon the addition of ion exchanger to the solution. Therefore, if the pH value is increased the equilibrium will shift to the anionic form. The uranyl ion in solution at higher pH (>7.5) is an anionic form. Starik and Kolyadin also reported that the adsorption of uranium on the anionic ion exchanger could be increased by increasing the partial pressure of carbon dioxide over a solution of a certain pH and that the adsorption of uranium on glass as a function of the partial pressure of carbon dioxide showed the opposite trend (Note: the products of hydrolysis are cations and they possess specific affinity for glass). Furthermore, by comparing the mobility of uranium in organic matter-free solutions under electric fields with that of seawater, Starik and Kolyadin concluded that uranium in seawater does not form organic complexes and, at pH greater than 7.5, the uranyl ions exist as carbonate complexes. Since the carbonate ion concentration greatly exceeds the uranyl ion concentration in seawater, the complex will be of the form $UO_2(CO_3)_3^{4-}$ (uranyl tricarbonate complex; UTC).

Kennedy [199] also found that the uranyl ion is insoluble in natural seawater media as well as in artificial seawater from which bicarbonate was removed but with pH restored to the original value (8.0) with sodium hydroxide. The uranyl ion is also insoluble in artificial seawater which was similarly treated and from which organic complexing agents were definitely absent. In the experiment he found that no uranium was detected on a bed of cation exchanger and that only a small amount of uranium was detected on a bed of anionic exchanger if the solution contained no sodium bicarbonate. He found that, with the addition of bicarbonate, high adsorption of uranium on the anion exchanger was detected.

Therefore, Kennedy concluded that the uranium is held in solution in natural seawater through the action of the bicarbonate or carbonate ion and it is present in anionic form. Considering the excessive concentration of the carbonate ion in seawater relative to the uranyl ion and the stability constants of carbonate complexes, the conclusion was that only UTC could exist in solution in natural seawater.

Ogata and his co-workers [307] calculated the concentration of the uranyl ion in sea water and the ratio of uranyl complexes in seawater by consideration of the possible reactive ions present in reasonable concentration and their stability constants. They found that the concentration of UTC is 1.37×10^{-8} M; $UO_2(CO_3)_2^{-2}$: 5.46×10^{-11} M; $UO_2(OH)_3^-$: 2.43×10^{-10} M; $UO_2(OH)_2$: 1.53×10^{-12} M and their ratios in seawater are 97.88%, 0.38%, 1.73%, and 0.01% respectively at 25°C and the normal ocean surface pH value of 8.1. Although Ogata *et al.*'s work did not list all possible ions in seawater and did not consider all possible stability constants for the concentration calculations, examination of those stability constants not included by Ogata *et al.* from Sillen's Table [361] reveals that these constants were small enough to be neglected.

From the work cited above, it has been concluded that the uranyl ion in natural seawater forms anionic complexes with carbonate ion. By considering the stability constants of uranyl carbonate complex species and the concentrations of carbonate and uranyl ions, the most probable complex ion will be UTC.

2.2 Oceans and Currents

Recent reported values for the dissolved uranium concentration of seawater have centered around 3.3 ppb (See Table 2.2.1). These values represented samples from all over the world, and uranium is considered to be well mixed in the oceans as are most major elements.

Ku *et al.* [222] reviewed the reported concentrations of uranium from the last two decades. They noted an average concentration of 3.3 ppb and pointed out isolated values that resulted in a large overall range. Analysis, by Ku and co-workers, of 63 samples collected from the Arctic, the Pacific, the Antarctic and the Atlantic oceans revealed a constant ratio of uranium to salinity. The reported uranium to salinity ratio, at the 95 % confidence level, is $(9.34 \pm 0.56) \times 10^{-8}$ for the seawaters analyzed with salinities ranging from 30.3 to 36.2 ppt. Seawater at 35 ppt salinity would have 3.35 ± 0.2 ppb uranium based on this ratio. Examination of the abundances of the various elements in ocean waters (Table 2.2.2) shows that uranium ranks reasonably high on the list. It is on the order of 1000 times more concentrated than gold, for example, and it has been estimated that it is one of the most important resources of the oceans in terms of quantity and current market price [40].

At a 3.3 ppb concentration, the total world ocean volume of 1370 million cubic kilometers represents approximately 4.5 billion tonnes of uranium. It is more realistic, however, to consider only the uppermost water of the oceans as accessible for uranium extraction. The well mixed upper 100 m of the ocean contains about 3.6% of the total ocean volume. This represents, at the same concentration, 160 million tonnes total of uranium available. The oceans could provide then, a significant resource

Table 2.2.1 Concentration of uranium in seawater.

Year	Observed Concentration (ppb)	Location	Reference
1956	3.39	N. Pacific, N. Atlantic, Gulf of Mexico, Florida Straits	[335]
1957	0.9	Baltic Sea	[210]
1959	2.2	Indian Ocean	[41]
1960	3.3	Bay of Biscay and English Channel	[418]
1964	3.1	Drake Passage	[380]
1964	2.3	N.W. Pacific-Oceanic waters 0-110m	[268]
	3.3	370-7000m	
1964	1.9	Coastal waters 0-200m	[270]
	3.3	400-1000m	
1964	3.0	Indian and Southern Oceans, S. China Sea	[391]
	3.1	Southern Ocean subsurface waters	
1964	1.5-3.3	S. Pacific, Atlantic, Arctic, and Caribbean	[389]
1964	3.7	N. Atlantic	[277]
1965	1.0-4.5	U.S. coastal waters	[64]
1965	2.2	U.S. coastal waters	[65]
1965	3.0	N.W. Pacific coastal waters	[S 34]
1966	3.63	N.W. Pacific surface waters	[272]
	3.15	N.W. Pacific 630-6780m	

Table 2.2.1, Continued

1967	3-4	Gulf of Mexico, oceanic waters	[288]
	2-3	coastal and shelf waters	
1968	2.8	Arabial Sea coastal waters	[351]
1969	3.5	Gulf of Mexico, oceanic waters	[347]
	2.1-17.3	coastal waters	
1969	3.5	Indian Ocean, open waters	[56]
1970	3.2	N.E. Pacific	[369]
1970	3.4	N.W. Pacific, oceanic surface waters	[271]
	3.3	oceanic waters below 500m	
	2.8	coastal waters	
1970	3.31	Unknown	[52]
1971	3.16	N. Pacific, GEOSECS stn.	[394]
1971	3.40	Japanese coastal waters	[155]
	3.1	Unknown	
1972	3.41	N.W. Pacific surface waters	[237]
1972	3.01	N.W. Pacific, waters below 500m	[273]
	3.23	coastal waters	
1977	3.35 *	Atlantic	[222]
	3.37 *	Pacific	
	3.43 *	Arctic	
	3.27 *	Antarctic	

* All values were normalized to a salinity of 35.0 ppt.

Table 2.2.2 Average abundances of the elements in the earth's crust, river waters, and ocean waters; oceanic residence time and probable principal dissolved species in seawater (adapted from Riley and Chester [327]).

Element	Earth's Crust (μg/g)	Average River Water (μg/l)	Ocean Water (μg/l for S=35 ppt)	Oceanic Residence Time (yrs)	Probable Main Dissolved Species
Oxygen		8.8×10^8	8.56×10^8		H_2O
Hydrogen		1.119×10^8	1.078×10^8		He (g)
Chlorine	130	8000	1.987×10^7		Cl^-
Sodium	2.4×10^4	9000	11.05×10^6	2.6×10^8	Na^+
Magnesium	2.0×10^4	4100	1.326×10^6	4.5×10^7	Mg^{2+}
Sulfur	260	3700	9.28×10^5		SO_4^{2-}
Calcium	4.2×10^4	1500	4.22×10^5	8.0×10^6	Ca^{2+}
Potassium	2.4×10^4	2300	4.16×10^5	1.1×10^7	K^+
Bromine	2.5	ca 20	6.8×10^4		Br^-
Carbon		1200	2.8×10^4		HCO_3^-
Strontium	375	50	8.5×10^3		Sr^{2+}
Boron	10	10	4.5×10^3		$H_3BO_3, B(OH)_4^-$
Fluorine	625	100	1.4×10^3		F^-, MgF^+
Silicon	28.2×10^4	4000	10^3*	8.0×10^3	$Si(OH)_4$
Nitrogen		250**	500***		N_2, NO_3
Argon			450		Ar (g)
Lithium	20	3	180	2.0×10^7	Li^+
Rubidium	90	1	120	2.7×10^5	Rb^+
Phosphorus	1.0×10^3	20	70*		HPO_4^{2-}
Iodine	0.5	ca 5	60*		IO_3^-, I^-
Barium	425	10	30*	8.4×10^4	Ba^{2+}
Molybdenum	1.5	1	10	5.0×10^5	MoO_4^{2-}
Zinc	70	10	5	1.8×10^5	Zn^{2+}
Aluminum	8.2×10^4	400	5*	100	$Al(OH)_3$?
Uranium	2.7	0.04	3.3	5×10^5	$UO_2(CO_3)_3^{4-}$?
Iron	5.6×10^4	670	3*	140	$Fe(OH)_3$
Copper	55	5	3*	5×10^4	Cu^{2+}, $CuOH^+$
Arsenic	1.8	ca 1	2.3		$HAsO_4^{2-}$
Nickel	75	0.3	2	1.8×10^4	Ni^{2+}
Manganese	950	ca 5	2*	1400	$Mn(OH)_3(4)$?
Vanadium	135	1	1.5	1×10^4	$(H_2V_4O_{13})^{4-}$; HVO_4^{2-}, VO_3^-

Table 2.2.2, Continued

Element	Earth's Crust (μg/g)	Average River Water* (μg/l)	Ocean Water (μg/l for S=35 ppt)	Oceanic Residence Time (yrs)	Probable Main Dissolved Species
Titanium	5.7×10^3	3	1	160	$Ti(OH)_4$?
Chromium	100	1	0.6*	350	Hydroxy complexes
Cesium	3	0.05	0.5	4.0×10^4	Cs^+
Selenium	0.05	0.2	0.45		SeO_3^{2-}
Krypton			0.21		Kr (g)
Antimony	0.2	1	0.2	3.5×10^5	$Sb(OH)_6^-$?
Neon			0.12		Ne (g)
Tungsten	1.5	0.03	0.12	10^3	WO_4^{2-}
Silver	0.07	0.3	0.1	2.1×10^6	$AgCl_3^{2-}$
Cobalt	25	0.2	0.08*	1.8×10^4	Co^{2+}
Germanium	1.5		6×10^{-2}	7.0×10^3	$Ge(OH)_4$
Cadmium	0.2		5×10^{-2}	5×10^5	$CdCl^+$, Cd^{2+}
Xenon			5×10^{-2}		Xe (g)
Mercury	0.08	0.07	5×10^{-2}*	4.2×10^4	$HgCl_4^{2-}$
Gallium	15	0.1	3×10^{-2}	1.4×10^3	Hydroxy complexes?
Lead	12.5	3	3×10^{-2}*	2×10^3	Pb^{2+}, $PbOH^+$, $PbCl^+$
Zirconium	165	3	2.6×10^{-2}		Hydroxy complexes?
Tantalum	2		2×10^{-2}		
Bismuth	0.17		2×10^{-2}	4.5×10^4	?
Yttrium	33	40	0.013	7.5×10^3	Hydroxy complexes?
Niobium	20		1×10^{-2}	300	
Rhenium	0.005		1×10^{-2}		ReO_4^-
Thallium	0.45		1×10^{-2}		Ti^{3+}
Tin	2	0.04	0.01		Hydroxy complexes?
Hafnium			8×10^{-3}		
Helium			7.2×10^{-3}		He (g)
Gold	0.0004	0.002	5×10^{-3}*	5.6×10^5	$AuCl_2^+$
Lanthanum	30	0.2	34×10^{-4}	440	La^{3+}
Neodymium	28		28×10^{-4}	270	Nd^{3+}
Scandium	22	0.004	1.5×10^{-3}	5.6×10^3	Hydroxy complexes?
Cerium	60		12×10^{-4}	80	Ce^{3+}?
Dysprosium	3		91×10^{-5}	460	Dy^{3+}

Table 2.2.2, Continued

Element	Earth's Crust (μg/g)	Average River Water* (μg/l)	Ocean Water (μg/l for S=35 ppt)	Oceanic Residence Time (yrs)	Probable Main Dissolved Species
Erbium	2.8		$9x10^{-4}$	690	Er^{3+}
Ytterbium	3		$8x10^{-4}$	530	Yb^{3+}
Gadolinium	5.4		$70x10^{-5}$	260	Gd^{3+}
Ruthenium			$7x10^{-4}$		
Beryllium	2.8	<0.1	$0.6x10^{-3}$	150	Hydroxy complexes
Praseodymium	8.2		$6x10^{-4}$	320	Pr^{3+}
Samarium	6		$45x10^{-5}$	180	Sm^{3+}
Holmium	1.2		$2x10^{-4}$	530	Ho^{3+}
Thulium	0.5		$2x10^{-4}$	1800	Tm^{3+}
Terbium	0.9		$14x10^{-5}$		Tb^{3+}
Europium	1.2		$13x10^{-5}$	300	Eu^{3+}
Indium	0.1		$1x10^{-4}$		Hydroxy complexes?
Thorium	9.6	0.1	$4x10^{-5}$*	350	Hydroxy complexes?
Lutecium			$1.2x10^{-7}$	$.45x10^{3}$	
Radium		$4x10^{-7}$	$1.0x10^{-7}$		Ra^{2+}
Protactinium			$2x10^{-10}$*		
Polonium			$2x10^{-11}$*		
Radon		$2x10^{-12}$	$0.6x10^{-12}$*		Rn (g)

* Considerable variations occur.

** Combined nitrogen plus about 15 mg dissolved molecular nitrogen per liter.

*** Inorganic carbon.

Note: The composition of river waters depends greatly on the geology of the source area.

of low grade liquid uranium ore. Further, uranium has a residence time of approximately 500,000 years (see Table 2.2.2). This represents an influx of about 9000 tonnes annually. The input is primarily to the surface water so the upper 100 m can be considered as a constantly renewed source.

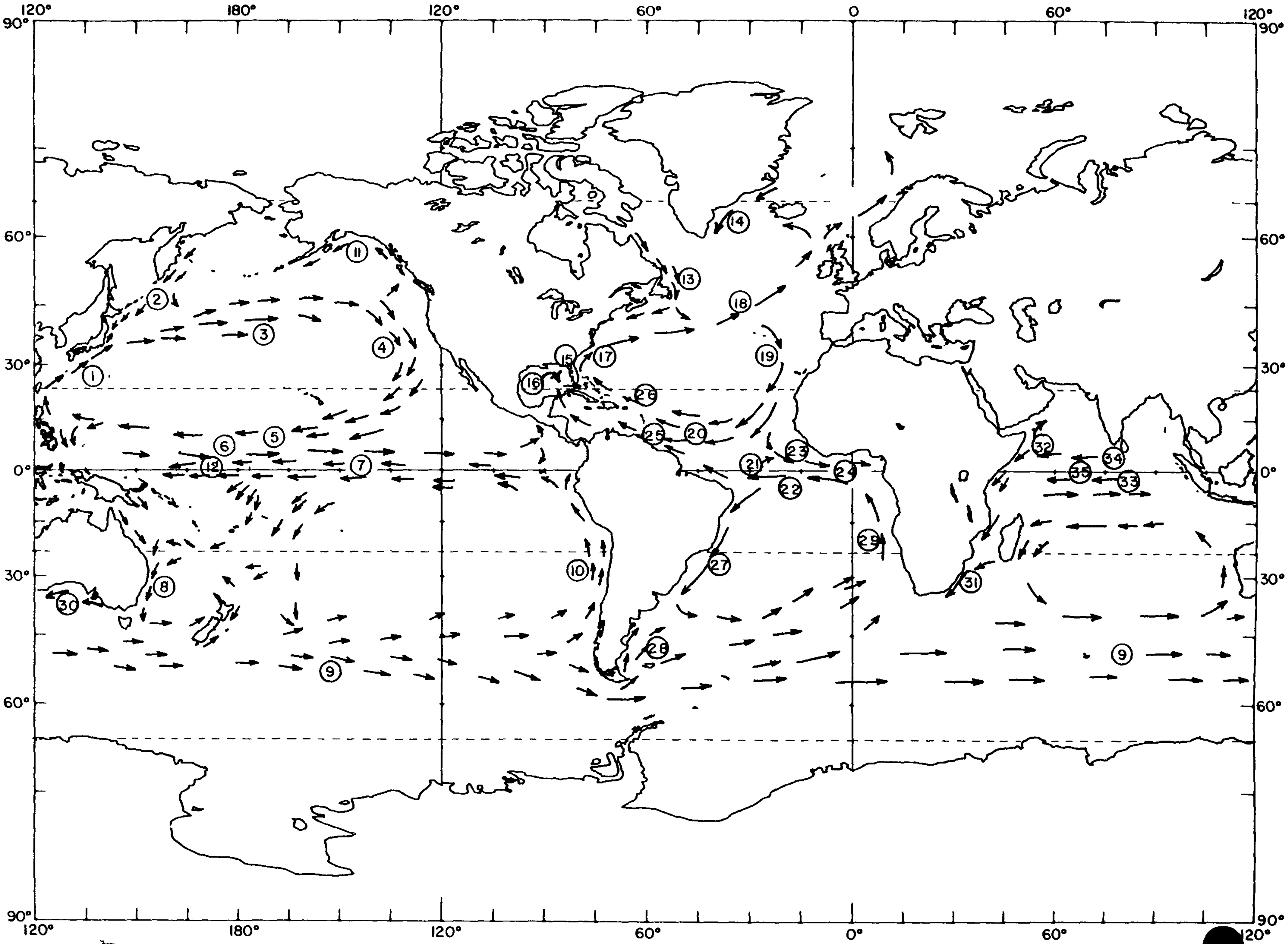
Major oceanic currents (Fig.2.2.1) transport a much greater volume of water than U.S. rivers and the magnitude of this flow of seawater is closer to that which would be desirable in an uranium extraction process (see the Feasibility Study). Major currents which might be utilized in part include the Gulf Stream, the Florida and/or the Antilles Currents on the Atlantic Ocean and the California Current on the Pacific. The major currents, their transport and approximate annual uranium resource potential are listed in Table 2.2.3.

These figures indicate that the currents contain a very large potential resource. Partial utilization of this resource should be possible for a virtually indefinite time span when considering the magnitude of uranium extraction considered in this study and the present input of uranium from the rivers.

2.3 Rivers

River transport of dissolved uranium has been studied to evaluate its role as a source in the oceanic cycling of uranium [347; 348; 394]. Uranium concentrations in stream and river water show some variability. This is thought to be, in part, the result of variations in precipitation over the drainage basins and differences in rock types which form the basins [347,348]. The uranium content of phosphate fertilizers is also considered to contribute as much as 0.3 ppb to the runoff of U.S. rivers that drain basins of high agricultural production [348]. The Mississippi-Missouri river system is considered to drain such a basin and reported concentrations vary from 0.10 to 2.39 ppb [348].

Analyses of rivers and streams that drain nonfertilized areas (north-western Canada) show a range of 0.26 to 1.64 ppb with an average value of 0.60 ppb for dissolved uranium [394]. Rivers that drain basins containing uranium bearing strata have been reported to contain slightly greater concentrations of dissolved uranium. The Rio Grande in Texas and its system of tributaries is considered as such and has reported values



Mill lindrical Projection (adapted from H.F. Frolander, Copyright © 1977)

World Ocean Surface Currents Map #1

Figure 2.2.1. Major surface currents of the open ocean. This figure accompanies the list of currents and table 2.2.3. The number of investigators whose work contributed to the construction of this figure and table are too numerous to cite here. Instead a selection of review articles and other references are presented. From them and their reference list more information than in this table is obtainable: 117, 127, 141, 147, 182, 207, 287, 291, 319, 354, 384, 407, 421, 423, S22, S33, S34, S37.

Key to Current Systems shown in Figure 2.2.1.

1. Kuroshio
2. Oyashio
3. Kuroshio Extension
4. California Current
5. North Equatorial Current (Pacific)
6. Equatorial Counter Current (Pacific)
7. South Equatorial Current (Pacific)
8. East Australian Circumpolar Current
9. Antarctic Circumpolar Current
10. Peru Current
11. Alaska Current
12. Equatorial Undercurrent (Pacific)
13. Labrador Current
14. East Greenland Current
15. Florida Current
16. Loop Current
17. Gulf Stream
18. North Atlantic Current
19. Canary Current
20. North Equatorial Current (Atlantic)
21. Equatorial Counter Current (Atlantic)
22. South Equatorial Current (Atlantic)
23. Equatorial Undercurrent (Atlantic)
24. Guinea Current
25. Guiana Current
26. Antilles Current
27. Brazil Current
28. Falkland Current
29. Benguela Current
30. Flinders Current
31. Agulhas Current
32. Somalia Current
33. South Equatorial Current (India)
34. North Equatorial Current (India; in summer opposite flowing monsoon current)
35. Equatorial Counter Current

Table 2.2.3. Characteristics of individual ocean currents and uranium resources

a. Pacific Ocean

Current	Av. Speed (cm/s)	Transport ($10^6 m^3/s$)	Characteristics* T (°C); S (ppt)	Uranium Resource (tonne/yr)
Oyashio			-1 to 8; 30 to 33	
Alaska	10	5 to 10	4 to 13; 29 to 32.5	7.3×10^5
California	10-25	11	9 to 18; 32.5 to 34	11.7×10^5
Kuroshio	125-225	50	18 to 26; 34.5 to 35.5	53×10^5
Kuroshio Extension	125	100	16 to 18; 34.5 to 35	106×10^5
N. Equatorial		15	25 to 29; 34 to 35	15.7×10^5
Equatorial Counter	50	25	24 to 29; 34.5 to 35.5	26.6×10^5
Equatorial Under	80	20	14.5 to 16.5; 34.9 to 35.1	21.2×10^5
S. Equatorial	20	11	25 to 29; 34.2 to 35.2	11.6×10^5
East Australian	150	40	18 to 22; 35.4 to 35.7	43×10^5
Peru		19	11 to 17; 33.5 to 35	19.8×10^5

* T(°C) and S(ppt) denote temperature and salinity respectively.

b. Atlantic Ocean

Current	Av. Speed (cm/s)	Transport ($10^6 m^3/s$)	Characteristics T (°C); S (ppt)	Uranium Resource (tonne/yr)
Labrador		10	-1 to 11; 32 to 28	9.1×10^5
E. Greenland		3	0 to 5; 34.8 to 35.2	3.2×10^5
Florida	210; 160	34	23 to 25; 36.0 to 36.3	37.1×10^5
Gulf Stream	110	100*; 150	15 to 25; 35.4 to 36.4;	106×10^5
N. Atlantic		35	10 to 15; 35.4 to 36.0	37.2×10^5
Canary			25 to 26; 36 to 36.5	
N. Equatorial		<5	25 to 27; 36.0 to 36.9	$<5.5 \times 10^5$
Equatorial Counter		<5	26 to 27.5; 35.5 to 36.1	$<5.1 \times 10^5$
Guinea			20 to 25; 34.5 to 35.5	
Equatorial Under		14	12 to 15; 35.2 to 35.6	15×10^5
S. Equatorial		7	25 to 27; 35.9 to 36.7	7.7×10^5
Guiana	40	24	25 to 27; 34.2 to 35.1	25.2×10^5
Brazil	30-40	10	19 to 24; 36.5 to 37	11.1×10^5
Falkland			4 to 8; 34.1 to 34.6	
Benguela	10-20	15	14 to 17; 35.2 to 35.7	16.2×10^5
Antilles	10-20	12	25 to 27; 36.5 to 35.6	13.1×10^5
Loop (Gulf of Mexico)	50; 200	25	23 to 27; 36 to 36.5	27.5×10^5

* used here for calculating the uranium resource.

c. Antarctic Ocean

Current	Av. Speed (cm/s)	Transport ($10^6 m^3/s$)	Characteristics T(°C);S (ppt)	Uranium Resource (tonne/yr)
Antarctic Circumpolar	50	125	3 to 8; 33.9 to 34.1	1.23×10^5
E. Wind Drift	5	<5	-2 to 0; 33.6 to 34.0	$<4.8 \times 10^5$

d. Indian Ocean

Current	Av. Speed (cm/s)	Transport ($10^6 m^3/s$)	Characteristics T (°C); S (ppt)	Uranium Resource (tonne/yr)
N. Equatorial			27.5 to 28.5; 34 to 36	
Equatorial Counter			27 to 29; 34 to 35	
S. Equatorial	10-30	40	27 to 29; 34.8 to 35.6	42.5×10^5
Somalia	70	65	26 to 26.5; 35.1 to 35.6	69×10^5
Agulhas	70	80	22 to 25; 35.3 to 35.6	86×10^5
N.E. Monsoon	50		27.5 to 28.5; 34 to 36	
Flinders	5	5	11 to 15; 34.6 to 35.7	5×10^5

of 1.15 to 3.40 ppb for samples representing several locations and times [367]. This system, however, discharges a relatively small volume.

Table 2.3.1 contains estimated values for the calculated annual output of uranium by the Mississippi-Missouri river system, the Columbia river system and the Rio Grande system. These systems represent the upper limits of U.S. river volume, uranium concentration and resource. The Amazon river system, the world's largest, is included for comparison.

Although these river uranium concentrations are moderately high, one must not consider that transport by the rivers as the potential uranium resource. Note that even for the largest river, the Amazon, the total transport of uranium is too low to consider seriously in this study. The Mississippi, because of its much higher concentration, approaches the required transport if its entire flow were utilized by the extraction plant. As with all rivers, however, at least seasonally the Mississippi's sediment load would preclude its use in presently conceived extraction systems (see the Feasibility Study). It would also be impossible to block the entire river flow, or a significant portion of it, without severe social, economical and environmental damages. Based on these arguments, rivers are excluded from further considerations.

Table 2.3.1. Uranium resources from rivers and an average power plant

Source	Transport ($10^6 m^3/s$)	Uranium Concentration	Uranium Resource (tonne/yr)
Mississippi River	1.8×10^{-2}	1 ppb	550
Columbia River	8×10^{-3}	0.6 ppb	154
Rio Grande	1.9×10^{-5}	3.4 ppb	2.1
Amazon River	1.2×10^{-1}	0.03 ppb	116
Average Coastal Power Plant	1.4×10^{-5}	3.3 ppb	1.5
Pumped Uranium Extraction System		3.3 ppb	1000

2.4 Other: Mineral Deposits and Marine Organisms

2.4.1 Sediments and Shells

Estimates of uranium concentrations in marine sediments as well as the rates of deposition have been made in order to evaluate sedimentation as a removal site in oceanic uranium cycling [52; 340; 347; 348; 400; S3]. Enrichment of uranium is found in two types of sediments. Anaerobic sediments show concentrations of 3-32 ppm [210; 248] in the Baltic Sea. Other results include 2-6ppm for the black muds of Norwegian fjords [376], 2.5-7.5 ppm [52], and 4.8-28 ppm [400] for various anaerobic sediments. There are estimates that the accumulation of uranium in the anaerobic portion of the Santa Barbara Basin is on the order of 128 micrograms per square centimeter per 1000 years [400].

Degens _et_ _al._ [114] suggested that a change in condition from an oxygenated lake to an anaerobic basin, about 5000 years ago, is responsible for the unusual accumulation of uranium in Black Sea sediments. They reported an average concentration of 25 ppm and estimate a potential resource of about 7 million tonnes of uranium. This agrees reasonably well with other determinations of 3 to 32 ppm for anaerobic Black Sea sediments [248].

Carbonaceous sediments are the other principal removal site of uranium. These sediments are composed of the remains of organisms which precipitate calcium carbonate as hard parts. Co-precipitation of uranium takes place to a small extent and results in higher concentrations relative to the seawater environment. Values reported vary somewhat with depth and location and range from 0.4 to 60 ppm [52,345,347,348,S3]. Sackett and Cook [347] estimated that the Yucatan Shelf area might be co-precipitating 10 tonnes of uranium yearly with the Florida shelf area co-precipitating somewhat less. Rydell _et_ _al._ [345] reported that a core taken from calcareous sediments on the crest of the East Pacific rise show high uranium concentrations averaging about 44 ppm over an 8.5 m core. Baturin [S3], in his study of uranium cycling, estimated that the concentration of uranium in modern sediments does not exceed 10-60 ppm.

The sediments below the Red Sea brines have been analyzed for uranium though no values for the uranium content of the actual brine were reported by Ku [113]. Values for the three types of sediments found were: calcareous sediments, 0.76 to 1.17 ppm; iron-rich geothermal deposits, 6.00 to 31.3 ppm; mixed sediments 1.23 to 3.73 ppm uranium. These samples represented a variety of locations and depths within the sediment types.

The shells of marine organisms have been analyzed for uranium with concentrations found in the parts per million range. Values of 0.001 to 0.45 ppm [65] were reported for bivalve shells. One report listed a range of 0.01 to 3.3 ppm for a variety of shell types with certain species of gastropod shells having the lower concentrations and corals having the higher values [76]. Corals were reported to contain 2.0 to

2.8 ppm uranium [402]. Mollusk shells were reported to have 0.9 to 1.4 ppm uranium and shells from certain encrusting organisms on mussels have values of 0.18 to 0.25 ppm [392].

These reported values for uranium concentrations in the sediments and shells are lower than that in the land ores. Therefore, it is concluded that the marine sediments and shells are not economically attractive resources at present.

2.4.2 Manganese Nodules and Phosphorites

Uranium is found in mineral deposits of a different origin than that of the anoxic basin accumulations or carbonaceous oozes. The better studied deposits, manganese nodules and phosphorite formations have been analyzed for uranium and values reported in the parts per million range as follows.

Manganese nodules have been reported as having uranium concentrations of 1 to 13 ppm range [221; 346; 388]. Kunzendorf and Friedrich [225] reported an average value of 4.9 ppm for 119 Central Pacific manganese nodules and in a separate report [224] showed that uranium in one sample decreased from as much as 8.3 ppm on the surface exposed to seawater to 3.4 ppm in the surface exposed to sediments. Another analysis by Ku and Broecker [220] yielded an average value of 6.7 ppm for various depths in one nodule from the North Pacific. Baturin and Kochenov [S4] reported a range of 3 to 120 ppm for Southwest African samples, 8 to 54 ppm for samples from the shelf off Chile and 1 to 7 ppm in samples from submarine mid-Pacific mountains.

Sackett and co-workers [348] used a value of 8 ppm to estimate that the total worldwide deposition of uranium in manganese nodules amounted to approximately 100 tonnes yearly.

The uranium concentration in phosphorite formations is not as well established and shows some variation in the available data. Altschuler, Clarke and Young [S1] determined the uranium content of six Pacific Ocean phosphorites and a range of 41 to 125 ppm was found. Calvert [S7] listed three unpublished values of 68, 115 and 128 ppm uranium for Southwestern African shelf samples. They represented different forms of phosphorite.

Kolodny and Kaplan [211] reported values ranging from 6 to 524 ppm with averages for areas ranging from 72 to 230 ppm. After studying isotopic ratios they also concluded that their samples were 800,000 years old and were currently eroding rather than forming.

From the work cited above, it is concluded that the uranium concentrations in the marine mineral deposits are lower than the land ores and are not economically attractive.

2.4.3 Marine Organisms

Many marine organisms have been reported to concentrate uranium to levels exceeding that of the surrounding seawater (Table 2.4.1). Degens _et al._ [114] reported that a 10,000 fold enrichment by cocoliths must have occurred in order for sediments in the Black Sea to contain their high values. They further reported that diatom-dominated living plankton were found in uranium-rich [20 ppb] water which showed a 10,000 fold enrichment. They suggested that sugars and proteins within the plankton were responsible for the concentration.

Although it has been suggested [161; 302] that marine organisms can be used to extract uranium from seawater, it is not technologically practical at present. Any "farming" operation requires extremely large ocean surface area [219] in order to allow enough organisms to grow. Presently, it takes approximately 250 square kilometers of surface area to grow organisms to extract 1 tonne of uranium [303]. Even assuming that certain organisms could concentrate uranium 10,000 fold and grew at an extremely high rate of 200 kg/m /year, it would take 1600 square kilometers of "farmland" to produce 1000 tonnes of uranium per annum. This assumes that the seawater in the farm is well enough mixed to maintain a high uranium concentration. Further, even at 10,000 fold enrichment, the uranium concentration in this organism would still be very much lower than the poorest grade land ores now in production [285] and would be economically unattractive. Consequently, the concentration by marine organisms is of considerable interest only in terms of the method of concentration rather than as a possible resource (See Sections 5.3 and 8.1).

2.5 By-products and Co-products

The possibilities of extracting uranium as a by-product or extraction of co-products with uranium are obviously attractive in terms of improving the feasibility of using the ocean as a resource. The currently existing facilities and those planned for the near future which handle large volumes of seawater have been considered as possible sites for uranium extraction [149; 201]. The facilities handling the largest volumes of seawater have been desalination plants and coastal power plants, including both nuclear and fossil fuel plants. In consideration of the resource potential, calculations were based on a 3.35 ppb uranium concentration and year round operation of all plants with 100 % uranium recovery.

In the United States and U.S. territories, the 12 largest plants for desalinating seawater have a combined capacity of processing 84,000

Table 2.4.1. Concentration of uranium by marine organisms

Organism	U Concentration (ppb)	Concentration** Factor	Reference
diatom-plankton		10,000*	[114]
plankton	170-780 dry wt	48-260	[271]
algae	40-2350 dry wt	10-733	[271]
tropical algae	100-1700 dry wt	30-520	[125]
green algae	43-135 fresh	16-49	[392]
brown algae	154-710 fresh	66-279	
red algae	441-637 fresh	160-254	
zooplankton		170	[203]
corals	3300	1000	[75]
corals	1500-2830 average 2200	460-840 Average 660	[402]
mollusk bodies	133-180 fresh	64-77	[392]
fish	9-46 fresh	2-18	[392]

*uranium enriched environment: Black Sea

**g U per g organism/g U per g seawater

tonnes of seawater per day [126]. This would yield 0.105 tonnes of uranium annually passing through these plants. The single largest plant has contributed only 13% of this value. Estimates of 0.5 to 1 million tonnes of seawater per day plants have been predicted when the demand for fresh water increases worldwide [201]. This still represents only about 1 tonne of uranium per annum even at 100 % recovery.

The available data for nuclear power plants using seawater from open coastal points or from reasonably open bays shows that approximately 20 to 25 such plants are currently in operation or will be operational in the near future [25; 188]. The 16 plants for which water flow data were available (Table 2.5.1) would process approximately 26 tonnes of uranium annually in their cooling water. The largest plant, which consisted of 3 units, would circulate about 4.5 tonnes of uranium per annum.

It has been estimated that the uranium resource made available by a present day nuclear plant's use of seawater is currently only 5% of a typical reactor's fuel needs [149].

Coastal power plants that utilize coal, oil or gas and use seawater for cooling were considered, if the source for cooling water was open ocean points or reasonably open bays. Water handling data for 31 such plants (Table 2.5.2) located on the coast of the continental United States [101] indicated that, at 100% efficiency, approximately 70 tonnes of uranium might be processed each year.

From the foregoing discussion, it appears that currently existing facilities and those planned for the near future do not represent a significant fraction of anticipated needs and cannot be considered to constitute viable adjuncts for uranium extraction from seawater at this time.

Ocean Thermal Energy Conversion (OTEC) plants might be worth consideration as a "co-producing" system. Requirements for these plants include large flows of clean seawater, both warm and cold. Some factors involved in the location of such a plant would also be favorable for uranium extraction, and the flow of clean, warm seawater would be advantageous to an uranium recovery scheme. The water flow for a theoretical 100 MW net output OTEC power plant would be at least 850 cubic meters per second; which represents a resource of about 89 tonnes of uranium per year assuming 100 % uranium recovery. The possibility that a number of such plants might be linked together is considered credible [152].

Magnesium is extracted from the oceans on an industrial scale and might be considered to provide a possible by-product operation for uranium. In 1973 Dow Chemical extracted 125,000 tons of magnesium from seawater [S9]. This, however, would represent about one third of a tonne of uranium at the ratio of magnesium to uranium concentration in seawater (See Table 2.2.2).

The Harwell study [197] has found that many elements are co-adsorbed by hydrous titanium oxide. The most concentrated of these were vanadium at 0.49 mg/g titanium and chromium at 0.049 mg/g titanium. These represent concentration factors of 250 and 1000, respectively. Japanese studies have indicated that vanadium, strontium and phosphorus could be co-products in their uranium extraction efforts [19].

Of the above mentioned trace metals, only vanadium is of interest economically although it is unlikely that it can be processed efficiently with current technology and the market price may go down with a large scale production (See Feasibility Study). The concentrations of vanadium in seawater are listed in Table 2.5.3.

Table 2.5.1. Nuclear power facilities using seawater from open coastal points or reasonably open bays.

Location (no. of units)	Seawater Source	Estimated Tonne U Per Annum
Wiscasset, Me. (1)	Montsweag Bay	1.9
Seabrook, N.H. (2)*	Atlantic Ocean	3.7
Plymouth, Ma. (2)*	Cape Code Bay	2.4
Charlestown, R.I. (2)*	Atlantic Ocean	3.7
Little Egg Inlet, N.J. (2)*	Atlantic Ocean	3.3
offshore N.J. (2)*	Atlantic Ocean	3.3
Diablo Canyon, Ca. (2)*	Pacific Ocean	3.2
San Onofre, Ca. (3)*	Pacific Ocean	4.5

Total Units 16 Total Tonnage ≈26

* Indicates not all units operational at date of listing. Calculations based on 100% efficient recovery year round. Data taken from Nuclear News, 1978 [25]; I.A.E.A. Report Power Reactors in Member States, 1977 [188].

Table 2.5.2. Coal, oil and/or gas power plants using seawater for cooling purposes.

Location (no. of units)		Seawater Source	Estimated Tonne U per annum
Yarmouth, Me.	(1)	Casco Bay	0.7
Salem, Ma.	(1)	Atlantic Ocean	1.7
Florida	(2)	Biscayne Bay	5.2
Florida	(3)	Tampa Bay	8.2
Florida	(3)	Gulf of Mexico	9.7
Gulfport, Ms.	(1)	Biloxi Bay	2.2
Corpus Cristi, Tx.	(1)	Corpus Christi Bay	1.1
Houston, Tx.	(2)	Galveston Bay	7.2
San Diego, Ca.	(2)	San Diego Bay	2.7
Ca., various	(12)	Pacific Ocean	23.8
Morro Bay, Ca.	(1)	Morro Bay	3.3
San Francisco, Ca.	(2)	San Francisco Bay	2.6
Total	31		68.4 tonne/yr.

*These calculations are based on year round extraction of 100% efficiency from seawater originating at open coastal points or reasonably open bays and having 3.3 ppb uranium.

Plant location and water flow data taken from [101].

Table 2.5.3. Concentration of vanadium in seawater.

Year	Observed Concentration (ppb)	Location	Reference
1939	0.3	Unknown	[289]
1951	2.4, 2.7, 5, 7	sites off Plymouth and west coast of Scotland	[62]
1965	3.3	Himeji, Japan	[281]
1966	0.6	Black Sea	[49]
1966	1.82±0.05	Surface water of Irish Sea	[89]
1966	1.7 to 2.4 average 2.0	mid Indian Ocean	[379]
1967	0.6 to 4.0 average 1.4	California Coast	[362]
1968	average 0.86±0.14	Menai Straits	[278]
1972	0.2 to 5.1	Tropical N.E. Atlantic between Canary Islands and Cape Verde Islands	[328]

CHAPTER 3

DISCUSSION OF CRITERIA FOR SITE SELECTION

The low concentrations of uranium in seawater necessitates that large volumes of seawater be processed for any significant amounts of uranium extraction. Obviously, an optimal plant siting would not only greatly reduce the construction and operating costs for the plant but also minimize the inevitable social and environmental impacts.

Criteria for selecting the plant site were identified. They range from oceanographic through engineering to social and environmental considerations and are described as follows:

3.1 Uranium Supply and Flushing

Ocean currents can either help or hinder the plant operation by bathing the plant area with seawater of maximum uranium content or recirculating seawater already processed by the plant. Maximum available uranium concentration is derivable as explained in the following sections.

3.1.1 Salinity Considerations

In the world ocean, surface salinity is at a maximum in the subtropical regions due to excess evaporation relative to precipitation [S34]. Values may exceed 37 ppt in the latitudinal band from 20 to 30 degrees (Fig. 3.1.1). Equatorward, salinity decreases to near 35 ppt and poleward, values are less than 33 ppt. Coastal regions may have values substantially less than 30 ppt due to river runoff and melting of ice. Generally, the more poleward an area, the more seasonal the fresh water signal. The western sides of the major oceans (i.e. the continental east coasts) have higher salinities at higher latitudes relative to the oceans' eastern side. This is due to strong poleward flowing ocean currents, such as the Gulf Stream, known as western boundary currents which transport high salinity waters poleward. Since the uranium concentration of ocean waters is roughly directly

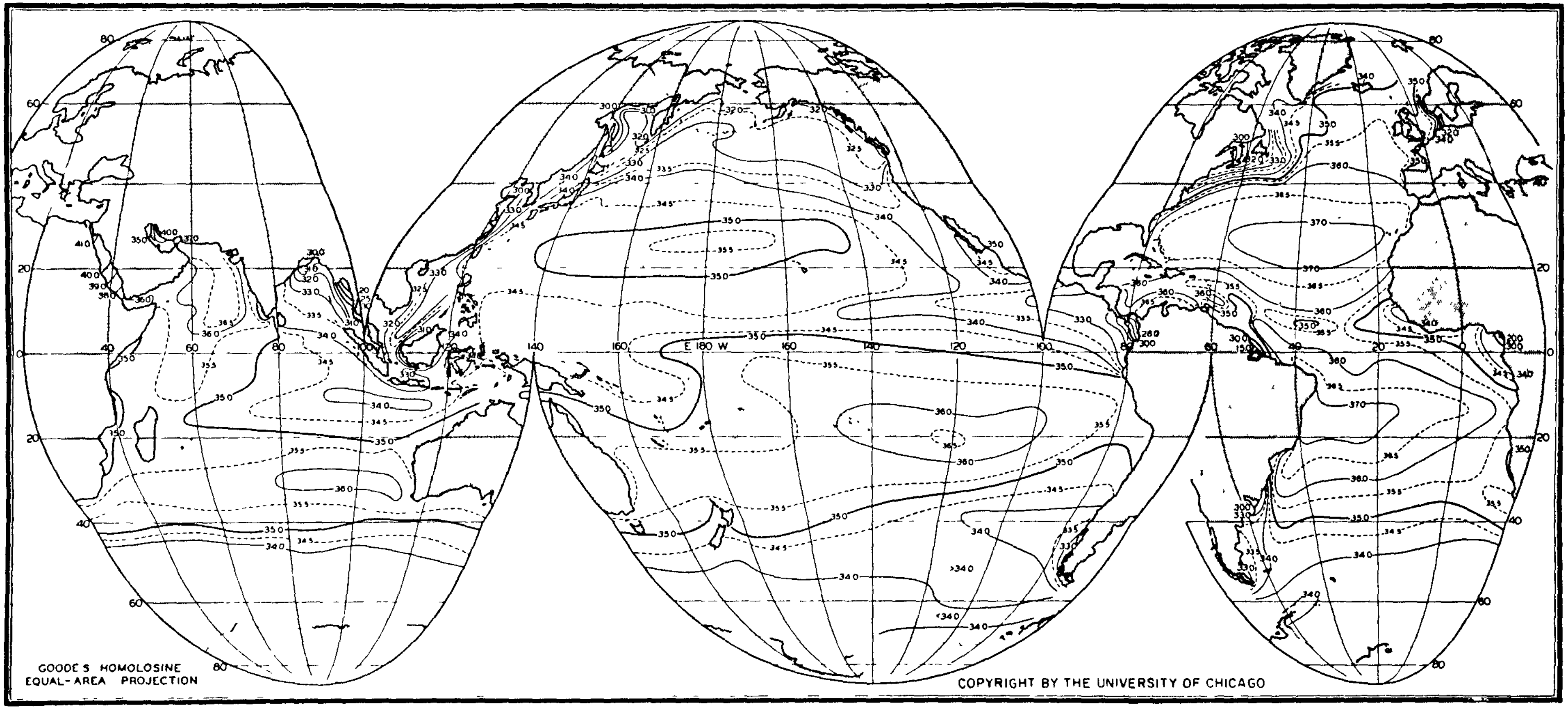


Figure 3.1.1 Surface salinity in ppt for the world ocean during the northern hemisphere summer (S34).

proportional to the ocean's salinity [222], higher salinity water is favored (see section 2.1). Excluding the immediate vicinity of river outflow, nearshore salinities for U.S. waters vary from approximately 28 ppt to 35 ppt, a variation of 20%. This variation includes areal and seasonal differences.

3.1.2 Currents and Mixing

In order to insure a maximum available supply of uranium, the plant must always be processing unscavanged seawater. Therefore, the flushing time should be on the order of the plant's throughput time. This can be accomplished by a current consistently flowing in one direction, not necessarily of high velocity [54]. Another means can be mixing forced by eddys, tides, waves, and other dynamic conditions. Usually, oceanic mixing is on the order of km/day which is roughly the scale of the plant flushing. Thorough flushing will also decrease the effect of wastes from the plant on the environment.

A simple scale analysis illustrates the magnitude of the difficulty involved in processing the seawater. The volume of seawater needed is tremendous (Table 2.3). To obtain 1000 tonnes of uranium a year, one billion tonnes (one billion cubic meters) of seawater need to be handled each day at 100% efficiency. The flux of seawater per day assuming a mean coastal current of 20 cm/s through a triangular cross section extending 10 kilometers from shore and increasing in depth from 0 to 100m is about 100 billion tonnes per day. However, this probably represents a maximum flux for many coastal environments because this area includes the complicated nearshore surf and littoral zone which communicates with the sea further offshore through a series of cellular motions [S11]. In addition, the 100 m contour may frequently be further than 10 km. Particularly in coastal environments, a mean current over these distances may be difficult to define because of the many types of variations and flows involved; e.g., eddies, longshore currents, rip currents, wave transport, bottom and surface currents, etc. It is not known what effect tapping this much seawater will have on the environment, but since the plant requirements represent a man made flow on the same scale as effluent from major rivers such as the Columbia River, the influence on the local circulation dynamics and ecosystem is expected to be appreciable. The influence of the Columbia River effluent, for example, is measurable tens of kilometers out to sea and along the coast. An additional consideration is the energy loss in pumping. To lift one billion tonnes of water a day (approximately twelve thousand cubic meters/second) requires several megawatts (Jack Nath, personal communication).

Ocean currents (Fig. 2.2.1), therefore, are perhaps the premier consideration for any land based operation to extract uranium from the sea due to the need of insuring that the intake of seawater to process is always of maximum uranium concentration. Any previously processed seawater that is entrained in the intake stream will result in a decreased yield of uranium. Because of the large volumes of seawater to process, the dilution of seawater is a serious problem. One cannot rely on oceanic mixing processes to accomplish a thoroughly mixed "fresh" seawater. Mixing coefficients range from about 10^5 square centimeters/second in nearshore environments to 10^7 square centimeters/second for deep ocean; hence, on a daily time span, scale lengths of 3 to 30 km are expected which are of the same scale as a pumped system. Therefore, currents are a necessity for removal of the old and the supply of the new seawater. This implies, as well, that the currents be unidirectional (or at least single quadrant) in order to avoid a back flushing situation. In other words, a current flowing at appreciable velocities in one continuous direction is preferred, or lacking that, at least one of predictable magnitude and direction. This may be, and probably is, an impossible criteria to fulfill. It seems that the improved methods of sampling and studying the ocean are finding oceanic variability so prevalent that the most predictable aspect of the ocean is its unpredictability. Many types of ocean motions have been studied, cataloged and, at least in part, explained. These range from eddies of sizes from kilometers to 100's of kilometers, meanders and waves in ocean currents, variations of directions and intensities of ocean currents, variations in characters such as temperature and salinity, turbulence and vertical structure variations such as micro-temperature structure (0.1 to 0.01°C in cm to m depth intervals) to name but a few. How these various phenomena, or combinations of phenomena, interact and feedback is an unsolved problem in oceanography. These interactions are highly nonlinear. Few studies have been made which are sufficiently detailed to produce small scale resolution and long enough to describe the time variabilitiy adequately. The "mean" current may be only a statistical entity in regions where the variability is high.

Because the coastal environment is a fixed boundary where topographic effects, wave effects, tidal effects, daily temperature changes, land/sea breezes, runoff, and increased frictional effects all interact together as well as with other factors, detailed models for near shore oceanography are not well established. Scales are small enough so that major currents do not exist over the shelves but rather currents which tend to be episodic, and quite erratic. The currents mentioned in the literature that tend to be most thoroughly studied such as the Gulf Stream, Kurioshio, California Current, etc. are all essentially open ocean streams. Consequently coastal plants will not generally have direct access to them but must instead rely upon them to provide some of the driving influence on the coastal circulation. It is the deep ocean currents which in a sense are the flushing mechanisms by which renewal of coastal water is accomplished. However, these currents are not those that are likely to flow along the coast in sight of land plants. In view of the complexity of the oceanographic situation, we suggest that one of the first priorities be a detailed sampling program in the site area to establish the environmental baseline data. Since the quantities of water and the size of the plant are probably large, it seems particularly important that numerical models be developed to analyze in detail the circulation patterns and the effects that plant structures will have on these patterns. To accomplish this it will probably be necessary to make current meter measurements at numerous locations for a year. Other parameters that should be sampled, although perhaps not continuously over a year, are salinity, temperature, nutrients, particulates, and other chemical quantities such as pH. Sediment cores, weather conditions, and bottom samples should also be obtained.

3.1.3 Oceanic Regions

The ocean is, in reality, not one massive body of water but is composed of many lesser, large provinces. The size and extent of these areas depends upon the definitional criteria used; the boundaries separating these regions are by no means impermeable, as mixing on various scales is accomplished across them. These realms, however, interact in very complex and not well understood ways.

In this study two of these boundaries are of particular significance. One boundary separates the coastal ocean and deep ocean. The deep ocean (also called open ocean, offshore ocean, blue water ocean, etc.) lies beyond the continental slope, while the coastal ocean lies between land and the continental slope; i.e. above the continental shelf. The average width of the continental shelf is about 75 km. Often the boundary between the continental shelf and continental slope is taken to be the 200 m isobath because at or near this depth the ocean floor steepens rapidly. This means that only about 1% of ocean waters are in a coastal environment at any given moment. In view of a coastal site location, it is principally coastal seawater which must feed the extraction processes and carry away plant "wastes", although the accessability to open ocean water will be greatly enhanced in regions of narrow continental shelfs.

The second boundary lies between what is known as the cold water sphere and warm water sphere. This boundary is located in the main thermocline, (region where the vertical temperature distribution has the greatest decrease with increasing depth), usually at the 8 C isotherm and essentially separates the surface waters, (depths from a few meters to at most about 500 m), from the deep waters. In cross section, the surface waters roughly look like a lens floating upon the deep waters; thickest in the subequatorial, somewhat shallower in the equatorial regions, and shallowing to zero depths before reaching the poles. Since the mean ocean depth is nearly 4000 m the surface waters make up less than 1/20 the ocean volume, assuming a maximum uniform layer of 200 m. In the polar regions, especially the Antarctic, the cold, nutritious surface waters are more similar to the deep water.

The energy driving the circulation in the deep and surface waters orginates from different sources, although, the sun ultimately drives all circulation. The deep ocean is largely driven by changes in the density stratification due to temperature and salinity differences, whereas the warm water ocean receives its energy from stresses imposed by the wind. Thus, the two regions can also be distinguished as the thermohaline driven ocean and the wind driven ocean. The mechanisms responsible for the driving forces (evaporation and precipitation, cooling and freezing, wind stress, and storms) act to varying degrees on both spheres so that each is not unique from the other. Typically, these two domains communicate on the order of hundreds of years.

An important consequence of these divisions of the ocean is that the uranium resource is not as vast as simply the volume of ocean times uranium concentration. Potentially it is, but in practice over time scales compatible with human needs any extraction scheme can only draw upon a limited portion of the ocean; the surface waters and near coasts for a land based operation.

3.1.4 Tides

Tidal currents are present to some extent throughout the oceans, but as the tides along a coast have essentially the characteristics of a standing wave, often little net water flow is accomplished over the period of the tidal cycle. Few regions of the world have tides exceeding 5 meters and for the most part, those regions are found in subpolar latitudes. Large tides in warm oceanic environments are found at the mouth of the Amazon, along the northwest coasts of India and Australia [147]. For the United States, only the southern coast of Alaska (bordering on the Gulf of Alaska) has such tides, although there are areas located near the continental United States at the mouth of the Colorado River, the islands of British Columbia, and the famous Bay of Fundy which have large tidal ranges. As far as a tidal system is concerned, the best opportunities for the United States would probably be as a joint operation with another country.

3.2 Temperature

As one might expect, ocean surface temperature distributions [S34] are roughly warmest in the tropics and coldest at the poles (Fig. 3.2.1); a range of about 30 °C to less than -1 °C (note that salinity lowers the freezing point of water to below 0 °C). However, the isotherms do not parallel latitude but instead reflect a northward shift of warm water on the ocean's western boundary (eastern continental coasts) and southward shift of cool water on the eastern side. This pattern results

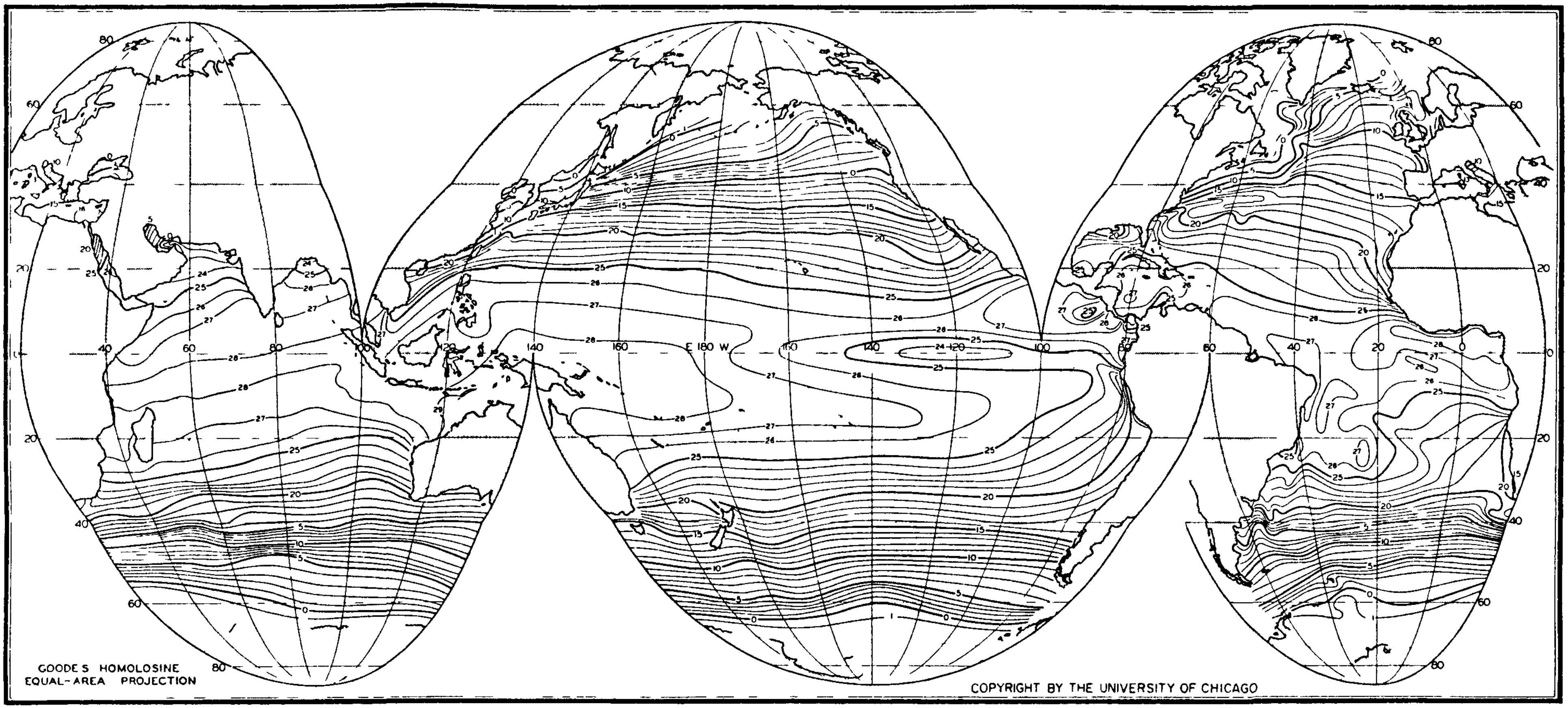


Figure 3.2.1 Surface temperature in centigrade for the world ocean during the northern hemisphere winter (S34).

from the gyral surface ocean circulation of a strong poleward flowing western boundary current, like the Gulf Stream, and a more diffused equatorward flowing eastern boundary current, like the California Current. Theory and some experimental work indicate that warmer temperature increases the efficiency of uranium extraction (see Feasibility Study). The maximum temperature ranges for U.S. waters considering both season and area are about 0°C to 30°C. Generally, one finds higher salinities associated with warmer waters. Few sections of the United States have both warm water and high salinity through the year. The regions discussed in Chapter 4 having these qualities are confined to islands of the Pacific, principally the Hawaiian Islands, the Caribbean island of Puerto Rico, and the Virgin Islands. The Florida Keys and southern Florida is also nearly tropical year round.

3.3 Fouling

Calcium carbonate deposits are likely to occur at warmer temperatures whereas biological fouling is more likely at colder temperatures because these waters tend to be more productive. Particulate loads are likely to be higher in productive regions and near river outflows.

Besides having advantageous high salinities (35 to >36 ppt) and warm temperatures (>27°C), tropical waters may be thought of as being the literal deserts of the oceans. This low productivity [208] results in tropical ocean waters being among the clearest found. Recent work indicates primary productivity values usually ranging from less than 30 milligrams carbon/square meter/day to infrequently 70 milligrams carbon/square meter/day [127,147]. Due to the low level of life, particulates are almost exclusively less than 10 micrometers in diameter [S14]. Microplankton are typically less than 60 micrometers whereas macroplankton can be up to 1 millimeter in diameter. River born material of sizes greater than 5 micrometers settles for the most part within the continental shelf regime only tens of km from shore [S14] (on the Wentworth scale sand is 0.062 to 2 mm, silt is 0.004 to 0.062 mm, and clay is 0.004 mm). Much of the inorganic material in the open ocean is wind born [S18]. The low productivity is related to the limited communication between the warm and cold ocean spheres mentioned earlier. Nutrients are high in deep waters where there is no light for plant production. Where the deep waters are brought to the surface, eq. regions of upwelling such as the United States northwest coast, are localities with higher productivities which support fishing industries.

3.4 Topography and Geography

Due to the large quantities of water to be moved, it is desirable to have minimum offshore-onshore slope in order to have the smallest head. The plant needs a large area for construction and operation, which expansive beaches and low lying hinterlands provide. If a large amount of earth must be moved then costs could rise appreciably. Since some of the plant facilities are likely to be located offshore, some relatively shallow water with good foundation seems desireable. However, broad shelves with their probable poorer circulation are definitely not wanted.

Another important consideration is the supply of fresh water. Large quantities are needed. Therefore, a river would be valuable, however, runoff from the river will adversely affect the salinity, suspended particulate concentration, and possibly temperature nearshore.

3.5 Demography

In order to build and operate, facilities such as power, transportation, services, housing and such are needed. Does the labor force have to be imported? To some degree these requirements oppose the geography requirements since urban areas with the markets, supply, etc. are also likely to have stricter land use laws, more expensive low lands and so forth. Often the low lands conducive to plant siting are also the heaviest settled regions.

3.6 Geology

Some attention must be paid to natural hazards such as earthquakes, floods, tsunamis and volcanoes. It is possible to build foundations to handle earthquakes and other hazards. Tsunamis probably present more difficult design problems because separate barriers to intercept the waves seem necessary which may in turn alter the seawater circulation. A major consideration with volcanoes is the ash and gas they emit. Whether the location is swampy, sandy, hard rock, and so on will impact greatly on the construction cost.

3.7 Climate

Adverse climate conditions, in particular intense storms and hurricanes, must be considered. Damage can be caused both from waves and the severe currents and concurrent sand scouring which is set up. The tropics and subtropics are the spawning grounds for damaging tropical cyclones and hurricanes. These severe weather conditions need not strike land to cause damage because of storm surges.

3.8 Other Considerations

Navigation, land use and zoning, regulations, recreational use, and commercial fishing are among the factors, when known, to cover here. Other useful information is whether the local population desires industry.

Generally, the more biologically productive regions are in colder waters, primarily due to the upwelling of colder, more nutrient rich deep waters to the surface. For example, these conditions prevail along the Pacific Northwest coast. Local highly productive regions also may occur near river outflows and oceanic regions ajacent to salt marshes. Consequently, some of the detrimental environmental factors to a pumped or tidal system, are beneficial to a scheme invoking marine farming (i.e. taking advantage of marine organisms to extract uranium).

3.9 Conclusions

It is possible with enough money and good engineering methods to surmount many of the construction problems posed by the site location.

We feel the major criteria to be concerned about are the oceanographic ones. The large plant costs (see Feasibility Study) indicate for even a catastrophe with a very low probability of occurence, that there are high financial risks involved.

CHAPTER 4

REGIONAL CHARACTERISTICS OF US ENVIRONS

4.1 Introduction

United States coastal waters have been divided into nine regions (Fig. 4.1.1) by considering the criteria mentioned in chapter 3 and other guidelines [148]. These regions are: 1) North Atlantic, 2) Middle Atlantic, 3) South Atlantic, 4) Gulf of Mexico, 5) Caribbean, 6) Pacific Southwest, 7) Pacific Northwest, 8) Alaska, 9) Pacific Islands.

4.2 North Atlantic

The coast of the Gulf of Maine forms the North Atlantic Coast of the United States. Between Cape Cod and the Bay of Fundy, the states of Massachusetts, New Hampshire, and Maine border the Gulf. Population density is high as far north as Portland, Maine. Further north population density is low, although recreational use remains high. Acadia National Park has a coastal location about midway between Portland, Maine and the Canadian border at the mouth of the Bay of Fundy. This region is famous for its tidal range (on the order of 15 m). The southern Gulf of Maine has less range, for example Boston's maximum range is about 3.5 m [127].

Depths in the Gulf of Maine are on the order of 400 m or less [83] and hence it is a relatively shallow ocean body. It is for the most part a shelf regime. However, waters in this Gulf are considerably more transparent relative to coastal waters in the other two Atlantic regions as measured by Secchi dish [127]. Georges Bank lies along its southern extent. The primary access for open ocean water is via the 250 m deep Northeast channel between Georges Bank and Nova Scotia. This passage apparently permits the Labrader current to have an influence on the Gulf of Maine circulation [83]. Most of the region is a rich fishing ground that has been a source of recent difficulties between the United States and Canada in resolving territorial water disputes.

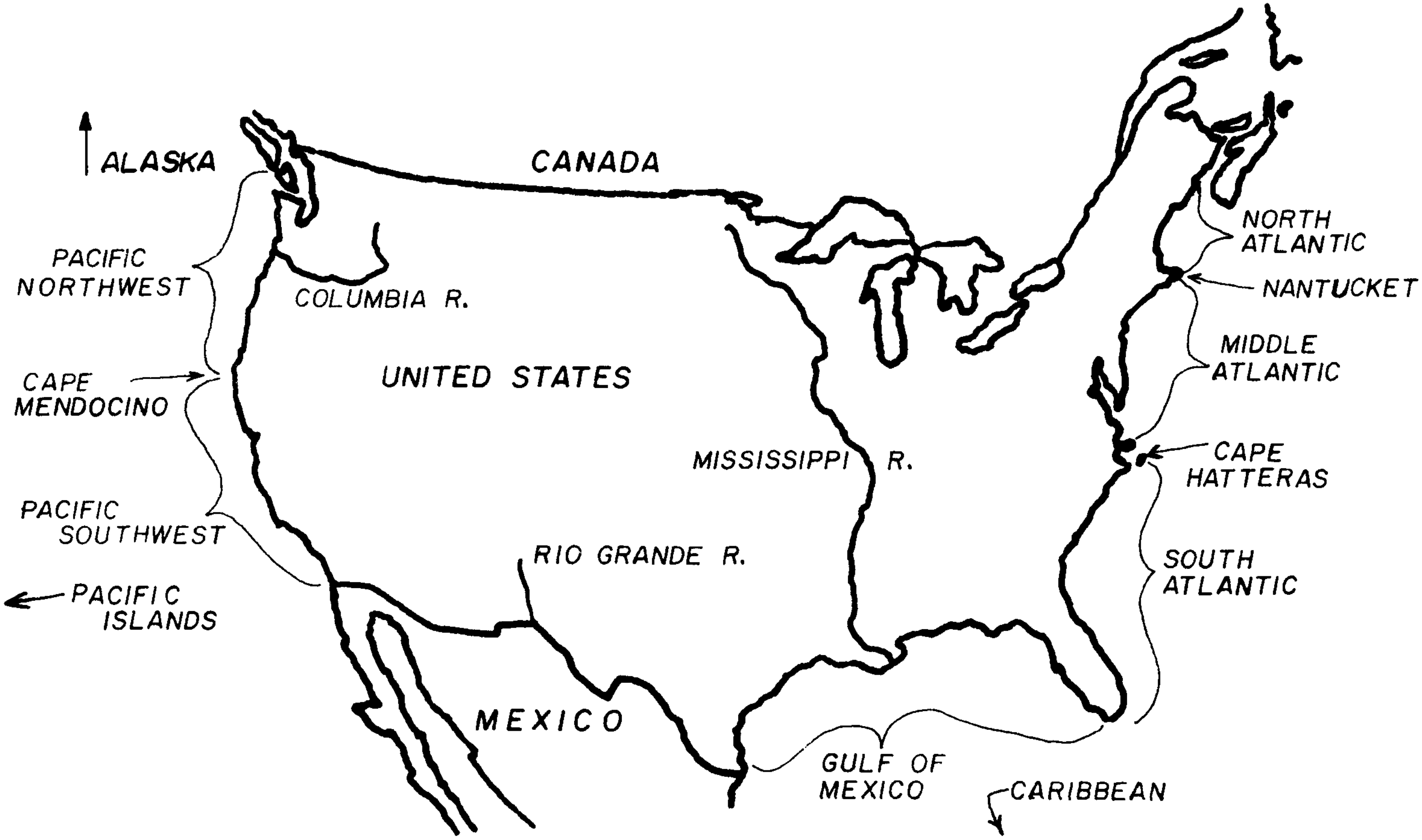


Figure 4.1.1 Map of the United States showing the division of the coastal regions defined in this report.

Circulation in the Gulf is predominately a large cyclonic eddy (counterclockwise) of varing strength throughout the year [83]. Portions of the southern part of the eddy apparently feed either a clockwise circulation over Georges Bank or contribute to the coastal flow southwestward around Cape Cod. The mean drift is 0.5 to 1.5 cm/s, however tidal currents can be as strong as 60cm/s in regions [83]. In addition to the general southward coastal flow, there is a coastal upwelling with an offshore surface component and onshore bottom component [83].

Winter and summer temperature and salinity (Fig. 4.2.2) values are respectively less than 2°C to 15°C and 32 ppt to 30 ppt [127]. River runoff is 1/2 to 1/3 that of the mid and south Atlantic coast accounting for the lower salinity range for this region. In spite of the more severe winter of the New England states, the sea air interaction is apparently somewhat less intense than off the mid and south Atlantic coasts.

A joint venture with Canada would be possible for this region provided a tidal system is planned. The cold year-round surface temperatures are a severe disadvantage and indicate a pumping system would be better located elsewhere.

4.3 Middle Atlantic

The Middle Atlantic states extend from Nantucket Shoals-Cape Cod in the north to Cape Hatteras in the south, and consist of Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, and Virginia. Undoubtedly this region is subject to the most intense population pressure both along shore and offshore of any United States area.

The continental shelf widens north of Cape Hatteras (e.g. the 200 m coutour is less than 75 km off Hatteras and about 225 km off New York). East of Nantucket this contour encompasses the fertile Goerges Bank. Despite the relatively broad shelf region, cross shelf mixing does take place as indicated by the temperature and salinity structure [142]. The New York Bight is completely flushed in 6 to 10 days which apparently is independent of the river input [48]. A number of mechanisms contribute to the mixing, among them being tides. This is not a region of large tidal range. Maximum ranges are less that 2 m [13].

The predominate surface drift is west and south from Cape Cod to Cape Hatteras [48]. The flow is slow; on the order of 0.4 to 1 cm/s and quite variable, frequently also having a northward component particularly in summer. Nevertheless, the annual character is a southward and

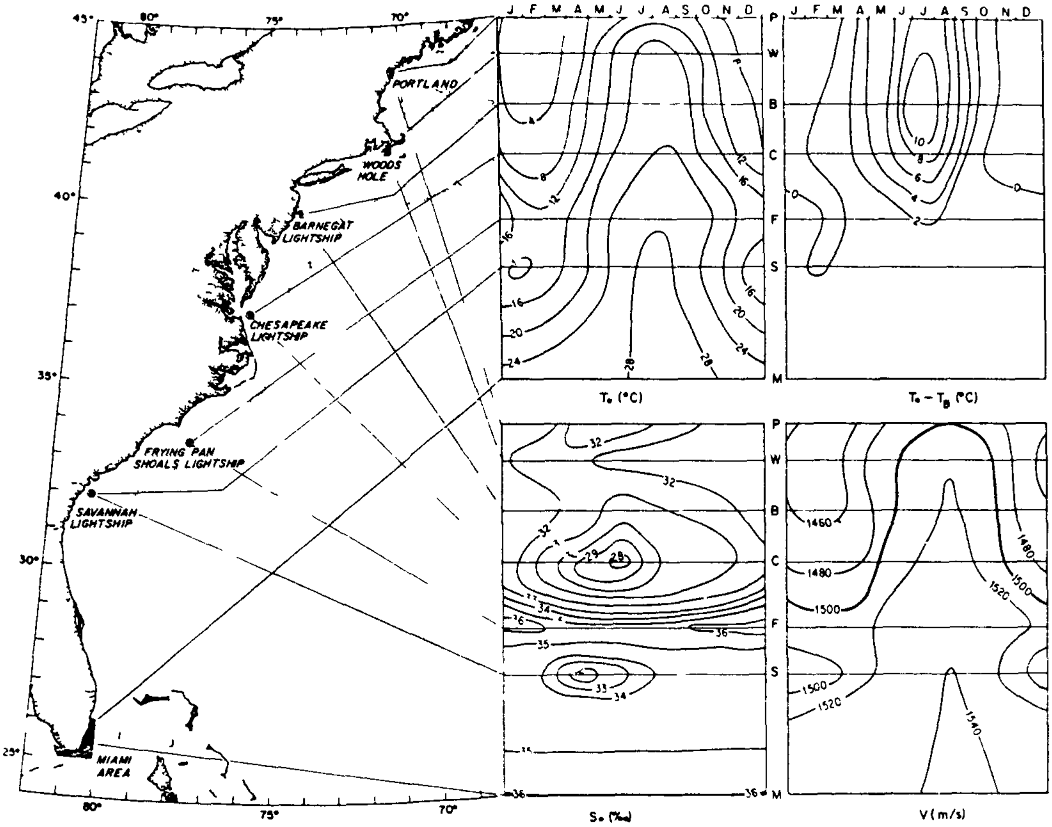


Figure 4.2.1 Temperature and salinity (centigrade and ppt) at selected coastal sites along the eastern seaboard (127).

westward component over the inner half of the shelf, and an offshore component over the shelf's outer half [83]. This flow is considered a cold current relative to the offshore Gulf Stream over the continental slope which has temperatures of over 20°C in winter and 26°C in summer [142]. A significant portion of the drift integrates into the Gulf Stream in the vicinity of Cape Hatteras where the Gulf Stream begins to flow more seaward of the continental slope. Alongshore transport has been estimated at approximately 8000 cubic kilometers/year, which represents 60 times the total river runoff to the area and only 0.3% of the Gulf Stream transport.

Maximum sea surface temperatures (Fig. 4.2.1) usually occur in August ranging from about 19°C near Cape Cod to 26°C near Cape Hatteras. The winter temperatures in these areas are near 1°C and 5°C respectively [75]. Summer salinities are near 32 ppt and 30 ppt and winter values are about 32 ppt and 32 ppt respectively for the two regions [75]. The Chesapeake Bay mouth has spring time salinities near 28 ppt due to the large fresh water input during this period. In late spring and summer, temperature tends to dominate the density structure whereas in late fall and winter salinity dominates [142]. From late autumn through the winter, the entire shelf water regime undergoes intense sea-air interaction when the cold dry continental air masses (high pressure, cyclones) move over the shelf water. Mixing in the shelf regime is accomplished quite rapidly during these storm events since quasi-equilibrium is established in about 6 hours [227].

The New York Bight composes a major portion of the Middle Atlantic Bight. Perhaps in part as a consequence to the huge volume of waste dumping (93% by volume in 1974 for all US coastal waters [147]); this region has been extensively studied in recent years. The general circulation for this region probably applies elsewhere along the shelf. With the Hudson River exporting water and particulates the Bight is a typical estuarine system. It is second to the Chesapeake system in volume outflow to the Atlantic seaboard. Salinity increases seaward [142] while particulates decrease [60]. Late summer salinity values are 30 ppt to over 34 ppt and a suspended particulate concentration over 200 ppb within about 10 kilometers of shore to less than 100 ppb further offshore over the slope Presumably, the particulate concentrations are less in winter; salinity, however, is greater at >32 ppt to over 34 ppt nearshore to offshore. The nearshore to offshore temperature ranges for winter and summer are 2 to >4°C and 15°C to >18°C, respectively. Lateral mixing is an important process in flushing the shelf in that the surface flow is offshore while the onshore mass balance occurs near the bottom [142]. In other words, shelf water flows seaward; slope water flows shoreward. Furthermore, the stratification is such that lateral mixing is probably enhanced. A convenient boundary for the slope water to shelf water regime was found to be the 34 ppt isohaline [142].

During half the year low sea surface temperatures make this region an unfavorable locality (see Feasibility Study). Further, the social and environmental impacts and other population considerations rule this section of the United States coast out of any further inspection.

4.4 South Atlantic

This region encompasses a large range of oceanographic and topographic conditions. It extends from Cape Hatteras in the north to the Florida Keys in the south. (the Florida Keys are included in this region, although their location could place them in the Gulf of Mexico discussion. Their geological and environmental aspects could also place them in the Caribbean discussion.) The states of concern here are parts of North Carolina, South Carolina, Georgia and Florida. Throughout this region is a wide coastal plain with swamps that may extend well over 100 km inland. Some areas along the coast are densely populated, particularly southern Florida. Georgia, South and North Carolina have major portions of their coastline quite sparsely settled. Much of their coastline is bordered by wet lands, large marshy regions inland from the barrier islands and the coast, which are fertile and favored habitats for diverse populations of marine, shore, and land life. These marshlands contribute to the productive sport fishing for bluefish, striped bass and others, as well as commercial yields of shrimp, crab and menhaden. The barrier islands form a unique set of islands along the Atlantic coast seaboard. They extend from the north Atlantic coast to the Central America coast and thus form the longest chain of islands of this type in the world. Due to their fragile nature and the ecological environment associated with them, they are being increasingly protected on both the state and federal levels.

The climate throughout this region is governed by the interaction of polar and tropical air masses. Rainfall annually is in the range of 150 to 200 cm [396,397]. Winters are mild and the summers hot. In winter the winds usually set from the north while in summer they are from the south and southwest, with speeds usually less than 10 m/s [11,16]. Summer wind speeds are (over half the time) less than 5 m/s, however, occasional tropical storms and hurricanes bring resultant gale force or greater winds as well as storm surges [11; 127]. Winds from the southerly quadrant can bring about upwelling conditions in turn bringing cooler, saltier and nutrient rich waters near the surface [374]. The abundant rainfall leads to adequate runoff along the coast. Georgia and South Carolina total about 1000 cubic meters/second and 2000 cubic meters/second respectively [396,397]. Most of Florida's runoff is into the Gulf of Mexico and only about 160 cubic meters/second total flows into the Atlantic. Especially for Florida but also for Georgia's and the Carolinas' coast the runoff is not so excessive as to widely depress the salinity values nearshore along the coast. The low salinity band found along the coast is usually within 10 km of shore and may be practically nonexistent in winter when runoff is smaller [374]. However, the sediment load carried into the ocean is noticably greater further to sea than observed for the mid and north Atlantic regions [248]. Particulate load falls from 30 to 4 ppm in the first 5 km (further offshore graph precision indicate concentrations near 0 ppm) offshore although near the river mouth these values can be greater than 500 ppm [27]. South of Cape Canaveral these values fall off dramatically being less than 0.1 ppm within several kilometers of shore [248]. Furthermore, Manheim et al [248] found that seaward of a few kilometers offshore mineral grains greater than 4 micrometers were less than 3% of the suspended matter.

Depending on whether one samples in the north or south of the South Atlantic region both the temperature and salinity range (Fig. 4.2.2) can be seasonably either favorable or unfavorable for uranium extraction. In the northern regions, around Cape Fear for example, the variation may be from 12-27°C and 32.75 ppt to 35.57 ppt [374] while off Miami there is very little seasonality; the temperature and salinity values remaining near 23-28°C and 35.7 ppt to 36 ppt [127]. The tidal range is from 1.3 m to 2.3 m to 0.5 m along the coasts of South Carolina, Georgia and Florida, respectively.

The Gulf Stream plays a major role in the circulation along this coast. The extent and manner in which this current affects the coastal environment, however, varies significantly north and south of the West Palm Beach, Florida region (Fig. 4.4.1). This is because the Gulf Stream follows or remains seaward of the continental shelf-slope break. The topography steers the mean flow. Off Boca Raton, West Palm Beach area this shelf break is about 4 km offshore, off Georgia it is approximately 200 km offshore, and off Cape Hatteras it is about 50 km offshore. The intensity with which the Gulf Stream drives the coastal circulation is therefore stronger south of West Palm Beach. In actuality the current in this vicinity is the Florida Current which exits the Gulf of Mexico through the Florida Straits with a volume transport of from 25 to 33 million cubic meters/second [284]. Along the Florida coast, it joins the extension of the Antilles Current, becomes the Gulf Stream and gains volume all along the South Atlantic seaboard. Velocities in this current can be great. In the Florida Straits are values of 200 cm/s [13,16,24] and off the Florida coast are values of a 100 cm/s [S 17,77]. The warm temperatures, high salinities and large volumes and velocities associated with the Florida Current, Gulf Stream system indicate that this region should be considered as a potential area to site an extraction plant and will be considered in somewhat more depth.

4.5 Gulf of Mexico

The deep water circulation of the eastern Gulf of Mexico is dominated by the Loop Current. The Loop Current connects the Yucatan Current which enters the Gulf through the Yucatan Strait with the Florida Current in the Florida Straits [186]. The current must make an anticyclonic (clockwise) turn to exit the Gulf, hence the "loop". The extent of penetration of the Loop current into the Eastern Gulf is highly variable [186,192], ranging from 24°N in midwinter up to 29°N in summer. Large anticyclonic eddies are often formed in late summer, which detach

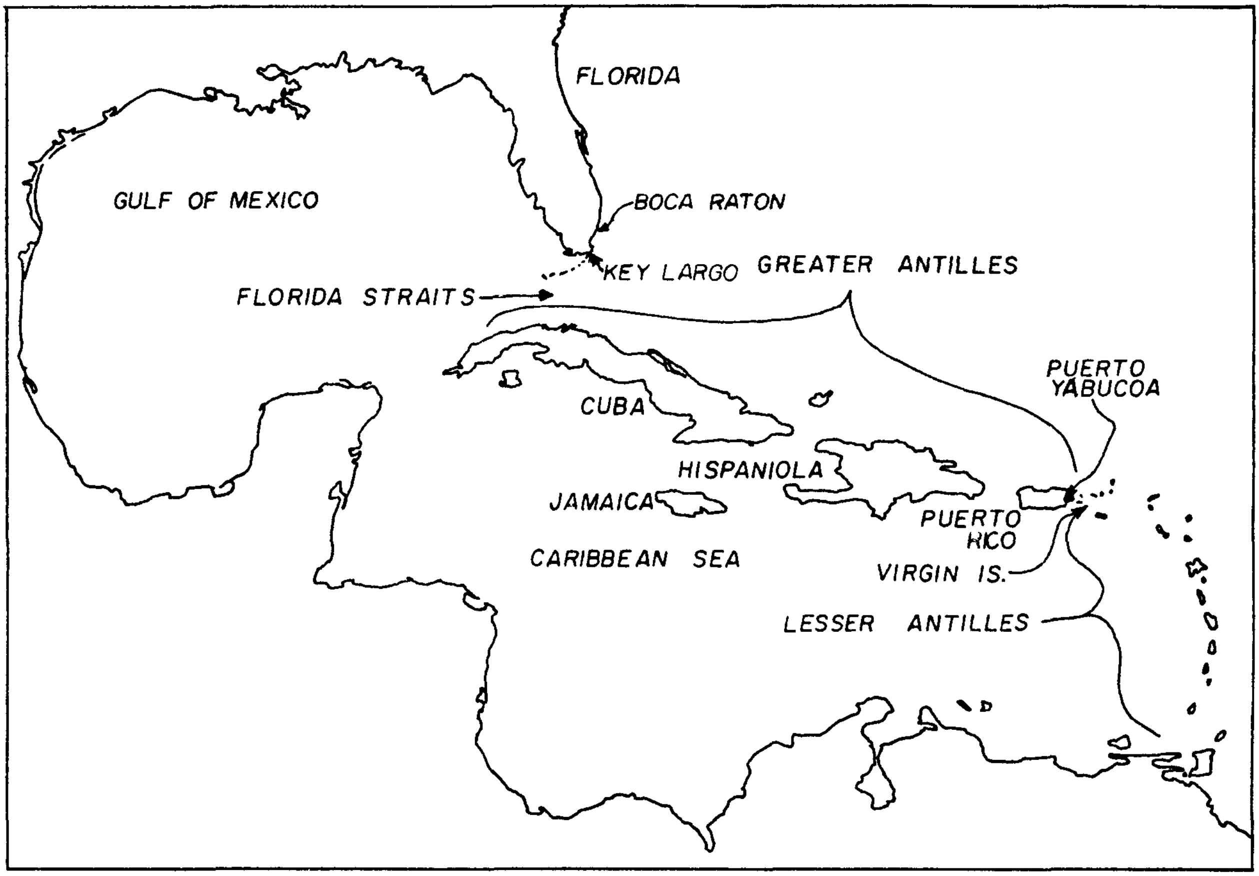


Figure 4.4.1 Map of the Caribbean showing the location of the Puerto Yabucoa, Puerto Rican site. Also shown are alternate sites along the southeast coast of the United States (Boca Raton and Key Largo).

from the Loop current and tend to migrate into the central and western Gulf [236,257]. The current is topographically constrained by the Campeche Bank off the northern coast of the Yucatan Penninsula and the West Florida Bank. The current is typically 90-150 km wide with velocities of 50-200 cm/s and a transport of 25-30 million cubic meters/second [236]. Temperatures in the Central Loop Water are 18-25°C with salinities of 36.5-36.8 ppt [186].

The circulation over the Western Florida Shelf is driven by the Loop Current system and local wind stress, resulting in a pattern of northerly and northwesterly transport, essentially parallel to the coast. Current velocities are generally less than 50 cm/s [192]. A series of cyclonic eddies propagate over the northwestern shelf [18,192]. The temperature range in the shelf waters is 20-28°C. Salinity varies widely along the central and northern coast due to river runoff and can range from 15-35.5 ppt. The minimum values occur in late winter near the mouths of rivers. In the Florida Bay region between the southern tip of mainland Florida and the Keys, currents are stronger, temperatures are >20°C throughout the year, and salinity remains high (>30 ppt) being little influenced by drainage. Currents are more westerly in this area, and a westerly counterflow along the northern edge of the Florida current has been observed [78]. Along the North Florida, Alabama and Mississippi coasts, onshore and westerly transport is the predominant circulation feature.

The particulate contents of the Gulf appear to have been little studied. The Loop Current is characterized by a relative paucity of particles near its core and high concentrations of particulates in the upwelling regions around its perimeter [87]. Because of the highly productive estuarine and salt marsh ecosystems along the shelf and the shallow mud and sand bottom, these waters have been characterized as "brackish". The eastern Gulf has prevailing northerly winds during late fall and winter and southerly flow during the remainder of the year. Winds and waves are generally moderate throughout the year with the exception of an occasional hurricane. Precipitation ranges from 100 cm/yr at Key West to 150 cm/yr along the Alabama Coast.

The western region of the Gulf of Mexico is less well-studied than the eastern Gulf, but the predominate circulation feature is a large anticyclonic gyre centered at about 24°N [293]. This is apparently partially driven by a branch of the Yucatan Current which turns westerly along the northern edge of the Campeche Bank [293]. Temperature and salinity are both high (25-28°C,>35.5 ppt) with little annual variability in the central waters.

Along the Louisiana and Texas coasts, the nearshore circulation is predominantly westerly and much of the Mississippi River efflux is dispersed to form a region of lowered salinity (32 ppt) along this coast.

Primarily because of the very broad shelf and therefore long distances to the offshore current systems, an uranium extraction plant should not be located in this area. Further, the high particulate loads would be a serious problem, as would the limited availability of fresh water in some regions.

4.6 Caribbean

The general circulation in the Caribbean Sea is a broad flow to the west as incoming waters from the Guiana and North Equatorial Currents merge to form the Caribbean Current [141]. This is a wide current encompassing the width of the Caribbean, with an average speed of about 30 cm/s, in both summer and winter with little annual variability [138]. The maximum velocities occur in the southern half of the region [141], with velocities of 50 cm/s calculated off the Venezuelan shelf. At the western end of the Caribbean, the narrow Yucatan Current which connects with the Gulf of Mexico reaches velocities of 150 cm/s [141].

Seasonal variability is minimal in the Caribbean. The difference in average surface temperatures between the warmest month (Sept; 27-28.5°C) and the coldest (Feb.; 25.5-27°C) is only 3°C [S37]. Surface salinity is somewhat more variable; a band of lower salinity water (35.5 ppt) is present across the central Caribbean in summer and early fall produced by a combination of river runoff and the salinity minimum of the Equatorial doldrums [141]. Three major rivers influence the surface salinity: the Amazon, Orinoco, and Magdalina, with a combined maximum flow of about 0.2 million cubic meters/second in late summer and early fall [S37]. Rainfall is heaviest (50.5 cm) in the summer half-year (20.5 cm in winter) [S37], but the region as a whole has a marked excess of evaporation over precipitation and runoff effects are largely restricted to the surface waters along the North and Northeastern coast of South America and the Waters surrounding Hispaniola and Puerto Rico [S37].

Much scientific attention has been paid to the deep water circulation of the Caribbean, but only the shallower waters are of concern in the present context. Underlying the surface water proper at depths of 50-200 m is the Subtropical Underwater [S37], which originates in the central Atlantic and is advected into the Caribbean. This water mass is warm (>20°C) and is identified by a subsurface salinity maximum [264] with values >37 ppt over much of the region. South of the shallow plateau on which Puerto Rico and the U.S. Virgin Islands are located is the Anegada-Jungfern Passage, the deepest connection between the Caribbean and the Atlantic. Through the upper 400 m of this narrow (25 km wide) channel some 2 million cubic meters/second of warm, saline water is transported into the Caribbean at speeds of 6-15 cm/s [264]. The shelf around Puerto Rico is shallow (50 m) with a very steep shelf break and is overlain by well-mixed Caribbean surface water [138]. Temperatures near the shelf edge range from 26-29°C and salinity varies from 34.6 ppt to 36.2 ppt with currents of 10 cm/s [138].

The probable favorable mean currents moving warm, walty water that is relatively free of suspended material indicate that Puerto Rico, the only large United States land area in the Caribbean, should have available sites. The prime siting choice (Puerto Yabucoa, Puerto Rico) will be discussed in Chapter 6.

4.7 Pacific Southwest

Only the state of California, south of the region around Cape Mendecino, has the coastline defined as the Pacific Southwest. Although, this is a very populated coastline, (the coastal plain of the Southern California Bight north of Los Angeles to San Diego has over 11 million people alone), areas of sparsely settled coastline exist. An important factor causing this is the rocky, relatively mountainous coastline. Fresh water runoff is minor south of San Francisco, as reflected by the paucity of bays and harbors from Point Conception to the Mexican border. Runoff is only about 4 million cubic meters per day and most of this water is involved as municipal waste water. A plant requiring large quantities of fresh water will probably have to compete with municipalities for fresh water availability.

The southward flowing California Current is the major offshore flow affecting the circulation in this region. It is a broad 600 to 1000 km wide eastern boundary current and ranges from only 100 to 500 meters deep. Transport calculations indicate approximately 10-12 million cubic meters/second. North of Point Conception, its eastern edge may be quite near (40 km) the coast line. Generally, the continental shelf is quite narrow (about 20 km) all along the coast, however, at Point Conception the shelf tends to broaden southward as the coastline strikes eastward defining the region of the Southern California Bight. The California Current does not follow the eastward trending coast and therefore the distance between the shore and current approaches 200 km in this vicinity [246].

The mean speed of this current is in the range from 10-20 cm/s but it has sometimes been found to be over 50 cm/s. A northward counter current is often found inshore from this current. This feature is especially persistent in the Southern California Bight and leads to a large cyclonic eddy called the Southern California Eddy [246]. Water in this gyre may take from 10-20 days to complete a half revolution assuming a velocity of 15 cm/s. The California Current has been found to be a rather complicated system displaying large and small scale time and spacial variability. Along the Southern California coast, several meanders apparently develop over a period of a few months which may in turn break off from the main current to form eddies. The length of meanders may be 300 to 400 km and may attain velocities of 20 to 40 cm/s [51].

Coastal currents nearshore, lying between the surf zone and the offshore currents mentioned above are dominated by tides, winds and coupling to the offshore currents. Typical values are 5 to 20 cm/s at a location from 5 to 10 km offshore and at a 15 m depth. Drift bottles have been found to move onshore within days [246].

There are frequent direction shifts due to the tidal and wind forcing functions. Consequently, the picture appears to show a current regime that has marked variability from the shore surf zone to at least tens of kilometers from shore. The Southern California Eddy in particular indicates a very high likelihood of recirculating ocean water in the Southern California Bight region.

Tides range from 1 m to a maximum of 3 m in some localities [S25]. Swells may reach 2 m heights several times a month and wave heights range from 3 to 5 m maximum during storm conditions. Swells originating from storms in the equatorial and South Pacific ocean are dominant in the summer and fall and for the other seasons a northern origin is usual.

The Pacific is frequented by tsunami, however, there is no record of any large tsunami (>3 m) striking the Southern California Coast since historical times. Nevertheless, the possibility of an occurrence should not be overlooked because this area of the United States is seismically very active. Indeed, earthquakes of damaging intensity should be considered likely to occur.

Temperature is only seasonally marginally favorable and salinity is generally unfavorable from the point of view of uranium extraction. The temperature range is about 12 to 20°C seasonally off Southern California and will decrease northward. Salinity values are approximately 33.5 ppt to 34.5 ppt with maximum values in late summer. The California Current is responsible for bringing cooler, less saline waters from the north southward.

The waters along the coast are moderately fertile and support sport fishing as well as some commercial fishing. Kelp and sea grass have presented fouling problems in coastal power plants [S2].

In view of the poor fresh water supply, the generally cool temperature and low salinity coastal waters and the high degree of seismic activity, the Pacific southwest has not been further considered for potential sites. The rough topography of the shoreline limits the available sites and the Southern California Eddy in the Southern California Bight is an added detraction for this southern region.

4.8 Pacific Northwest

The shoreline of the Pacific Northwest coast consists of broad sandy beaches interrupted by numerous rocky outcrops and headlands, often with steep cliffs. Inshore from the beach, there is a rapid increase in elevation along the Oregon and northern California coasts. The inshore region of northern Washington has a less steep topography. The depth at 1 km offshore varies from about 5 m to 30 m [72]. The deepest values are off the southern Oregon coast, south of Cape Blanco. For other parts of the coast, the depth at 1 km offshore is rarely greater than 12 m. Five km offshore, the depth varies from 20 m in the north to greater than 70 m off Cape Blanco [72]. The bottom is mostly sand and mud with occasional rocky outcrops.

The Pacific Northwest is situated in a band of predominently westerly winds. Along the coast, winds are usually from the northwest in the summer and the south or southwest in winter. The monthly averaged wind speeds, range from about 3 m/s at Eureka, California to 6 m/s at Cape Disappointment, Washington [72]. Storm winds are much more frequent in the winter.

During the summer, the significant wave height off the central Oregon coast is usally less than 2.5 m. In winter, the significant wave height is much higher, and is likely to exceed 5 m on at least one day of each winter month [365].

Tides are semi-diurnal with a significant diurnal component, so one of the two daily high tides is higher than the other. The tidal range decreases from north to south along the coast with a range of about 1 m at Newport, Oregon [365].

Nearshore surface circulation is driven by the local winds, and currents are largely parallel to the offshore isobaths. In response to fluctuations in the local wind field, currents exhibit considerable variability over periods of several days [180,365]. Mean circulation during fall and winter is to the north but is highly variable. The spring and summer circulation is southward and much less variable [180]. Periods of local upwelling impose an offshore component into the general southerly flow. Year-long current meter records from a mooring at 100 m depth off Newport, Oregon show a net southward flow at 25 m of 10 cm/s [180]. There have been few studies of currents over the inner shelf. Currents in the shallow, nearshore regions appear to be generally southerly but weaker than those offshore [180]. Maximum current velocities in summer are greater than 50 cm/s and in winter greater than 100 cm/s [180].

Upwelling in the spring and summer and the annual reversal in current direction tend to reduce seasonal changes in temperature. In general, summer temperatures are about 5°C warmer than winter, (12-14°C in August vs 7.5- 8.3°C in January), but in areas of upwelling, summer temperatures may be lower than those in winter. From November through April, vigorous wind-mixing produces an isothermal water column in the nearshore waters [365].

Summer surface salinities are approximately 33.5 ppt and may be as high as 33.8 ppt near upwelling sites. The heavy runoff in winter and spring reduces salinities to about 32 ppt off the Oregon and California coasts [365]. The Columbia river discharge flows north along the Washington coast in winter and spring, reducing nearshore salinities to 25 to 28 ppt. Particulate concentrations in the nearshore waters are highest in winter and spring due to the heavy coastal rainfall and subsequent runoff [72,365].

The Pacific Northwest coast is sparsely populated along most of its length and there is little heavy industry. Population centers lie at the mouths of the numerous rivers and streams draining the Coast range. Aberdeen, Washington and Coos Bay, Oregon are the major centers of the timber industry, with large mills and port facilities. Many of the coastal towns have fishing fleets whose major catches are salmon, shrimp, and Dungeness crab. Most of the coastline is the focus of the tourist industry and is virtually all protected. The northern half of Washington's Pacific ocean coast is part of Olympic National Park. The Oregon Dunes region of the south central Oregon as well as numerous other local, state and federal parks exist along the coast.

For uranium extraction processes, the Pacific Northwest has generally unfavorable salinities. The currents bathing the coastal regime are not as strong as in other United States regions and like elsewhere, they show marked variability. Sea surface temperatures vary seasonally from marginal to poor and the shoreline is usually significantly sloped. Therefore, this region has been ruled out, however, it should be pointed out that these waters are very fertile and should be considered in any marine farming plan.

4.9 Alaska

For the purposes of this study, Alaska was analyzed in three regions: the Beaufort Sea and the Chukchi Sea (Arctic Ocean) in the north; the Bering Sea in the west which includes the northern sides of the Aleutian chain; and the Gulf of Alaska which includes the southern sides of the Aleutian chain and the "handle" along the Alexander Archipelago (Fig. 4.9.1). The Beaufort, Bering and Chukchi Seas were immediately ruled out due to their harsh climate, cold sea water and significant ice cover throughout much of the year.

The Beaufort-Chukchi Sea has summer sea surface temperatures less than 0°C [80]. Since rivers are a major source of water to the Arctic, the salinities are the lowest of any major ocean [147]. Summer values

Figure 4.9.1. Map of Alaska showing Cook Inlet.

near shore are 30 ppt with large areas less than 27 ppt [102]. In winter, heavy ice (1 m or more thick) exists which may not clear the following summer [80]. For example in 1975, Prudhoe Bay never had an open sea route of less than 1/2 ice cover. In addition, the Point Barrow area is subject to storm surges [80] during the summer. Since 1960, 13 such surges have occurred. The largest one causing extensive damage at Barrow in 1963 had 3 m waves superposed on a 3 m surge.

The Bering Sea has a milder climate than the Arctic but nevertheless harsh conditions prevail. Summer sea surface temperatures are as high as 6 C north of the Aleutians but only about 2°C in the Bering Strait [80]. Winter temperatures are about 3°C off the Aleutians and less than 0°C over most of the sea. Virtually the entire coastal region with the exception of the Aleutians has sea ice during the winter season. Salinities are higher than in the Arctic, ranging from about 31 ppt near the coast to 33 ppt along the Aleutians [146] and storm surges don't present near the danger they do in the Arctic.

Along the Gulf of Alaska coast the tidal range is among the largest in the world, and it is for this reason that this region is condidered as a possible site [149]. Anchorage at the mouth of the Cook Inlet attains a range of nearly 10 m [80]. Elsewhere along the coast ranges of 2.7 m (Kodiak), 5.6 m (Seldovia-mouth of Cook Inlet), 3.8 m (Valdez-Prince William Sound), 4.6 m (Hoonah Harbor, handle), 3 m (Sitka-handle), 4.8 m (Ketchikan-handle), 1.6 m (Cape Sarichef-Aleutians) [80]. For the most part, this region is ice free although both Cook Inlet and Prince William Sound do have ice from approximately December through March which may become 0.6 m thick [80]. Mostly, this ice occurs in sheltered coves. Large chunks of ice are occasionally a problem to small craft in some of the inlets, particularly Prince William Sound. Sea surface temperature is more favorable along the coastal region then the rest of Alaska. This is partly due to the influence of the Alaska current the major ocean current affecting this region. It is considered a cool current having near the Aleutians the following temperature/salinity range: 8°C/32.6 ppt (summer) to 3°C/33 ppt (winter). Its volume transport is 5-10 million cubic meters/second [387]. Filaments of this current are responsible for high velocities, 45 cm/s have been recorded [130] through some of the Aleutian Straits. In January, the temperatures are greater than 6°C along the handle to near 4°C along the Aleutians; however, Cook Inlet attains 0°C. In June, temperatures are greater than 11°C along the handle to about 8°C Cook Inlet and along the Aleutians [80]. Salinities are generally greater than 32.4 ppt in winter and 32.0 ppt in summer offshore [116] but many of the inlets and fjords are substantially less. Most, if not all, the fjords are positive estuaries (Precipitation plus run off exceeds evaporation) and may be characterized by salinities of 24 ppt to 28 ppt seasonally. Storm surges are rare in the Gulf. During Winter 70% of the waves were less than 2.5 m and 20% of these less than 1.5 m [80]. However, tidal waves, a serious hazard, are significant both due to this region being adjacent to a very seismically active zone and to focusing of tsunami originating from earthquakes elsewhere around the Pacific. Tidal waves estimated at 30 m have occurred along this coast.

From the standpoint of tidal capabilities, Alaska, specifically the Gulf of Alaska, offers prime locales. The Gulf of Alaska is also a region of high marine productivity. Thus for facilities relying on either tidal power or biological production, the Gulf of Alaska is a likely region. However, the rest of Alaska is excluded from any consideration due to its remoteness, its climate and its cold, low salinity, surface waters with seasonal ice. Indeed, sea surface temperature of the entire coastal Alaska region is sufficiently low to remove this from consideration for other than a tidal or biological system.

4.10 Pacific Islands

Several of the U.S. island possessions in the central Pacific were considered as possible sites. Wake, Guam, the Marshall Islands and American Samoa all lie within 20 degrees of the equator and are oceanographically favorable. Surface salinities are often in excess of 35 ppt and water temperature is very rarely less than 20°C. The various branches of the Pacific Equatorial Current system provide reasonable circulation.

Fresh water availability is a major problem at all of these locations [396,397]. Rainwater must be collected in catchment basins because of the rapid runoff and lack of usable groundwater. The cost of constructing water collection and storage facilities and the additional land required would be major problems on these islands.

A second major obstacle to plant construction on these islands is the lack of locally available materials and resources. None of the islands is industrialized and port facilities are minimal. The logistics of a major construction project would be formidable and probably prohibitively costly.

The tropical North and South Pacific islands are subject to cyclones analogous to the hurricanes of the tropical Atlantic. Wind speeds may exceed 40 m/sec in these cyclones. Because of the tectonically active crustal margins ringing the Pacific, (the "ring of fire"), all of these islands may be subject to occasional tsunamis which result from earthquake activity.

The Hawaiian Archipelago is a series of volcanic peaks which rise nearly 5000 m from the ocean floor to form an island chain almost 4000 km long. The more northerly islands are composed of coral reefs and reef debris which surmount extinct volcanoes. Most of these northern islands are quite small and are included in a wildlife refuge for sea birds. At the southern end of the chain are high volcanic islands with fringing coral reefs. Almost everywhere, the 100 m elevation contour is less than 5 km from the beach.

The Hawaiian islands lie in the path of the Pacific North Equatorial Current; a broad, westward-flowing current driven by the trade winds. Maximum current velocities are about 40 cm/s with average velocities less than 20 cm/s. The current tends to be somewhat stronger during fall, and is weakest in spring [S38,S13], with volume transport ranging from 10 - 25 million cubic meters/second [S20]. The near surface water characteristics are those of the Central North Pacific; warm, highly saline water, low in nutrients, and exhibiting little annual variability. Near surface temperatures are greater than 20°C and salinities range from 34.5 ppt to > 35.0 ppt [S26,S10].

Current meter studies in Hawaiian waters have indicated that fairly large tidal effects are present in the nearshore circulation. In many areas, the tidal signal is the most energetic component of the nearshore circulation. The tides are of the mixed-type; semidiurnal with a pronounced inequality and a maximum range of about 1 m [S13]. Tidal current velocities are typically 20-30 cm/s but may be as much as 50 cm/s [S39].

A comparison of current measurements made throughout the Archipelago indicates an anticyclonic (clockwise) circulation pattern around each of the islands [S27] "In all channels, the flow on the western side is to the southwest while the flow on the eastern side is to the northwest, against the prevailing trade winds." [S27]. This circulation results from complex interactions of the tidal and North Equatorial currents with the nearshore bottom topography and the local wind field.

Because of the mountainous nature of the islands, rainfall varies widely from place to place. The eastern (windward) side of the island tends to receive much more rain than do the western slopes, over 800 cm/yr in some locales. Due to the steep terrain and porous nature of the volcanic bedrock, runoff is rapidly accomplished through a system of small streams. There are no large rivers or major freshwater lakes in the Hawaiian Archipelago.

The normal winds of Hawaii are the trade winds out of the east. Occasional winds from the west are called Kona winds. The islands are subject to Pacific cyclones which are less frequent than the equivalent hurricanes of the Atlantic. Because of the earthquake activity all around the circumference of the Pacific, these islands are also subject to wave damage from tsunamis.

The oceanographic environment of the Hawaiian Islands would be suitable for a uranium extraction site. The state is interested in attracting industry, and services and expertise are available locally; but the steep terrain and lack of large amounts of fresh water would probably preclude the development of an economically feasible plant.

CHAPTER 5

SUMMARY OF QUALIFIED REGIONS

5.1 Existing and Future Plants

The currently existing facilities and those planned for the near future which handle large volumes of seawater were considered (See 2.5) as possible sites for uranium extraction. However, these plants have a small amount of seawater passing through their systems and can only provide limited amounts of uranium. For instance, the 12 largest desalinating plants in the United States and its territories flush a total of 0.1 tonnes of uranium through their systems per annum. Similarly, the largest plant that extracts chemicals from seawater could only produce 0.3 tonnes of uranium per year from the seawater it processes.

Recovery of uranium from the cooling water of U.S. power plants that are adjacent to the open oceans could yield up to 100 tonnes per year. However, the largest power plant complex could produce less than 10 tonnes per year assuming 100 % recovery.

Ocean Thermal Energy Conversion (OTEC) plants might be worth further consideration. A single 100 MW OTEC power plant would provide 89 tonnes of uranium per year assuming 100 % recovery and several of them together might produce significant amounts of uranium. However, the large scale uranium extraction processes would undoubtedly add to the engineering difficulty and must be carefully investigated.

5.2 Floating Plants & Platforms

Since to some extent the advantages these facilities present are similar, we are treating them together. We assume that floating plants will be tethered to and platforms emplaced on the ocean floor. The most important advantage we see is the ability to locate in premier environments, for example in the equatorial current. In essence seagoing plants would remove the topographic constraints.

An attractive feature of floating plants would be their "mobility", i.e. they have the ability to graze on the best available seawater and avoid more or less deleterious conditions. These are some of the advantages envisioned for the ocean thermal energy conversion (OTEC) plants. (Jack Nath, personal communication). The size of the plants conceived to date indicate very large structures. Considering present technology, the building of these structures in the open ocean may not be feasible. A modular design concept could overcome some of the construction problems, and have perhaps the added advantage of increased mobility and lessened financial risk from possible disasters. One type of disaster that could strike in the open ocean is very large but rare breaking waves.

5.3 Marine Organisms

Use of biological organisms for uranium concentration is an idea which has been around for some time [160; 161], but due to a lack of appropriate organisms it has remained relatively unexplored. Sufficient light, air, nutrient and optimal temperature range are some of the necessary considerations for cultivation of marine organisms, thus they are useful only at the sea surface. The more promising known species often do not form colonies [303] and the size of their individual aggregation is small which makes them difficult to treat industrially. Progress has not been made in the separation of uranium from marine organisms [302] and at present, burning is the method used.

Despite these drawbacks, research concerning the separation of uranium from marine organisms needs to be continued. Detailed research not only could lead to a potential means of economically concentrating uranium by marine organisms, but also could help in understanding the concentration mechanism, type and location of binding. This could, in turn, lead to the discovery of better adsorbers.

5.4 Tides

As far as the United States is concerned, the only possible localities are along the Alaskan coast line bordering the Gulf of Alaska. High tides at least greater than 3 m, generally greater than 5 m, and often greater than 8 m are found along the Alaskan panhandle (the Alexander Archipelago) to the Aleutian Peninsula and Kodiak Island regions. Cook Inlet has the largest tides, as mentioned earlier, with localities nearing 10 m in range.

In order to insure a fresh daily supply of seawater, since tidal currents undergo approximately 180 phase shifts, there should also be a mean current superposed on the tidal oscillation. The Alaska Current flows along the shelf break beyond Cook Inlet. Therefore, the combination of maximinized tides and established current flow suggest a tidal site for this area is possible.

Only through a joint venture with some other nation would the United States be able to consider a tidal plant located in waters of favorable climate. However regions of high tides in the tropics and subtropics are few compared to subtropic and subpolar.

5.5 Currents & Pumped Systems

There are not too many regions that meet some of the basic requirements set forth in chapter 3. The main requirements are warm temperatures, high salinity, low concentrations of suspended material, an abundance of fresh water, and most importantly substantial steady currents.

The United States is fortunate to have several available regions and it could improve its site potential through joint ventures with other nations. One method of insuring no recirculation of processed seawater is to pump from one ocean to another. There are only a few regions of the world where this is possible, so again joint ventures with other nations would usually be necessary. Small facilities and plants producing uranium ore on the order of tonnes per year offer many more locations both nationally and internationally and could be tied with other operations such as desalination plants, cooling streams of conventional power plants, and dams (Tom Clark, personal communication).

Many islands are located in favorable ocean regions, however for the most part they are too small. Mountains seem almost a prerogative on islands in order to insure adequate rainfall. Usually mountains mean a narrow shelf and increased likelihood of nearshore currents. Unfortunately this frequently also means steep topography near the shore which limits the area available for building offshore structures. Hawaii is a prime example of these conditions. Over much of their area Puerto Rico and the other major Caribbean Islands are also mountainous and have narrow shelves. These islands do have larger areas of low lying coastline than the Hawaiian Islands. The prime site choice, Puerto Yabucoa on Puerto Rico's southeast coast, meets these conditions. The second choice is the southeast Florida coast which has two, perhaps more, possible regions; at northern Key Largo, and at Boca Raton. They are very similar in many oceanographic respects to Puerto Yabucoa.

The Georgia-South Carolina coastline has low potential site locations, and are not as impressed with the area as further south. It does not have a year around temperature and salinity value that compares favorably with Florida or the Gulf states. Furthermore the near shore circulation is apparently less reliable and certainly less intense. Florida's south eastern coast as mentioned has the magnanimous Gulf Stream extremely close to shore. Finally the particulate load most certainly is high relative to the Florida and Puerto Rico site although less than the Gulf of Mexico, United States shoreline. In light of the qualifications, the Pacific Southwest would appear to be as well or better suited than the South Atlantic. However Southern California has a generally denser population, a greater potential for seismic damage, generally significantly rougher topography and more coastal elevation. In addition fresh water supply is very questionable.

Florida's southeastern coastal environment is comparible to Puerto Rico's in many respects, however its greater population density and less available land indicate higher land costs, more stringent legal criteria and a generally heavier human usage. Supporting facilities, raw material and construction supplies are probably easier to obtain. Some energy conservation may be realized if the fresh water reservoir is elevated relative to the plant. For this reason, pumping costs for fresh water could be higher for Florida.

CHAPTER 6

DETAILED DISCUSSION OF SITES

The primary site region identified for a plant that depends on pumping seawater is located at Puerto Yabucoa, Puerto Rico. The site region for a tidal scheme is in Cook Inlet, Alaska. These primary choices are discussed in detail in this chapter. An alternative region is also identified and briefly discussed.

6.1 Pumped: Puerto Yabucoa - Puerto Rico

Puerto Yabucoa, a bay with an adjacent river valley at the southeast coast of Puerto Rico, is the primary choice. The important features of this area are discussed as follows.

6.1.1 Puerto Rican Environment

The site chosen for Puerto Rico is in the valley of the Rio (River) Guayanes (Fig. 4.4.1), which intersects the southeast coast. Other pertinent topographic regions associated with this area are Punta (Point) Guayanes, Punta Yequas and Puerto (Port) Yabucoa (Fig. 6.1.1, 6.1.2). The nearest major population centers are Yabucoa followed by Humacao to the north. A nearer small town of a few hundred residents is Playa de Guayanes. This site region will be discussed in the overall body of the Puerto Rico description and summarized in the following section. A problem with Puerto Rico oceanographically is that it has been much less studied than continental U.S. waters and coastal areas.

In 1952, Puerto Rico became a Commonwealth of the United States and in 1967, a referendum choosing between statehood, independence or commonwealth government passed in favor of the continuation of its present status. There has been an independence movement since the 50's sometimes with violent overtones, however, either commonwealth or statehood appear the favored political climate. The most recently elected governor (1976) favors statehood.

Puerto Rico is the most easterly and smallest of the Greater Antilles Islands of the West Indies lying approximately between 18 and 19 N latitude. It is a tropical island nearly rectangular in shape with the dimensions of 180 by 60 km. Although there are numerous fertile valleys and an encircling coastal lowland, overall the island is mountainous. Running the length of the island south of center is a relatively high mountain range, which is predominately cretaceous and consisting of granodiorite, quartz diorite, tuffaceous sandstone, siltstone, breccia, and conglomerate lava and tuff [333]. The highest mountains rise roughly 1300 m in the east and south.

The Rio Guayanes valley in the southeastern part of the island has an even relief of about 10 m over 5 km inshore and is basically alluvial deposits on a flood plane. Its width averages about 3 1/2 km over this distance. The beach front of about 10 km length and 1 km width is medium coarse sand (160 micrometers) typically calcite, quartz and volcanic rock fragments mixed with pebbles and cobbles. The next 2 km inland grades through swampy land into silt sands and gravels over the next roughly 3 km. Surrounding mountains are extensively shattered granodiorite and quartz diorite with cretaceous and some tertiary ages [333].

Despite being one of the more densely populated islands in the world having a population of over 3.2 million, large areas remain sparsely settled. This is no doubt partly due to its mountainous rugged interior. Fully a third of the population live in the San Juan metropolitan area with the other major area around Ponce having approximately 300,000. Yabucoa, located in the Rio Guayanes valley, has a population of about 35,000. Elsewhere in the valley, there is not much development and it is sparsely settled with the exception of a Sun Oil refinery mentioned later (Fig. 6.1.3, 6.1.4). Most of the rural homes appear to be in the surrounding hills. Puerto Rico's largest income source is from manufacturing (textiles, electrical and electronic, chemical, petrochemical and plastics) followed by agriculture and tourism. Apparently, Yabucoa has a strong agricultural base because the Rio Guayanes valley is mostly farmland, primarily sugar cane. Mining production is chiefly related to construction materials, primarily cement. Although there are essentially no railroads on the island, the highway system is adequate. The major cities are connected by good roads, whereas the roads between the lesser cities, while paved, tend to be narrow and winding. The major cities are serviced by daily flights and San Juan is an international airport.

Being situated in the path of the northern trade winds throughout the year, the prevailing winds are easterly [11,68]. Hence, the weather systems generally arrive at Puerto Rico from an easterly direction. The stable Bermuda High, located over the Atlantic, usually shifts somewhat northward in summer and a little southward in winter, resulting in the winds and weather patterns coming from the north-northeast in winter while in summer they are more nearly from the east [11]. Of course, various factors will perturb these conditions such as frontal systems and waves in the easterly wind flow which may cause increased wind velocities

Figure 6.1.1 Punta Guayanes Quadrangle, Puerto Rico; USGS 7.5 minute series (topographic). Scale is 1:20000. Contour land interval is 10m, depth curves and soundings in feet.


SCALE 1:20 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 KILOMETER
CONTOUR INTERVAL 5 METERS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOW WATER
Comunas
Río del Ingenio
Río Guayanés
P L A Y A
Playa de Guayanés
Escuela Eugenio María de Hostos
Central Roig
(YABUCOA)
YABUCOA
PATILLAS 30 KM
MAUNABO 12 KM
1.1 KM A TERMINO C 905
0.4 KM A EMP C 3
Zanja
Barra de Santiago
V A L L E D E Y A B U C O A
JUAN MARTÍN
Caño
Punta Fraile
Punta Icacos
Punta Guayanés
Puerto Yabucoa
Punta Quebrada Honda
C A M I N O N U E V O
Cerro Santa Elena
5'
2'30"
R I B B

(up to 15 m/s), heavy rains and a partial shift in direction to a flow from the southeasterly quadrant.

Puerto Rico, like other Caribbean Islands, lies in the path of tropical storms and hurricanes, therefore, severe wind velocities may be occasionally experienced (e.g. the maximum recorded winds of 250 km/hr occurred in 1928 at San Juan). Incidentally, this hurricane ("San Felipe") was the last major one to strike the eastern Puerto Rico and St. Croix (Virgin Islands) region. Storm and hurricane tracks are from the east and southeast [127,S32], hence the south and eastern side of the island probably bear the brunt of these "attacks". Tropical storm winds exceeding 16.5 m/s have been recorded in all times of the year at St. Croix which is located approximately 100 km east-southeast of Puerto Rico and, by inference, such forceful winds probably strike the east coast with like frequency. It has been estimated that an average of 8 hurricanes occur per year in the entire Caribbean of which only 2 strike islands [S21]. Between 1879 and 1955 13 "devastating" hurricanes passed in the vicinity of Puerto Rico (within ca. 1000 km) and since the energy from hurricanes is felt over more expansive areas than the storm locales, it is likely that at least some hurricane induced damage occurs on this frequency. Less than 30 major hurricanes and intense tropical storms struck in full force at St. Croix between 1770 and 1942 causing serious damage, 43 % of them were in August and 35 % in September [S32]. Basically Puerto Rico has a marine tropical climate showing only slight seasonal variations. Mean annual temperature is about 27°C ±3°C for locations everywhere along the coast. Generally, winds are strongest in the midsummer (6 to 8 m/s) and average about 4 to 5 m/s throughout the rest of the year [11,68]. The Atlantic side of the island tends to have the strongest winds [11,16]. There is only a relatively wet season and a relatively dry season; the former beginning around May while the latter begins between December and February depending on either a northern or southern location [396,397]. The most important factor governing rainfall is the mountains and their relationship to the prevailing winds. The northeast may receive over 380 cm/yr whereas the southwest coast may get less than 90 cm/yr [17]. The mountains also are cooler and have a bigger temperature range. The southern coast is in the rain shadow and the major portion of the runoff is northward into the Atlantic ocean.

Puerto Rico has the size and the mountains to enable it to receive enough rainfall so that generally water supply is not deficient. The discharge of the Guayanes varies between 1 and 6 cubic meters/second and, therefore, it is not one of the more significant Puerto Rican rivers. The major ones, some over 10 times the Guayanes' size, empty into the Atlantic. Runoff, however, over all the island is rapid, due to the limited mountain to ocean pathways. A study [33] has indicated a substantial aquifier exists in the Guayanes valley capable of supplying 80,000 cubic meters water per day. Pumping this would produce detectable salt water intrusion a few kilometers inland after 45 years. Consequently freshwater is available to the plant both from the river and supplementary pumping.

Figure 6.1.2 Puerto Yabucoa, Puerto Rico; U.S. Dept. of Comm. (NOAA; C&GS map number 916). Scale is 1:10000, soundings are in feet at mean low water.

PUERTO YABUCOA

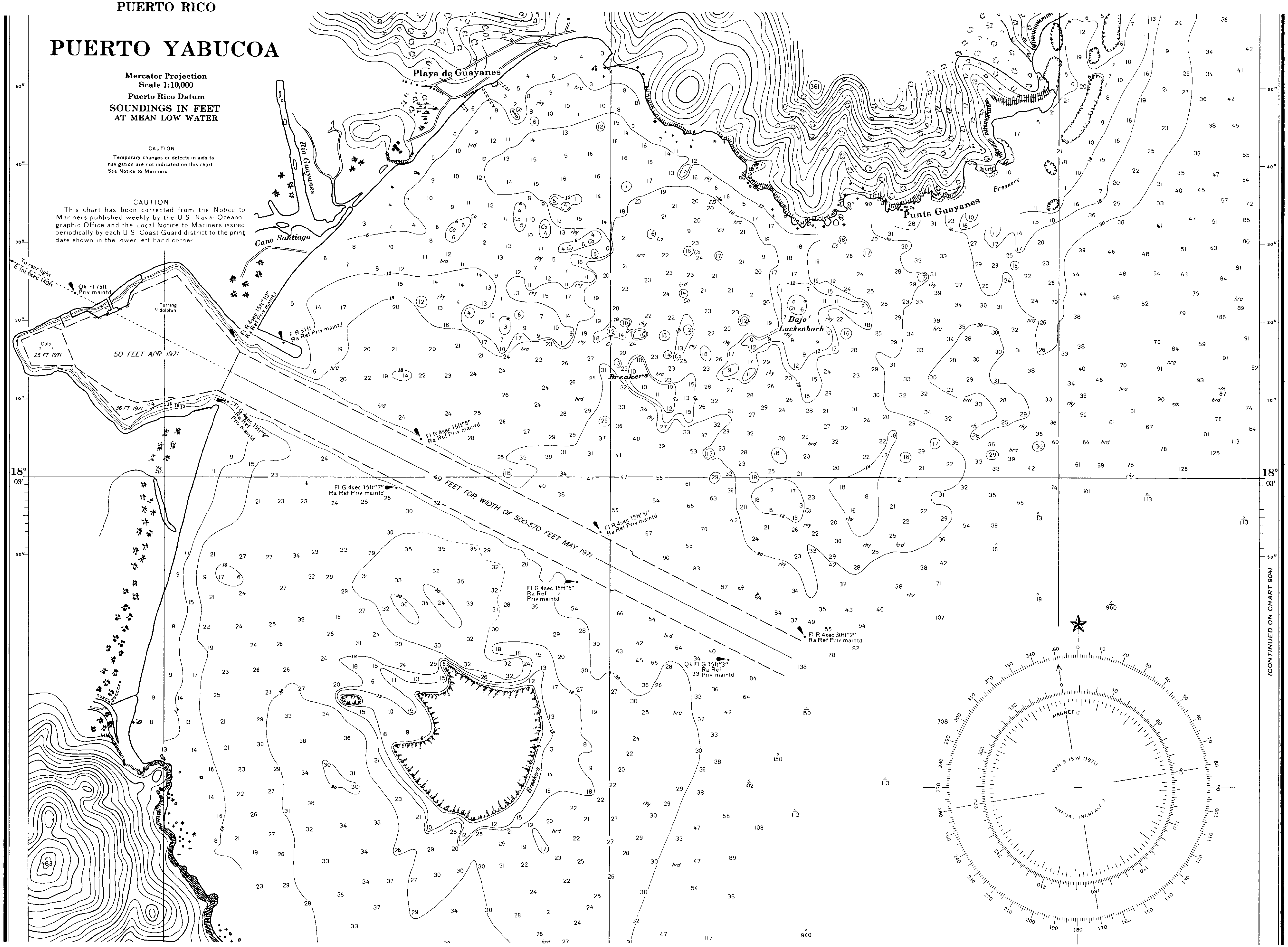
Mercator Projection
Scale 1:10,000
Puerto Rico Datum
SOUNDINGS IN FEET
AT MEAN LOW WATER

CAUTION

Temporary changes or defects in aids to navigation are not indicated on this chart See Notice to Mariners

CAUTION

This chart has been corrected from the Notice to Mariners published weekly by the U S Naval Oceanographic Office and the Local Notice to Mariners issued periodically by each U S Coast Guard district to the print date shown in the lower left hand corner



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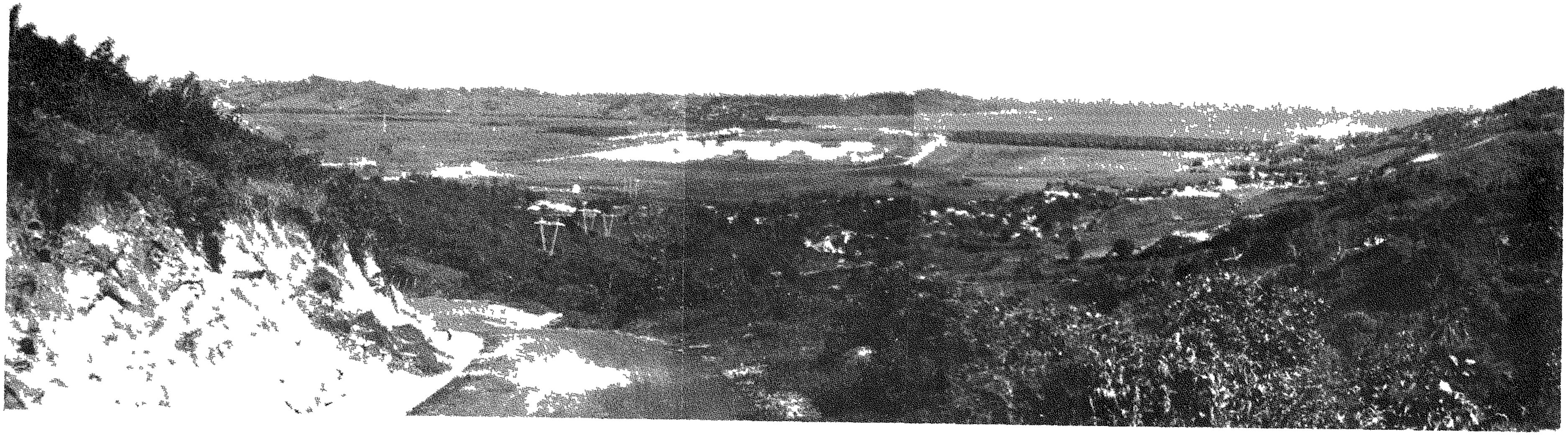


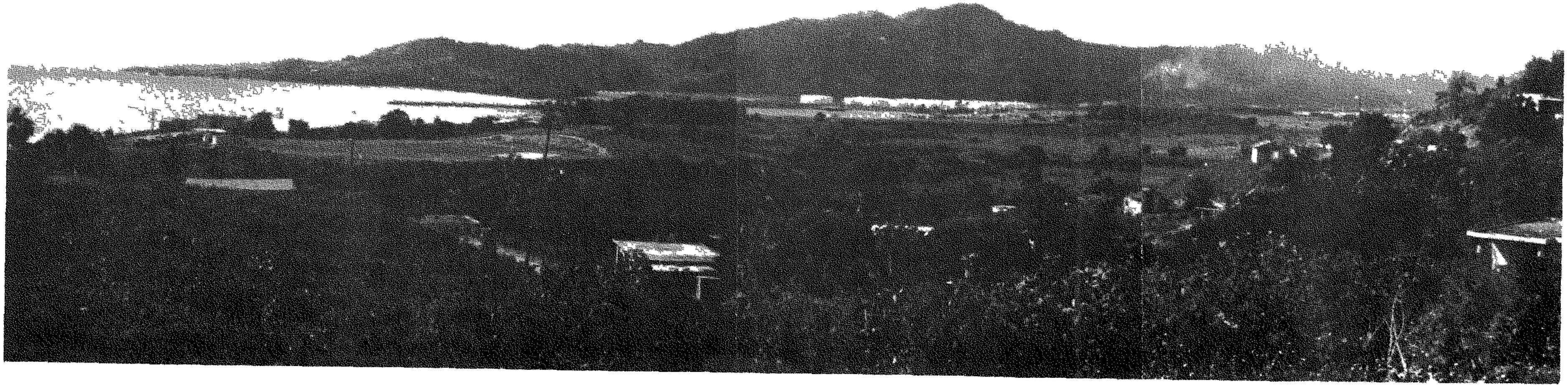


Figure 6.1.3. The view looking northward across the Rio Guayanes valley. Sun Oil facilities are visible in the center, and right of the center in the background is Punta Guayanes. The reef (figure 6.1.1 and 6.1.2) is marked by the white waves on the right side of the figure.

Figure 6.1.4 The view looking southward across the Rio Guayanes valley. This photograph was taken from a hill in Playa de Guayanes. Sun Oil facilities are visible in the center. In the far left is Punta Quebrada Honda.

Seismically this island is not located in a quiescent zone. Few deep quakes (> 100 km) occur in the region but there are numerous shallow (0-100 km) occurrences. This is because the boundary of the Caribbean Plate upon which Puerto Rico is situated is located north of the island, the lesser Antilles south and east of Puerto Rico is a subduction region, hence Puerto Rico is moving eastward relative to the North American Plate [127,147]. While the potential exists for damaging earthquakes, probably only two have occurred in the Caribbean region of sufficient intensity to generate tsunamis detectable at 1000 km or more from the source. Apparently, the north Atlantic has been subjected to a total of four over the last few hundred years [127]; the one in 1751 due to an earthquake off Portugal causing the most severe loss of life and property.

Puerto Rico is one island among many in the long chain of islands extending from South America to the United States which separates the Caribbean Sea from the Atlantic Ocean. On the north and south coast the shelf is quite narrow, defined by the 200 m contour and plunges rapidly to depths of over 1000 m. The northern shelf is less than 5 km wide, and the southern from 5 to 10 km [12,S37]. The southwest shelf is somewhat wider but the broadest shelf is on the eastern side and is known as the Virgin Island Platform. This platform extends 200 km eastward north of Punta Guayanes on the southeast coast [12]. Puerto Yabucoa between Punta Guayanes on the north and Punta Yequas on the south (a linear distance of about 7 km) has the 200 m isobath from 1 1/2 to 3 km offshore, beyond the depth plummets to near 4000 m before steeply shallowing off St. Croix (Fig. 6.1.2). This deep is the small Virgin Island Basin. Connecting it to the Atlantic is the Anegada Passage situated approximately between St. Croix and Virgin Gorda. This basin is connected in turn to the Venezuela Basin of the Caribbean via the Jungfern passage between St. Croix and Puerto Rico. Together, called the Jungfern-Anegada Passage, they form the deepest channel in the eastern Caribbean. Their sill depths respectively are 1815 m and 1910 m [264], hence the controlling passage to deep water circulation is the Jungfern.

The crucial role played by this channel in the circulation and exchange of water in the Caribbean has resulted in numerous oceanographic studies in this region [264,377,378,S37], although as is usually the case in deep water investigations, the coastal environments have been generally neglected. Nevertheless, the circulation and water mass characteristics in the more open ocean govern the coastal regime and much oceanographic information about the nearshore character can be gleaned from knowledge of deep oceanography.

Despite the many surveys conducted through and around this passage, there is still debate about the deep water inflow to the Caribbean. Some investigators [377,423], believes that the Caribbean deep water in the Venezuela Basin has been isolated for some time. Other evidence suggests that there is an episodic renewal of deep water into the basin [378] and still other evidence indicates a general influx [S37]. However, all evidence clearly shows deep water penetration at least as far as the Virgin Island Basin.

The deep waters being discussed here [141,264,S37] below approximately 1100 m are called North Atlantic Deep Water (NADW) and are characterized by potential temperatures (measured temperature corrected for adiabatic warming) less than 5°C and salinities of 34.85 to 35 ppt. In the depth range of 700 m to 1100 m is Antarctic Intermediate Water (AAIW) with a temperature/salinity range of 8 to 5°C/34.65 to 34.85 ppt. Above this water is Tropical Atlantic Central Water (TACW) which is a transitional water between AAIW and Subtropical Underwater (SUW). This latter has a salinity maximum (ca. 37 ppt) associated with it at about 200 m. Above this water, extending from the surface to about 100 m is the Tropical Surface Water (TCW) having a temperature/salinity range of 26 to 29°C and 34 to 36 ppt respectively. Seasonality and meterological events govern this range. The average mixed layer depth for temperature was 40 m and for salinity 20 m for oberservations made north of St. Croix [234]. Essentially, it is this water which is significant to the plant, however, even to a depth of 200 m (SUW) the temperature is still over 22 °C (Fig. 6.1.5). Also salinity increases with depth [264]. Hence, vertical mixing which causes short term (hourly to daily) variability in the surface waters will not degrade the quality of the plant's resource. An additional point worth noting is the marked stratification of the Caribbean water column to depths exceeding 1000 m. This means that the vertical mixing does not occur easily. One can see (Fig. 6.1.6, 6.1.7) that the temperature and salinity character found in the open ocean is essentially like that observed along the coast at least for selected times of the year [106].

Perhaps the most important single consideration for the plant at any site is the current structure; their mean and variability. The principle current of the Caribbean Sea is sometimes known as the Caribbean Current; it is part of the North Atlantic gyral system. Offshoots of the Antilles Current, the westward (and northward) flowing current along the Atlantic side of the Antilles Island chain, feed this current hence the general trend is a westward flow for the Caribbean current. However, the main axis of the current is located in the southern regions closer to the American continent [141]. Since on the order of 31 million cubic meters/second of water exits the Gulf of Mexico via the Florida Straits [284,354] which in turn is supplied by water entering through the Yucatan straits, continuity requires that the same amount of water enter the Caribbean from the Atlantic. The net transport is composed of the entire water column (the column need not and generally does not move as a unit), passages of varying depth exist all along the Lesser Antilles. Therefore, not all the influx to the Caribbean need enter at the Jungfern Anegada Passage and, in fact most does not, but rather as mentioned earlier through the southern Lesser Antilles. Recent measurements indicate a net transport into the Caribbean of about 2.5 million cubic meters/second [264]. However, this measurement only considers the central passage and not the entering waters over the Virgin Island Platform. The mean integrated velocity associated with these measurements was about 9 cm/s for the upper 200 m. Other studies indicate typical currents from west, southwest, and northwest at 20 to 80 cm/s in all seasons. Atlas charts even show currents exceeding 100 cm/s

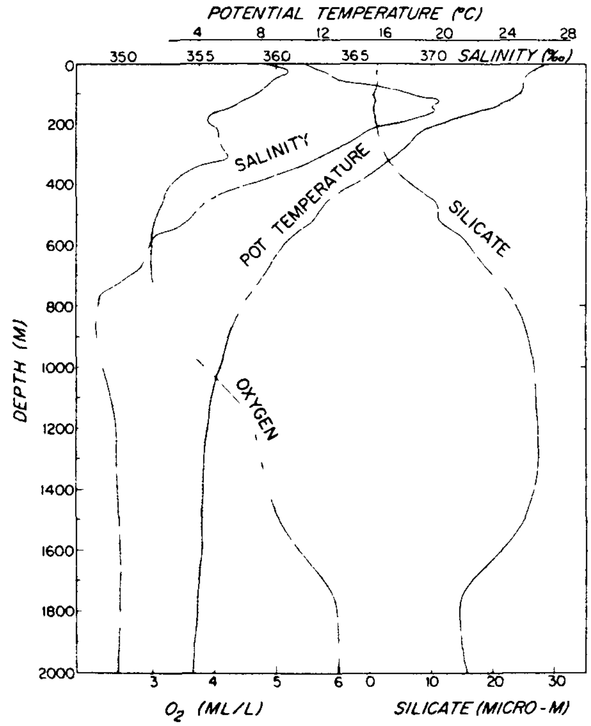


Figure 6.1.5 Vertical profile of temperature (°C), salinity (ppt), oxygen (ppm), and silicate (ppm) for a station in the Jungfern Passage (264).

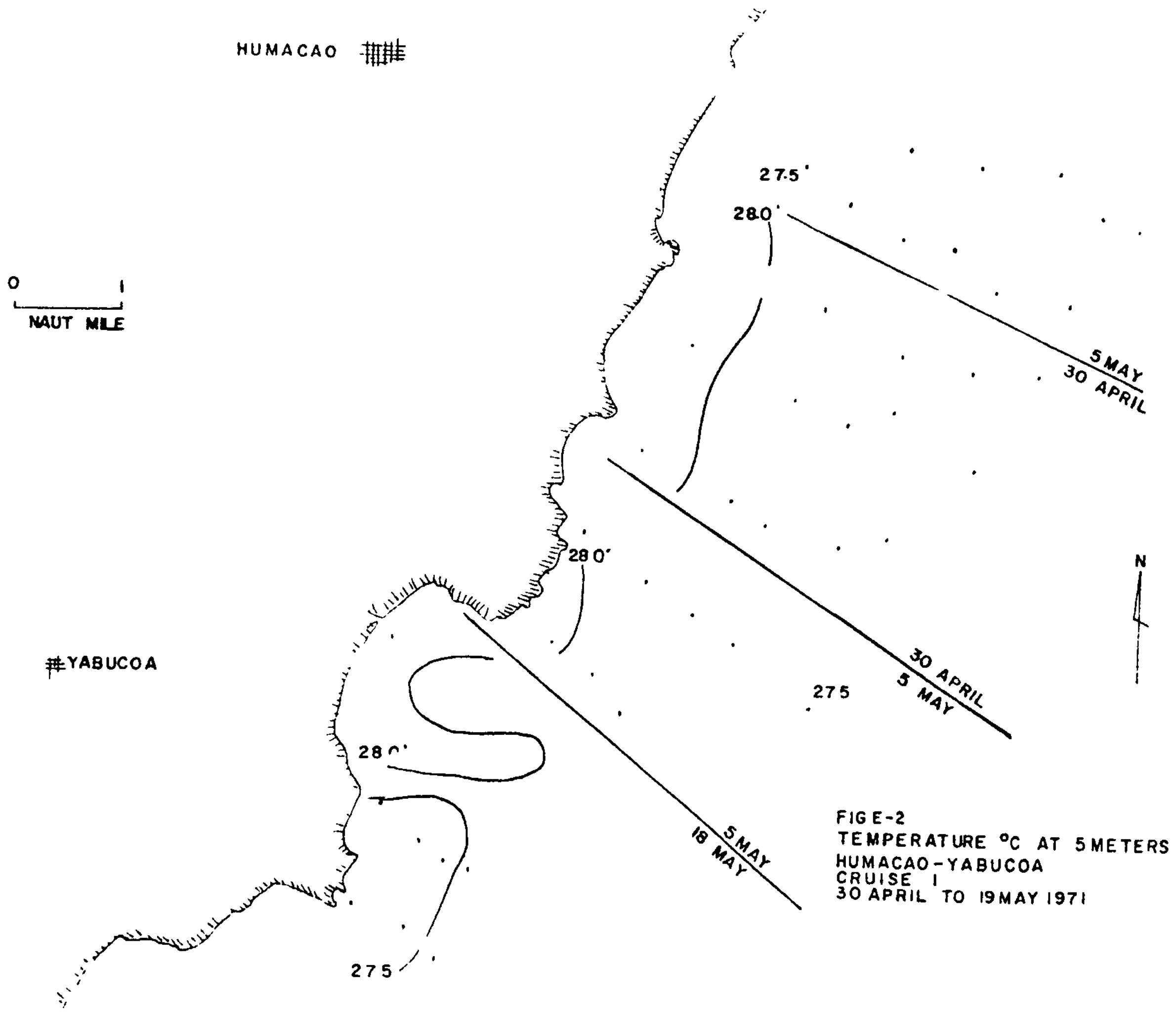


Figure 6.1.6 Contours of temperature in centigrade at a depth of 5 meters for the region of the Puerto Rican site (106).

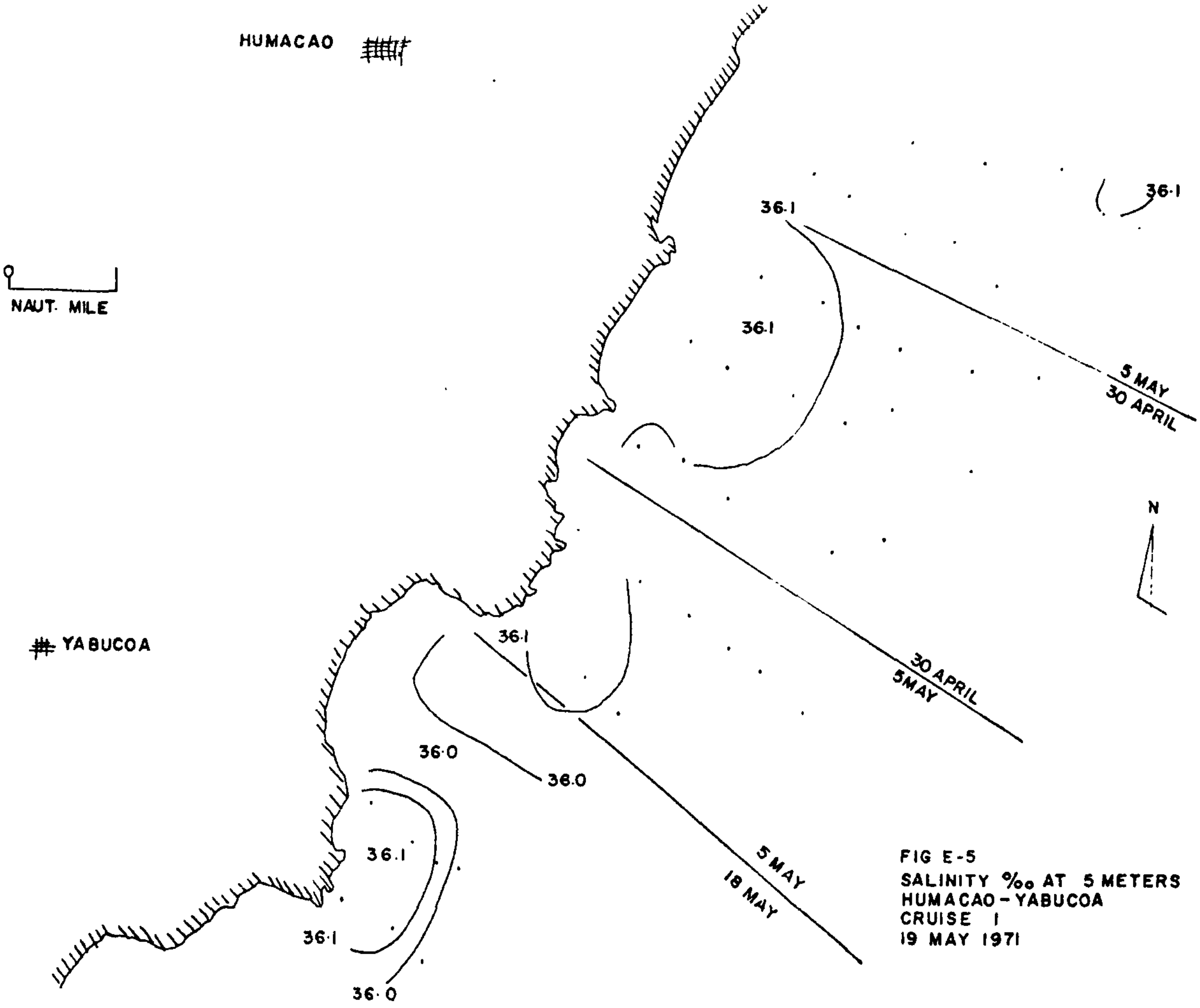


Figure 6.1.7 Contours of salinity in ppt at 5 meters for the region of the Puerto Rico site (106).

in this vicinity [13,16]. Similar velocities occur over the Virgin Island Platform except that near the coast, the currents are deflected southward to join the general westward flow. It has been noted from ship reports that there is a tendency for higher velocities near shore.

Short term meters (Fig. 6.1.8) indicate high southwesterly flow near the site area. The topography i.e. the isobath course and the Virgin Island Platform and Puerto Rican coast juncture appear to serve as a channeling influence on the currents and direct a westward flow around the southwest Puerto Rican coast.

Although all available information shows the prevailing currents are west, both along the northern and southern coasts of the islands, the short term currents may be quite variable and have easterly direction. The improved sampling techniques over the past few years have made the variability more noticable and indeed it is probable that all currents display such oscillation. Large eddies and meanders have been observed in the Gulf Stream for many years [S28,S31]. Recently small eddies called "spin off eddies" as opposed to "meander break off eddies" above have been shown to form and exist at time scales on the order of days [233].

One might expect similar variability in the Puerto Yabucoa vicinity due to being situated downstream from the Virgin Islands and the related sills. It is well known that currents interact with such topographic features to produce waves and shed eddies. Observations near St. Croix show highly variable structure with speeds ranging from 0 to 50 cm/s and having many direction changes especially when the velocity was less than 25 cm/s [234]. Dr. M. Hernandez (personal communication) noted looping current structure from drifter studies near shore along the southwest coast and north coast. Presumably, an interaction between tides, land-sea breezes and changing trade wind velocities induced these motions in which case one would expect such current features elsewhere along the coast. Tides, however, are small everywhere around Puerto Rico, less than 1/2 m, and mixed with diurnal and semidiurnal components [13,S24]. For a pumped system, this is an advantage because fewer pumps are needed to regulate the head (T. Clark, personal communication).

While the Virgin Island chain and other upstream islands may perturb the currents and introduce variability, they also provide some buffer for Atlantic storms. Wind velocity offshore indicates less severe conditions than in the Atlantic but, nevertheless, some rough seas are apparent [11]. In both summer and winter over 90% of the seas approach from easterly quadrants; 3/4 of the winter seas are less than a meter and another 16% less than 1 1/2 meter, in summer 82% of the seas are less than 1 m and 14% less than 1 1/2 meter. About 90% of the time the southeast coast experiences no swell; in winter 7% of the swell is from .3 to 2 m and 2% is from 2 to 4 m, whereas in summer, the values are 8% from .3 to 2 m and 4% from 2 to 4 m.

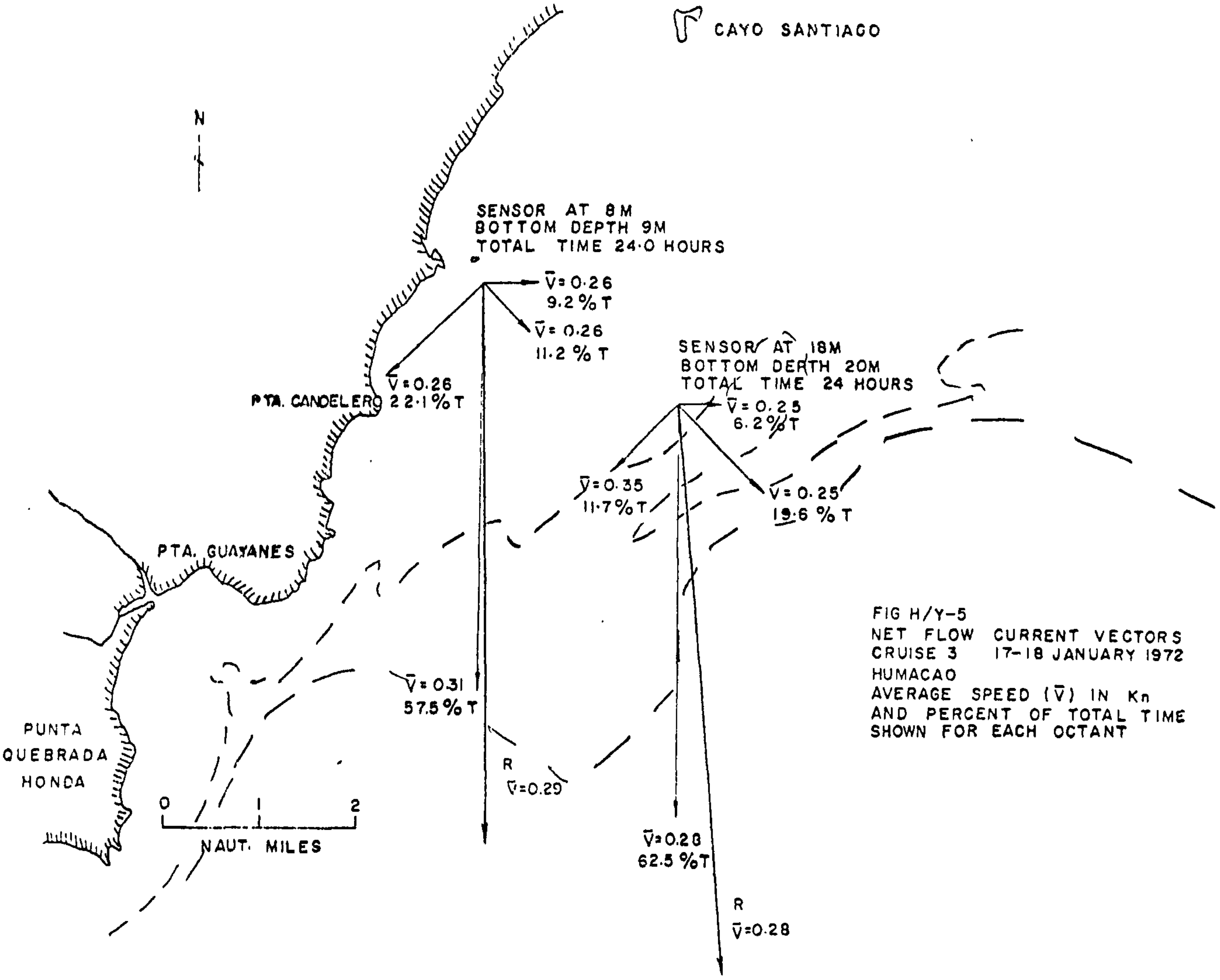


Figure 6.1.8 Short term current meter results for the region of the Puerto Rico site, velocity in cm/s (106).

Since Puerto Rico is a tropical island, the surrounding ocean is relatively barren. Practically the only commercial fishing is some lobstering off the northeast coast. Primary productivity is low with values from 100 to 250 mg C/m day [208]. Highly productive regions such as off the northwestern United States coast have values over 500 mg C/m day. Easterly trade winds impinging on the southeastern Puerto Rican coast are not conducive for upwelling conditions. As an example of relative chemical quantities values at 20 m are given for a station located northwest of St. Croix (Fig. 6.1.5). Dissolved oxygen is 4.35 to 4.89 ppm and the pH is from 8.1 to 8.2. Above approximately 250 m, silicate or nitrate are both less than 2 ppb while, phosphate is less than .5 ppb.

Since productivity is low, a particulate concentration like that of the tropical Atlantic is probable (remember that off the southeast coast deep ocean water is within several kilometers), this value is approximately 30 ppb and mainly of sizes less than 10 micrometers. Since rivers are not particularly large along the southeast coast, sediment carried into nearshore water is probably significantly less than for example off Georgia where values have been found to be as high as 40 ppm in the first 5 km off a shelf whose width exceeds 50 km [34,127]. Therefore, one could take these values as a very worst case estimate for the sediment load in the first several km of shelf along this coast.

6.1.2 Summary of Puerto Yabucoa characteristics

In concluding this section, it is worth noting that in general the waters around Puerto Rico are not well studied compared to other United States coastal waters. Before siting is actually initiated more measurements and model developments are necessary. Details of time and spacial variability are unknown. Nevertheless, it was possible to make some inferences and extrapolate known facts about the tropical ocean weather and offshore currents through the Jungfern-Anageda Passage and over the Virgin Island Platform in order to arrive at probable estimates about the oceanographic conditions in the vicinity of Puerto Yabucoa. The temperature, salinity, particulate and nutrient levels are favorable within kilometers of shore (the shelf width is only a few kilometers). Representative values are 25°C, 34.9 ppt, 30 ppb, and less than 2 ppb (phosphate, silicate and nitrates). The mean current has westward velocities of about 10 cm/s although over short time intervals much variability is observed. Seasonality is minimal both in the oceanographic environment and climate. Severe storms may occur but they appear to be rare events. Fresh water is available, however it is not overabundant. There are large areas of low lands. Sun Oil Company probably made a study of the environment in the Puerto Yabucoa area, both landward and offshore, prior to locating a refinery in the Rio Guayanes valley (built sometime in the early to mid 1970's). With the exception of this structure, the valley is virtually unoccupied. Sugar cane fields predominate across the 8 km of valley here and inland for approximately 10 km. In addition to building the refinery, the company has dredged a channel across the shelf (ca. 2 km) 15 m deep and 170 m wide.

Mention should also be made concerning the chance of encountering unexploded ordinance in this area. The U.S. Navy base, Roosevelt Roads, is located approximately 50 km to the north, and within the region, although north of Puerto Yabucoa, navy exercises are practiced.

Finally, offshore toward St. Croix there is a study being currently conducted for a possible OTEC (ocean thermal energy conversion) plant. Efficient operation of this type of plant also requires similar oceanic conditions, i.e. low productivity, some currents, and warm surface temperatures. Therefore, this area has been found favorable by other groups as well.

6.2 Tidal: Alaska

Except for the possibility of a tidal source of power there are very few features which favor an Alaskan location. Cook Inlet is famous for its tides which magnify going up the inlet. Anchorage has a range approaching 10 m, whereas Seldovia near the mouth has a 6 m range. Tides exceeding 3 m, for the most part, do not exist anywhere else in the U.S. [S24,S25]. Tides are semidiurnal. Accompanying this tidal rising and lowering are ebb and flood velocities which may exceed 200 m/sec [256].

Cook Inlet (Fig. 4.9.1) is a broad, shallow, elongated feature with approximate dimensions of 70 km by 60 m by 400 km (the Oregon-Washington coast is about 800 km long). This represents a volume of 170 billion cubic meters. To put this in perspective consider that for 1000 metric tonnes of uranium a year a plant 100% efficient needs to process about 20% of this volume. The mouth to the inlet consists of 3 entrances east to west (Fig. 6.2.1): Kennedy Entrance at the Kenai Peninsula, Stevenson Entrance and the Shelikof Straits along the western Cape Douglas [S23]. Maximum depths (200 m) in the inlet are at Stevenson Entrance. Cape Douglas forms the western lip and Kenai Peninsula forms the eastern lip. The bottom topography shallows and curves inward around the mouth in an arc between Kenai Peninsula and Cape Douglas [S23].

The surrounding land, as is true for most of the Alaskan Gulf coast, is mountainous, rocky, and pocked with numerous fjords and other embayments, which is one of the disadvantages to the region (Fig. 6.2.2). Freshwater runoff into the inlet is significant although it is extremely seasonal and, for the most part, enters at the upper end. The range is from 100 to 3000 cubic meters/second [17] with the maximum in June and

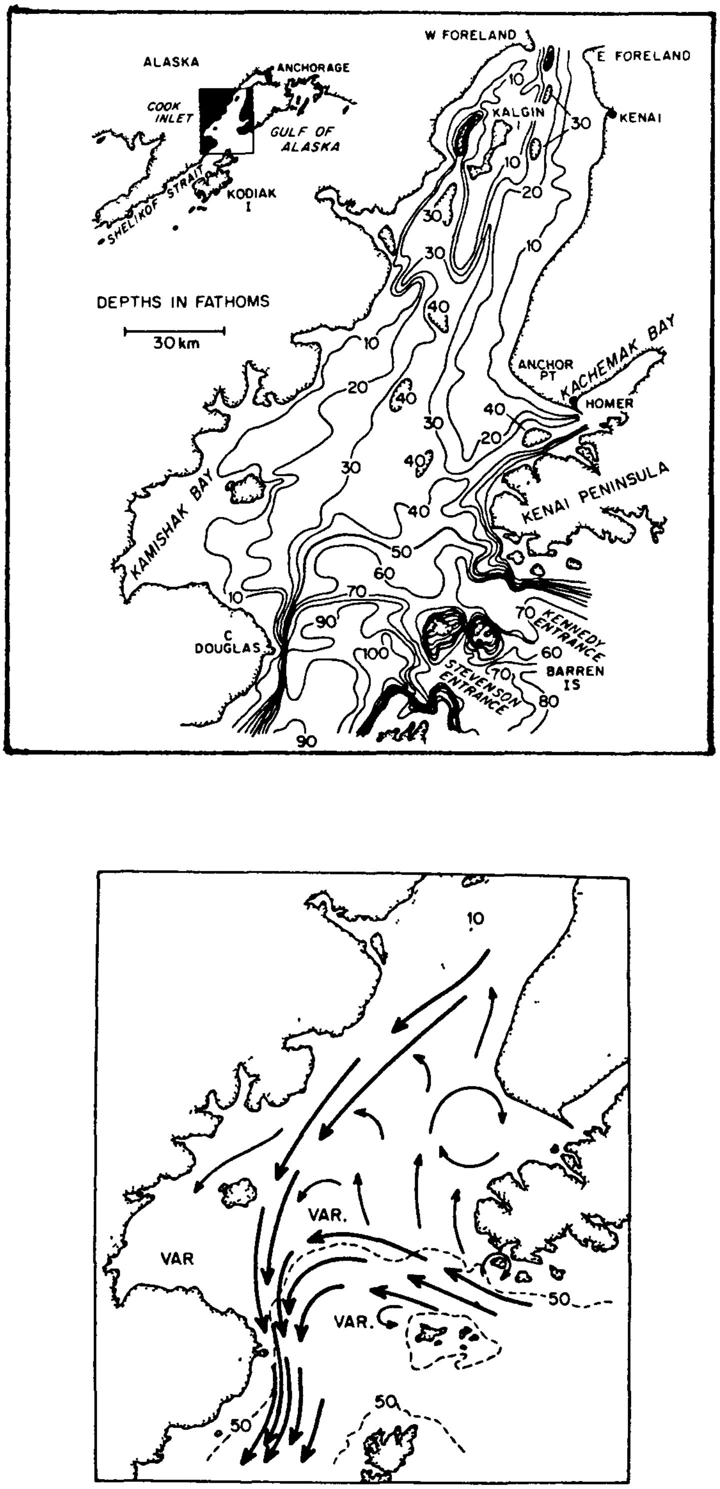


Figure 6.2.1 Topography and currents in lower Cook Inlet Alaska (S23).

July being associated with the spring and summer thaws. The mean discharge into the lower inlet, principally near Homer on the eastern side, is about 70 cubic meters/second.

Large climatological variations are expected. The Aleutian Low atmospheric pressure system located in the North Pacific has a profound influence on the weather over most of southern Alaska. In winter the intensification of this low produces northerly winds and subzero temperatures. Ice forms in most shoal areas, and rivers freeze over. Ameliorating summer conditions bring temperatures of 10 to 12°C, variable but predominately southerly winds, and fewer storms. The low leads to predominately easterly winds offshore in winter and westerly winds in summer [80,S23]. Easterly winds tend to cause a sealevel setup onshore with resultant downwelling, whereas westerly winds will induce upwelling.

Strongest currents in Cook Inlet flow southward in the western third of the inlet (Fig. 6.2.1), offshore from Cape Douglas [S23]. This current converges with another strong flow that enters the Cook Inlet mouth at Kennedy Entrance and moves cyclonically westward along the isobaths [S23]. Together they enter the Shelikof Straits. In winter the southerly flow transports ice as far as Cape Douglas [80]. Offshore circulation is dominated by the Alaska Current, which is a westward flow about 70 km offshore along the shelf break [80,116]. This current drives the westerly flow mentioned above. Mean values may be on the order of 10 cm/s [80,116] for these currents; however, regions have strong tidal signals such as in Kennedy Entrance and the Forelands, a constriction midway up the Inlet. Typical high velocities are 100 cm/s although greater currents exist at the Foreland and further north [256]. The eastern side of Cook Inlet has weaker northward flows with a mean value of about 2 cm/s [S23]. An important feature found in recent current meter records is frequent events on the scales of 3 to 4 days [S23]. Velocities of these events may be 30 cm/s; therefore, the overall velocity structure (a combination of tidal currents and oscillatory currents superposed on the average geostraphic flow) results in marked variability in the flow field.

Ocean temperature and salinity has a strong annual cycle and basically is of poor magnitude from a uranium extraction standpoint. Late summer typically found waters of 11-12°C and 29-31 ppt, while in spring corresponding values were 4-5°C and 30-32 ppt [S23]. One would expect winter values to be colder and perhaps somewhat saltier depending on the extent of ice formation. (Sea ice formation excludes salt as a brine from the ice crystal lattice thereby increasing the salinity of the surrounding water). In spring the colder temperatures tend to be in the northern areas of the inlet and in summer the southern central regions are colder. This is believed to be in part due to upwelling in the southern areas [S23]. Salinity decreases northward in all seasons although late summer also shows low salinity in the eastern regions near Kenai Peninsula. This is thought to be caused by advection of low salinity water from regions further east along the coast [S23]. Since

Figure 6.2.2 Seldovia, Alaska Quadrangle (composite of A-4,A-5,A-6); USGS 15 minute series (topographic). Scale is 1:63360. Contour interval is 100 feet and depth curves and soundings in feet at mean low water. This region is at the eastern side of the entrance to Cook Inlet.


(SELDOVIA B-5)
59°15'
151°52'30"
151°30'
KOYUKTOLIK BAY
Port Chatham
Portlock
Chatham Island
Clam Cove
Chrome Bay
Chrome
Kelp Point
Clam Point
Cabin
Cabins
Mud
Cone Mtn
Rock Mtn
Windy Bay
WINDY BAY
Badger Hill
CHUGACH BAY
Cabins
ELIZABETH ISLAND
Cape Elizabeth
Elizabeth Island
CHUGACH ISLANDS
CHUGACH PASSAGE
PERL ISLAND
Nagahut Rocks
Perl Rock
Dora Reef
East Chugach Island
EAST CHUGACH ISLAND
CHUGACH ISLANDS
R 13 W
SCALE 1:63 360
CONTOUR INTERVAL 100 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929
DEPTH CURVES AND SOUNDINGS IN FEET-DATUM IS MEAN LOWER LOW WATER

the principal source of low salinity water is from runoff in the headlands at the north of Cook Inlet and it roughly takes 3 months for the low salinity signal to arrive at the mouth of the inlet, a crude estimate gives a southward net velocity of 5 cm/s.

Compared to its aerial dimensions, Cook Inlet is quite shallow. Hence, the vigorously tidal mixing results in a water column of weak stratification. Bottom temperature and salinity values are not much different from the surface. In winter the bottom values may be slightly warmer and saltier provided there is no overturning. Summer will find the surface waters somewhat warmer and fresher. Throughout the water column in any season, however, it will be indeed rare to find water over 13°C and 32.5 ppt. These features, i.e. the stratification and current structure, have led some researchers [S23] to consider Cook Inlet physically more similar to a large embayment than an estuary which it is by strict definition. Estuaries have deep inflow and surface outflow; remember that, to a large extent, the inflow appears to be a broad weak surface flow along the eastern side of the inlet.

It is informative to do some first order calculations bearing in mind tidal currents of 100 cm/s and mean currents of 10 cm/s. In six hours at 10 cm/s the distance covered is about 2 km. Tidal currents translate 20 km. Therefore, it is entirely possible for tidal currents to back flush seawater past a point over the time of several tidal cycles. An oceanic horizontal diffusion coefficient of 10^7 square centimeters/second (probably an unrealistic maximum value, 10^5 square centimeters/second is probably better) gives a characteristic (e-folding) length of 9 km in 6 hours so that diffusion at best can occur only on the same scale as advection.

In view of the likelihood of limited flushing within Cook Inlet, we feel a location at the mouth of the entrance may be more favorable. This would be either in the vicinity of Cape Douglas or in the nearshore islands along the Kenai Peninsula (Fig. 6.2.2). Of these two, the latter is favored for several reasons. Cape Douglas is part of a National Monument and, more important, its feed stream would consist of a large portion of Cook Inlet water. The Kenai region is bathed, on the other hand, by water derived from the Alaska Current [256]. Both regions are extremely rough topographically, do not have large freshwater discharges, and are remotely located. However, fresh water sources appear closer to the Kenai vicinity and population centers are closer. Due to proximity to shipping lanes, transportation is probably as good as may be expected for any Alaskan site. As mentioned in the general area introduction, this is a very seismic zone with an increased probability of earthquakes and tsunamis.

A serious drawback to this location is that the mouth of Cook Inlet is a rich fishing ground. The richness of the area is probably linked to the approximate westward flow arcing around the mouth which favors an upwelling situation [S23]. The winds aid, at least in the summer, to this upwelling. A plant located on either side of the mouth is likely to threaten these grounds because of its impact on the western current. This is particularly true of a site on the Kenai Peninsula. Using a 10 cm/s flow through the Kennedy Entrance yields a volume transport only about 10 fold greater than what the plant needs. Removing this much mass and energy from a current system seems likely to have serious implications on current dynamics.

6.3 Alternatives; Pumped: South Atlantic

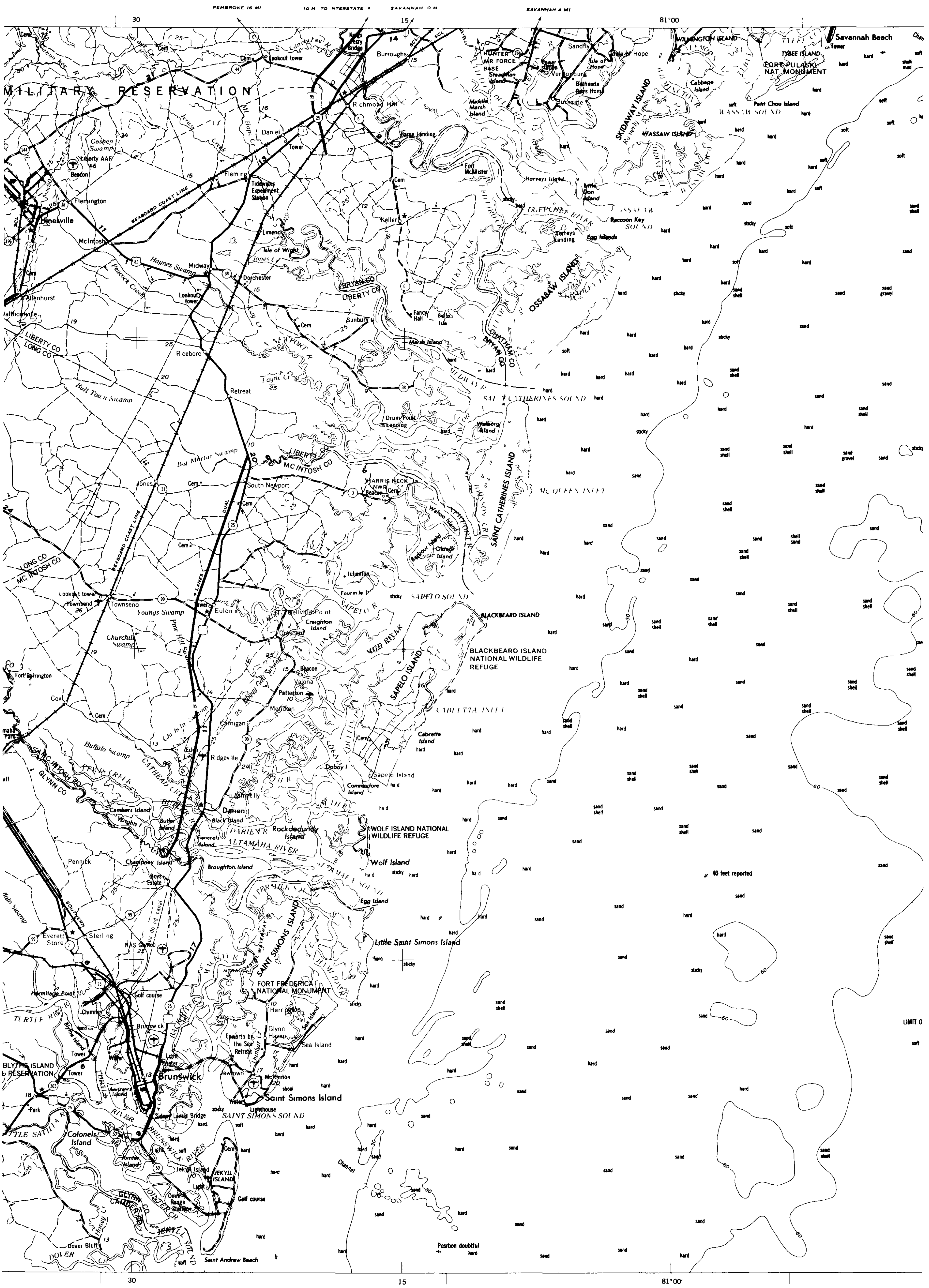
As mentioned in section 4.6 the South Atlantic may be considered for plant location. Because of the warmer saltier waters and proximity of the Florida Current, the southern Florida coastline is substantially better suited than the regions of Georgia and the Carolinas. Georgia and South Carolina offer far better availability of fresh water, and coastal land (Fig. 6.3.1). This land, however will be swampy and most likely protected as parklands and such (Fig. 6.3.2). Another point to make about the relative merits of these two localities is the increased particulates in suspension off the Georgia and South Carolina coasts (Fig. 6.3.3). This is probably due both to the greater runoff and wider continental shelf which prevents the Gulf Stream from sweeping the inner shelf. However, the disadvantages of higher sediment load, cooler, less saline water, and distant current could be remedied to some degree, provided additional pumping expenses are acceptable. Pipelines could be extended for tens of kilometers offshore in order to provide better access to Gulf Stream waters. The expense would probably be substantial due to construction, maintenance and pumping. The size of the pipelines would necessitate their burial, otherwise their structure would have a serious impact on the circulation regime. The greater distances offshore for the intakes would imply greater depths, for example, at 50 km offshore depths can be over 40 m. In terms of temperature, salinity, and particulates, intakes located at these depths have advantages. The temperature range is warmer and reduced (18 -26°C) and salinity is higher (>35 ppt) [34,374] because the effects of the seasonal heating and runoff cycle are buffered. Particulate concentrations are in the .01 ppm and less range [77,248].

Seasonality is minimal off Florida's southeastern coast (Fig. 4.2.1). Temperatures and salinities are high with values of greater than 24 C, 35.5 ppt [233,S17] year round. Suspended particulate concentrations are low, less than .1 ppm [248]. These values can be expected to hold within several kilometers of shore. Within 4 to 8 kilometers is the intense northward flowing Florida current. Hence oceanographic conditions suggest Florida being more optimal than the rest of the south Atlantic. However, fresh water availability is poor unless pumping from sources further inland is considered, and most of the coastline is also densely settled. Two regions where population pressure maybe somewhat minimized are around Boca Raton (near West Palm Beach) and the northern parts of Key Largo which has approximately 15 square kilometers of area on its northern tip. For southern Florida localities, it seems reasonable to expect high capital outlay to purchase land and acquire fresh water.

This report has mentioned numerous times the importance played by ocean currents in choosing a site for plant location. A steady voluminous flow is highly desired, even prerogative. For this reason the southeastern Florida region may be one of the "ideal" locations in the world. It has the Florida Current, a major component of the Gulf stream, only a few kilometers offshore. This current is part of the western boundary current system, hence it will carry warm, salty, relatively clean water northward. However, the omnipotent and ever present oceanic variabililty, while by no means reducing the importance of ocean currents, makes it difficult to assess the impact and reliability of current regimes in any area of site location. A high degree of variability in the current structure of the Florida Current and Gulf Stream is well documented [233,284,S16,S17,S28,S31]. These variations, often manifested as eddies and meanders, are an important and much studied problem in current oceanography [S22,S28] and at this point pose challenging problems to modeling the circulation on the global [S33] as well as local scale. Therefore the problems involved in interpreting and predicting the nearshore circulation will have to be accepted and recognized for any area of site selection. Since the Florida Current and Gulf Stream have been so extensively studied, one of the advantages of southern Florida is that a great deal of research has already been done in this circulation regime.

The type of variability seen within the Gulf Stream and Florida Current on various time and space scales result in velocity changes, speed fluctuations, and spacial and temporal changes in location; the latter two do not necessarily result in directional changes. It is the changes in direction which will have the most serious consequences for the plant pumping because of the danger of reprocessing seawater already depleted with respect to uranium. The large eddies observed in the Gulf Stream are sometimes called break off eddies and occur when meanders in the current "pinch off", or close on themselves. Scales may be on the order of several hundred kilometers and have lifetimes of many months and speeds ranging from 5-50 cm/s [S31]. The large, long lifetime eddies (200 km, 1 yr) seem to generaly originate downstream from Cape Hatteras as growing instabilities in the Gulf stream. These eddies move counter to the main current and coalesce back into the main flow in the vicinity of Cape Hatteras. Meanders of approximately 50 km scale move onto the shelf in the Georgia-South Carolina region on varying time scales [374] and on shore flow has been measured at depth [83]. Southward counter flow in shore of the Gulf Stream has been measured by drift bottle studies [42] and inferred from the density distribution [374]. Gulf Stream coupled eddies have also been observed drifting to the north [S16]. The width of the shelf in this region reduces the effectiveness of this coupling and therefore wind driven current phenomena are believed to be also important (S16). It is useful to assume a 20 cm/s velocity and a triangular cross section offshore with dimensions of 50 km and 40 m

Figure 6.3.1 Brunswick, Georgia; USGS topographic series. Scale is 1:250000. Contour interval is 50 feet and depth contours are also in feet.



Scale 1 250,000

5 0 5 10 15 20 Statute

5 0 5 10 15 20 25 30 Kilometers

5 0 5 10 15 Nautical Miles

CONTOUR INTERVAL 50 FEET
WITH SUPPLEMENTARY CONTOURS AT 25 FOOT INTERVALS

TRANSVERSE MERCATOR PROJECTION

1965 MAGNETIC DECLINATION FROM TRUE NORTH FOR THIS SHEET VARIES FROM 0° (00 MILS) FOR THE CENTER OF THE WEST EDGE TO 1½ (30 MILS) WESTERLY FOR THE CENTER OF THE EAST EDGE

FOR SALE BY U S GEOLOGICAL SURVEY WASHINGTON D C 20242

depth (see section 4.6). This gives a volume transport of 0.4 million cubic meters/second. A 1000 tonne/year uranium extraction plant at 100% efficiency must process about 5% of this volume, therefore the plant is approaching environmental scales.

Off of Florida another type of eddy fluctuation has also been observed (Fig. 6.3.4) which is coupled to the mean current. These are called "spin off" eddies [233,S17]. Their characteristics are an east-west length of 10 km and a north-south length of 20 to 30 km, with a northward translation speed of about 25 cm/s. Speeds within the eddies themselves may exceed 50 cm/s. They can form as frequently as every 1 to 2 days and live for several weeks [233,S17]. They are also believed to occur all along the Gulf Stream. When bottom topography is less than approximately 10 m the eddies apparently cannot exist. The volume of water contained in one of these eddies of minimum size is about 1 billion cubic meters which is about the volume needed to get 1 tonne of uranium ore a day. Since flushing of processed seawater is most reliably accomplished by a quasi-unidirectional flow, these freqently occurring small scale eddies will be difficult to deal with. Their probable occurence in any current means that no oceanographic region is ideally suited for the plant.

Figure 6.3.2 Landsat black and white (band 4) of the same area as figure 6.3.3. Notice the sediment plumes of lighter shade along the coast.

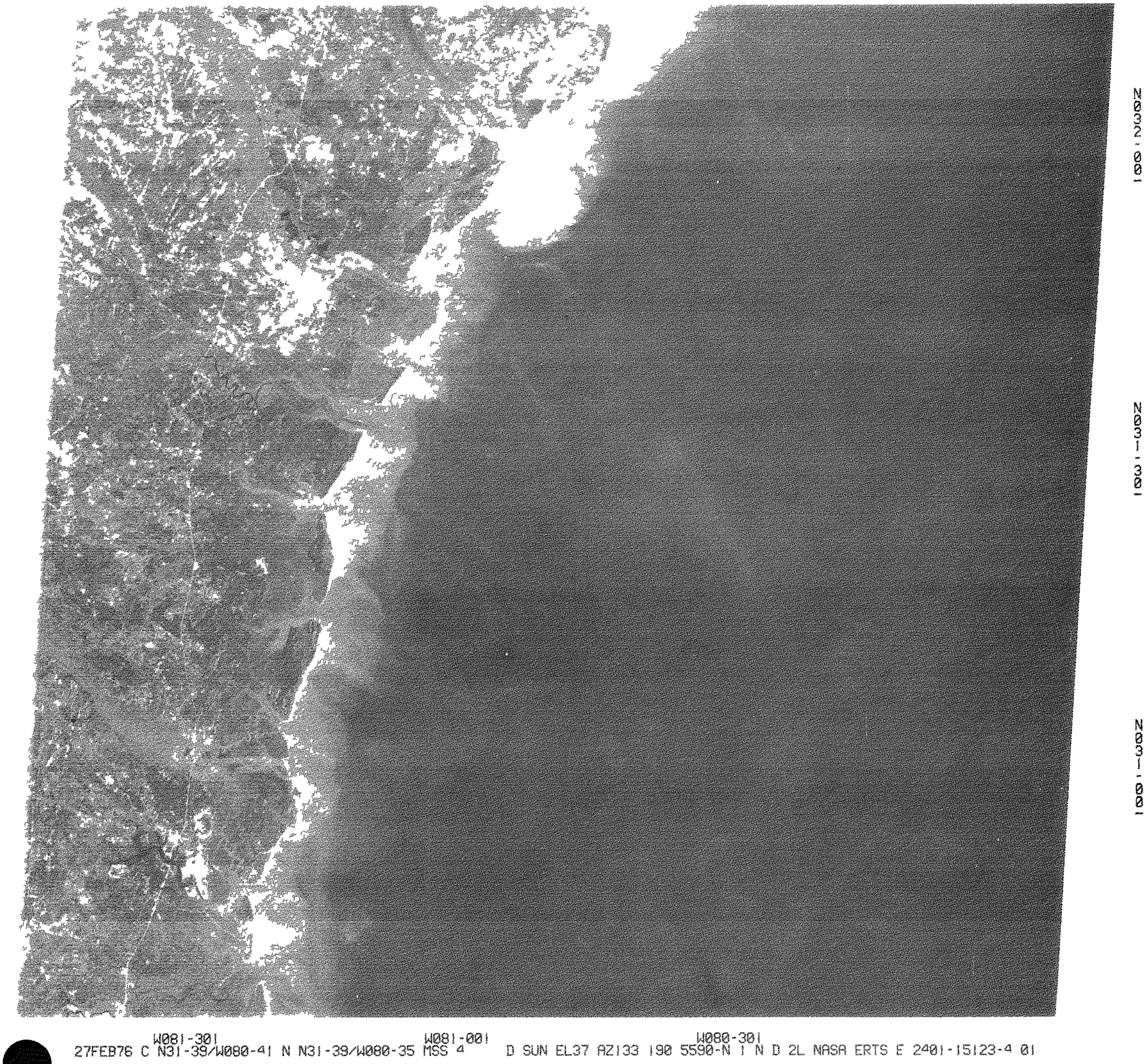

N032-00
N031-30
N031-00
W081-30
W081-00
W080-30
27FEB76 C N31-39/W080-41 N N31-39/W080-35 MSS 4 D SUN EL37 AZ133 190 5590-N 1 N D 2L NASA ERTS E 2401-15123-4 01

Figure 6.3.3 Landsat enhanced color composite of the Georgia and South Carolina coast. The dark area near the coast are wetlands seperated from the shoreline by barrier islands. The following is a synopsis of bulletins put out by the USGS, EROS data center concerning ERTS (Earth Resources Technology Satellite) and Landsat imagery. The satellite passes north to south and covers the globe in 18 days, viewing the earth at each latitude at the same local time with each pass. Each scene is at a scale of 1:1000000 and each side is 185 km. The scene is a distorted square due to the earths rotation. Through multiband scanning and controls it is possible to investigate features of dimensions near 20 m. The principal tool aboard the satellite is the multispectral scanner. Four bands are scanned: Band 4- (.5 to .6 micrometers, the green band) is good for delineating sediment laden water, shoals, reefs etc. Band 5- (.6 to .7 micrometers, red band) is good for viewing metropolitan areas. Band 6- (.7 to .8 micrometers, near infared) is good for viewing vegetation cover and land-water boundaries. Band 7- (.8 to 1.1 micrometers, far infared) is useful for the penetration of haze. The black and white photograph included here is at band 4. The color photograph is an enhanced or false color image produced by filtering 3 of the 4 bands and making a composite of them. In this case the bands used are 4, 5 and 7. Information about each photo is contained in the scale at the bottom. Pertinent blocks of information left to right are: date of exposure, latitude and longitude of center of image, latitude and longitude of perpendicular to satellite, spectral band , sun angles, and the last 15 characters are a unique image number.

USGS EROS DATA CENTER

03APR76 C N31-48/W080-33 N N31-48/W080-29 MSS SUN EL49 AZ122 190-6092-N-1-N-P-2L NASA ERTS E-2437-15112-5 01

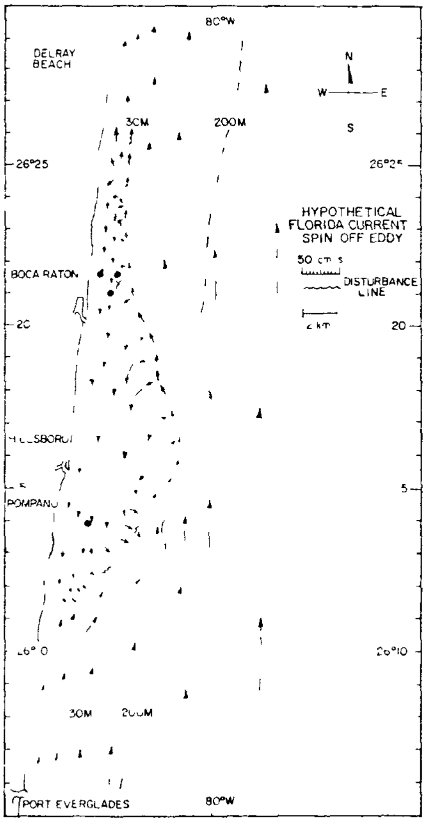


Figure 6.3.4 Current variability in the form of a spin-off eddy is shown landward of the northward flowing Florida Current (233).

CHAPTER 7

OTHER CONSIDERATIONS

Legal, environmental and social matters will be very briefly raised in this chapter. The main emphasis will be upon environmental considerations. We will essentially confine ourselves to the case of a pumped systems plant in a coastal location.

7.1 Legal

Legal considerations are quite outside the purview of this study except for possibly one or two points which might be raised. Ignored completely here are legal procedures which would be followed in order to comply with zoning, land use and other regulations. However two points should be made. First, many states and territories are placing increasingly stringent coastal zone management regulations on their books. These will make for increasing complexity of the legal procedures to be followed when initiating plant site acquisition and plant construction. Second, the construction of an extraction plant of the scale considered herein will inevitably influence local physical, chemical, biological and geological processes. While as will be pointed out in the next section, present technology can mitigate the impacts of these influences, even relatively small fisheries alterations or erosion effects, be they deleterious or even beneficial, could raise legal questions. These should be anticipated.

7.2 Environmental

Only a few specific points will be raised here. The large scale of the extractions plant in itself will have two important impacts. First, the physical plant will occupy a great deal of coastal land and inshore water. This will impact upon recreational and other uses. Second, the magnitude of the feed stream approaches significant fractions of most coastal current systems. Thus, any oceanographic process affected by local currents will be affected. This includes the local ecosystem as well as geologic processes such as sediment transport, beach erosion, etc. It is important to note that some segments of the local ecosystem could be improved by the structure and water movement of the plant, for instance, food and sport fishery populations.

Thus far only the environmental effects of the plant structure and water movement caused by the pumped stream have been addressed. There are of course also the effects of introduction of suspended fine grained absorbent and plant processing waste streams to be considered. Two points are most important here. First, the hydrous titanium oxide selected as the primary absorbent is a very inert material. Its effect on the local biota and beaches would most likely be similar to commonly occuring turbid river sediments. Second, with regard to both absorbent loss and loss of plant process streams it must be noted that, especially for such a large scale plant, materials losses would have to be kept at very low levels for economic reasons. This acts in favor of mitigation of untoward impacts. A final point is that the sheer volume of the plant outflow stream would serve to dilute what losses do occur to tolerable levels in the environment.

In summary, it would seem that available technology can minimize evironmental impacts. For a more complete discussion of this topic the reader is directed to the Feasibility Study.

7.3 Social

Again, this topic lies outside the authors' fields of expertise. However some marine related considerations may be noted here. First, although the plant configurations suitable to the extraction of uranium from sea water were not particularly labor intensive (see the Feasibility Study) they would nonetheless employ large numbers of persons in their construction and operational stages. This would create a new marine industry in the region of the plant site. Many of the planning and operational tasks would require marine oriented skills.

Second, the strong possibility exists that the plant's offshore structures would enlarge or create sport and food fisheries similar to what is commonly observed with offshore oil platforms. These would constitute secondary factors having social impacts, presumably beneficial.

Countering these examples of desirable outcomes would be the loss of recreational and tourist uses of the area. The overall balance of these social impacts could be better evaluated by others than ourselves.

CHAPTER 8

FURTHER RESEARCH AND DEVELOPMENT

Several research and development requirements were found during the execution of this program. They will be identified and discussed in the following sections.

8.1 Resources and Chemical Processes.

a) It was concluded in Chapter 2 that 98% of the uranium ion in seawater is associated with carbonate ions in the form $UO_2(CO_3)_3^{4-}$. However, the association constants used for the calculations were not measured in seawater. Although it is suspected that they do not vary appreciably with the change of media, only direct measurements in seawater can verify this. Further, the chemical state of uranium in seawater was only calculated at 25°C due to the lack of association constant data at other temperatures. Laboratory measurements of association constants at various temperatures that cover the oceanic temperature range are needed.

b) It is known that the uranium concentrations in seawater vary linearly with salinity in the open oceans (see section 2.2). However, no detailed information is available on uranium concentration near the selected plant sites. Direct measurements throughout the year are needed in order to obtain exact data on the uranium concentration in the source seawater near the plant sites. The concentrations of potential co-products, such as vanadium, should also be measured.

c) Since the pH and Eh of source seawater might affect the kinetics of adsorption, those values should be measured. Highly variable concentrations of trace metals, such as copper, must be measured and documented in order to assess their poisonous effects on the adsorbents.

d) Concentrations of elements that contribute to the clogging, fouling and scaling of seawater pipes and adsorbents must be measured. The important factors to monitor are: calcium, alkalinity, nutrient and organic matter concentrations, plankton and marine life densities and sediment load.

e) Uranium concentration in various strands of plankton and other marine organisms should be measured and the ones with high concentrating power should be cultured. This study not only explores a potential means of concentrating uranium from seawater, but may also lead to a better understanding of the mechanisms of uranium extraction.

8.2 Site Selection and Environmental Impact

a) A good knowledge of the general circulation of currents exists. However, detailed information on the localized nearshore flow patterns is often lacking. The seasonal variability in the flow direction and maximum, minimum and average velocity of the nearshore currents is also poorly understood and should be studied in detail for regions near the proposed plant sites. Numerical models must then be developed to analyze in detail the circulation patterns and the effects that plant structures and effluents will have on these patterns.

b) Detailed information on wind speeds, wave heights and other oceanographic characteristics, such as swells, tides and possible storm surges, need to be collected for the geographic regions of interest.

c) In depth local geological information for adequate civil and structural design is not available for the proposed sites. Collection of this information is one of the major steps preparatory to the construction of the plants.

d) The large volume intake and outflow can form very strong local currents which might affect fishing and shipping activities. The discharge might also stir up the bottom sediments, erode beaches and redistribute the resuspended particles. Detailed models must be developed to assess these effects.

e) Impingement and entrainment are potential problems for marine life. Careful studies must be conducted to make sure that no endangered species will be harmed by the uranium extraction plants. Every effort must be made to minimize the impact on marine life.

f) The redistribution of sediments might increase the turbidity of seawater and decrease the availability of solar energy below the surface. The resulting impacts upon the biological productivity need to be studied.

g) The impact upon marine life of the residual discharge from the elution and the loss of adsorber from either the normal processes or accidents must be studied. The chemical state and toxicity of titanium, the metal used in the most promising adsorber to date (See Feasibility Study), is poorly known and should be investigated. A program must be initiated to evaluate and investigate alternative environmentally acceptable methods for the disposal of any potentially harmful discharges. Basic guidelines and methodology must be developed for trade-off between economic and environmental concerns.

h) Environmental monitoring programs must be initiated to achieve baseline information on the biological, chemical and physical characteristics of the surrounding region so that any impacts after the plants are in operation can be determined. The monitoring programs must be continuous in order to assess the longterm effects.

i) The success of the project depends heavily upon the cooperation of the local community. Since public acceptance is essential, studies should be made to find out the possible reaction of the local community to the project.

j) A detailed environmental impact statement has to be prepared for the environmental protection agencies at the local and federal levels. The document should disclose the environmental effects of the extraction plants, effects of the operation of the plants on the economic and social welfare of the community, and measures proposed to minimize any adverse effects.

CHAPTER 9

CONCLUSIONS

The possibility of recovering uranium from the sea has been considered on the basis of the existing literature. Several important conclusions are now summarized under the topics, resource evaluation and site selection.

9.1 Resource Evaluation

a) The concentration of uranium in the oceans appears to be linearly correlated with salinity. At a salinity of 35 ppt, the uranium concentration is 3.3 ppb, which represents oceanic uranium content of 4 billion tonnes. The accessible ocean currents can supply virtually unlimited amounts of uranium for extraction. For instance, the Gulf Stream circulates over ten million tonnes of uranium annually. The cost at which the uranium is extracted from seawater might very well serve as a baseline maximum cost of uranium to be considered in the future [54].

b) Most of the uranium in seawater forms anionic uranyl carbonato complex ions. At 25°C and pH 8.1, approximately 98% of the uranium in seawater combines with carbonate ions to form $UO_2(CO_3)_3^{4-}$ and 1.7% of the uranium forms $UO_2(CO_3)_2^{2-}$. Two species of hydroxides; $UO_2(OH)_3^-$ and $UO_2(OH)_2$ take up the rest of the uranium.

c) The supply of uranium to the oceans is continuous at a rate of approximately 9,000 tonnes per year by continental weathering and river runoff. The input is to the surface layers of the sea and is, therefore, accessible.

d) River waters in general have lower uranium concentrations than seawater. Some rivers do have high uranium concentrations but their volumes of flow are so much less than ocean currents that the rivers are a less favorable uranium resource. For instance, the Mississippi River discharges only 550 tonnes of uranium annually compared to the ten million tonnes circulated by the Gulf Stream.

e) Shells, sediments and other marine deposits have variable concentrations of uranium. These concentrations are usually lower than those in ores which occur on land and for this reason their materials do not seem to constitute attractive resources at present.

f) It was concluded that it is impractical to combine desalination plants with seawater uranium extraction facilities because of the limited capacity of the desalination plants. The available uranium production from the largest desalination plants under consideration today is only 1 tonne per year [242].

g) Coastal power plants circulate limited amounts of seawater for cooling purposes. Again the amounts are too small to be considered useful in the present context. Further, these plants are often located in estuaries where uranium depleted water would be trapped and more or less poorly flushed. Even assuming continuous uranium supply and 100% recovery, the U. S. coastal power plants would have a total capacity of producing only 70 tonnes of uranium annually.

h) Certain species of marine organisms have the ability to concentrate uranium in their tissues. Considering the observed concentration factors observed so far it is at present impractical to "farm and harvest" marine organisms on the scale under consideration here.

i) Vanadium appears to be the only possible co-product although it is economically unfavorable to extract at present. This subject is discussed in the Feasibility Study.

9.2 Site Selection

a) A number of stringent conditions to be met for plant siting were discussed. The important ones are as follows: Constant, dependable uranium supply; high naturally occurring seawater salinity and temperature; low risk of fouling; favorable topography, geography, demography and geology; mild climate; low use conflicts and minimal environmental impact.

b) Floating plants and platforms were considered unfavorable in this feasibility study of uranium extraction from seawater. Therefore, potential sites for such configurations have not been treated in this report. Although this is also discussed more fully in the Feasibility Study, it may be stated here that experience with large scale operations of this type was inadequate to permit an economic feasibility estimate. However, future improvement in technology may favor these schemes.

c) Cook Inlet, Alaska was identified as the most likely plant site if a tidal system was to be used. The site was described in detail although it was recognized that a tidal system was rated as the second choice in the Feasibilty Study.

d) Punta Yabucoa, Puerto Rico was identified as the prime choice for a plant site for this feasibility study. The important features that led to this choice were:

- The location is less than three kilometers from the continental shelf edge where the warm, strong and steady Antilles Current brings a constant resupply of fresh seawater to the bay and takes away the plant discharge.
- An area of more than six square kilometers of the river flood plain adjacent to the shoreline is less than three meters above mean sea level.
- An estimated 40 million gallons (150,000 cubic meters) per day of fresh water is available for process use. Storage reservoirs that would double the supply are feasible (See Feasibility Study).
- The present human population density of the area is low.

e) Several topics requiring further research and development were revealed during the execution of this project. They were identified and discussed in the previous chapter. Briefly, they are:

- Much better measurements of the association constants of the complex uranium chemical species which occur in seawater. No direct measurements over the range of seawater temperatures, or indeed directly in seawater itself have ever been made.
- Direct measurements of the actual uranium concentrations in the local waters of the most favorable U. S. territorial sites should be made as soon as possible. Analagous measurements must be made for any potential co-products.
- Concomitant data also required for potential sites include the oceanic chemical parameters which would affect the extraction process, either for the better or worse, e.g. dissolved oxygen levels, pH and oxidation-reduction potential of the sea water, trace metals which might interfere with the extraction and as a baseline against which to monitor contamination by the plant, inorganic and biological fouling parameters, etc.
- Biological concentration of uranium from seawater should be studied both as a potential, if low volume, source and for the possibility it offers of potentially improved inorganic extraction processes.
- Site selection information is in general much too meager for the needs of accurately evaluating the feasibility of the oceanic uranium resource. Detailed information on local currents, meteorological, climatic, geographic, and geologic data are required. Much undoubtedly exists which could not be accessed and collated for this limited study, and more should be done in that regard.

- The large volume of the process streams considered in this study constitute a very significant fraction of the local currents at any site considered. The effects of such process streams should be modelled hydrologically, and considered from geological, biological, and chemical viewpoints as well.

- Environmental and societal impacts will also have to be treated in great depth considering the requisite huge physical scale of the extraction plant required. Although it appears that these impacts are amenable to mitigation by current technology, certainly the scale considered here will challenge that technology.

APPENDICES

APPENDIX I

GLOSSARY OF TERMS AS USED IN THIS REPORT

absorption	- strong attachment of a substance to an absorber by penetration of the substance through the absorber surface.
adsorption	- the condensation of gases, liquids or dissolved substances onto the surfaces of liquids or solids, usually due to attraction of opposite charge.
anaerobic	- airless; often used interchangeably with anoxic although this is not rigorously correct.
anoxic	- in the absence of oxygen.
anticyclonic	- a clockwise rotation of fluids in the northern hemisphere and a counterclockwise rotation in the southern hemisphere.
barrier islands	- low lying fringes of land skirting the shoreline, usually having relatively thriving ecosystems.
BFEC	- Bendix Field Engineering Corporation.
bight	- a bay formed by a bend of the coastline.
biological productivity	- generally some measurement or estimate of the amount of new biological matter formed, often given in terms of mass of carbon or tissue per unit sea surface area per unit time.
brine	- a solution that is very concentrated (often near saturation) in dissolved salts. Brines occur naturally, as in deep pools in the Red Sea, or as a result of seawater treatment such as from some desalination techniques.
chemical species	- the particular form that a chemical element takes in a certain set of conditions. The term embraces molecular, ionic, complexed, colloidal, or other forms.
colloidal	- refers to substances with large molecules or containing large aggregates of molecules. Colloidal particles suspend in the solution and do not settle out.
continental	- usually defined as the shallow water platform that

continental slope	- the term used to describe the steeper (3 to 6 degrees) portion that runs from the continental shelf "break" to the sea floor.
cyclonic	- a counterclockwise rotation of fluids in the northern hemisphere and a clockwise rotation in the southern hemisphere.
desalination	- the process of removing salts from seawater in order to produce fresh water.
DOE	- United States Department of Energy.
downwelling	- vertical downward motion of water; see upwelling.
ecosystem	- a community of living organisms, together with its environment, considered as a unit.
eddy	- a rotating flow of water or air embedded in or running as part of the main current.
effluents	- liquid discharges.
Eh	- a measure of the oxidation-reduction potential of a solution. Positive Eh values occur under oxidizing conditions and negative values indicate a reducing environment.
elution	- a selective process of stripping attached species from an adsorption medium, usually by washing with a solution having a greater chemical attraction than the species of interest.
ENC	- Exxon Nuclear Company.
estuary	- a coastal section or embayment, with a fresh water input, that generally provides a unique ecosystem owing to its shallow depth, enclosure, salinity range and stratification, tidal flushing and nutrient accumulation. However, many other factors are involved in estuaries.
fouling	- growth or accumulation of some biological or chemical material which interferes with the operation of a system.
gyre	- a large scale circular or spiral motion of currents like that of the general surface circulating in each hemisphere of each ocean.
interstitial water	- that water which occupies the volume between particles of sediment.

ion exchange	- a chemical process used to selectively replace ions in solution with other ions of like charge through contact with an ion exchange medium.
isobath	- refers to surface of constant depth. In graphical representations isobaths are contours of constant depth.
isohaline	- refers to a surface of constant salinity. In graphical representations isohalines are contours of constant salinity.
manganese nodule	- a black or brown solid structure, nodular in shape, from potato-size down to sand-size; commonly found on the sea floor in areas of low sedimentation rate, composed primarily of manganese and iron hydrous oxides.
meander	- a looping or approximately wavelike flow which occurs in currents and may form into eddys
neutron activation	- an analytical technique for quantitative determination of trace elements; involves activating a sample by bombarding it with neutrons and measuring the resultant gamma ray energy spectrum.
NOAA	- National Oceanic and Atmospheric Administration.
nutrients	- are those elements or compounds necessary for life in biological communities. They usually include nitrates, phosphates and silicates. Other things, such as organics can also be considered as nutrients.
offshore	- refers to the direction of motion whether it be wind, water, sediment etc. The direction of motion is away from the shore.
onshore	- refers to the direction of motion whether it be wind, water, sediment etc. The direction of motion is toward the shore.
OSU	- Oregon State University.
particulate matter	- fine particles in the air or water.
pH	- in practical use pH is a measure of the amount of acidic hydrogen ion. Low values of pH (<7) indicate acidic conditions and high pH values (>7) indicate basic conditions.
phosphorite	- a calcium phosphate mineral.

phytoplankton - photosynthesizing unicellular plants that are considered to be the primary production in the oceanic food cycles. They move along with the motion of the water.

ppt, ppm, ppb - parts per thousand, million and billion respectively. 1 ppt equals 0.1%.

residence time - is generally regarded as the total amount of time of something divided by the rate of input or removal.

S(ppt) - salinity.

salinity - refers to the total amount of salt dissolved in a seawater sample. Salinities are usually expressed in parts per thousand (ppt) or per mille (‰).

sea - refers to the occurrence on the sea surface within a windy or stormy area of irregular waves of many periods coming from many directions.

short ton - 2000 pounds; equals 0.9072 tonnes.

sorption - the process of being absorbed or adsorbed when the exact process isn't known.

swell - refers to waves that have traveled out of a stormy or windy area.

T - temperature.

titanium - a chemical element often found in its dioxide form (titania, TiO_2) in minerals. It is used in the manufacture of stainless steel and combines with other metals to form many alloys.

tonne - a metric ton of 1000 kg. This equals 1.102 short tons.

transport - refers to a volume of water moved. Transport rates are usually in terms of cubic meters/second or cubic kilometers/second.

tsunami - a sea wave caused by a sudden disturbance of the sea floor; also known popularly as a tidal wave or as a seismic sea wave.

trace metals - those metals which occur in seawater, whether naturally or unnaturally, in very minute amounts.

upwelling - vertical upward motion in the water column bringing deeper waters near the surface and induced by such factors as wincs, topography and density changes.

uranyl ion - UO_2^{2+}

USGS - United States Geological Survey.

UTC - uranyl tricarbonate complex, $UO_2(CO_3)_3^{4-}$.

vanadium - a soft, steel white element, used as an additive in steel alloys.

µ - symbol for micro- meaning 10^{-6} of whatever unit is associated with it; i.e., µg=microgram or 10^{-6} gm.

APPENDIX II

Puerto Rican Site Visit Report, December 1978

A trip to Miami, Florida and Puerto Rico was made by Arthur C-T. Chen and Michael R. Rodman in early December, 1978, to gather detailed information concerning the optimum site in the area of Puerto Yabucoa and the Guayanes River Valley. The schedule of events follows with a list of persons and groups we've contacted.

On Sunday, Dec. 10, Arthur C-T. Chen perused the Rosenstiel Library of the University of Miami. The primary result was a group of theses on the chemistry of uranium in the sea water environment.

On Monday, we collected more information at the Rosenstiel and NOAA (National Oceanic and Atmospheric Administration) libraries but the major accomplishment was in the meeting with Dr. Thomas Lee of the University of Miami. Much information flowed in this meeting. Although his main research has been in the current system off Florida and southern Georgia, his ideas probably apply to the rest of the east coast; indeed, probably everywhere there is a major offshore current system. His feeling is that probably nowhere will we find a consistently flowing nearshore current and this stems from his recent research with "spin off" eddies on the landward side of the Gulf Stream which cause, rather than southward currents, northward flow with periods of days to at the very most 3 weeks. In addition to these circulation discussions, he supplied us with contacts in Georgia and North Carolina to check on the flow regimes in this area. He has also participated in an OTEC study off Puerto Rico and suggested that we contact Lloyd Lewis in Washington, D.C. who in turn gave us the name Dr. Gary Goldman in Mayaguez, Puerto Rico.

On Tuesday, at the University of Puerto Rico in Mayaguez, we visited with Dr. Manuel Hernandez. He confirmed our impressions of the nearshore circulation along the south coast which is to the west but with variations. One interesting result, however, is that along the west coast, the circulation is northward into the Atlantic. However, we basically obtained little concrete reference material from him. Then we visited with Dr. Gary Goldman who is an OTEC oceanographer stationed near Mayaguez. His information was much the same as Hernandez', however, bombs is the key word here. Much of the area along the east coast is a USN game range and thus there is supposed to be much unexploded ordnance on the sea floor, though north of the Guayanes site (Puerto Yabucoa). Again, we obtained little in the way of concrete references, although Goldman is preparing an annotated bibliography. Basically, a large percentage of the oceanographic information is locked up in reports which are either private or difficult to ferret out. Further, these studies are apparently limited. At least the one we were able to find was a water quality/pollution study for the entire coast which has some treatment of the site area. An important and detailed report undoubtedly exists for the Guayanes area, however! Sun Oil has located a refinery there.

Both Hernandez and Goldman informed us of this and our site visit on Wednesday confirmed it. We visited and photographed areas along the east coast from Fajardo to Punta Tuna (Cabo Mala). First impressions have this coast being rather unpopulated. Sun Oil company, located in the Guayanes River Valley is virtually the only major facility around. This valley is mostly sugar cane, therefore, land, lots of it, exists much as the USGS maps show. A forty foot channel has been dredged for shipping and it appears to be nearly perpendicular to the coast. It seems to present some shipping advantages since there are no railroads and the highways are far from expressways. Water does not appear at all abundant south of about Humacao. (In fact, nowhere on the island did we see any raging rivers). In the bay north of Guyanes (Puerto Yabucoa) separated by Punta Icacoas is a very large, expensive resort area, Palmas del Mar, where land is available but appears to be going fast to condominiums and resort facilities.

Thursday was spent at two USGS facilities and the Puerto Rico Environmental Quality Control Board in San Juan obtaining maps and reports. Friday was spent in Miami and then onto Corvallis.

An overall assessment of the impressions gathered from our site visit reveals that the Puerto Yabucoa area indeed has many outstanding features that are required for the uranium extraction plant. These important features are:

- Location is less than three kilometers from the continental shelf where the steady, strong and warm Antilles/Caribbean Current offshoots bring a constant supply of fresh seawater to the bay and take away the discharges.
- Over six square kilometers of the river flood plain adjacent to the shoreline is less than 3 meters above mean sea level.
- The population density is low and land appears to be available.

Several contacts were made. Their specialties, names and addresses are listed below:

Dr. Thomas Lee - (oceanography along the southeast coast)
University of Miami
Rosenstiel School of Marine and
Atmospheric Sciences
Miami, Florida 33149

Dr. Lloyd Lewis - OTEC (DOE)
Washington, D.C.
(202) 376-4891

Dr. Manuel Hernandez - (oceanography around Puerto Rico)
Dept. of Marine Sciences
University of Puerto Rico
Mayaguez, Puerto Rico

(809) 832-4040 (marine station)
(809) 832-3439 (dept. office)

Dr. Gary Goldman - (oceanography concerning OTEC (primarily site in SE Punta Tuna)
Center for Energy and Environment Research (CEER)
University of Puerto Rico, DOE
College Station
Mayaguez, Puerto Rico 00708
(800) 832-1414

Dr. Don Sasscer - Head of OTEC for CEER
(the old AEC-DOE Nuclear Lab)
Mayaguez
(did not visit)

Dr. Juan Bonnet - Director of CEER
Mayaguez
(did not visit)

Junta de Calidad Ambiental (Environ. Quality Control Board) - (reports on oceanography, water quality environmental laws and studies)
President (head) is Pedro Gelabert,
San Juan, Puerto Rico.

Nauticenter, Inc. - (nautical charts)
50 Covadonga Ave.
San Juan, Puerto Rico
(old San Juan)

Departmento de Recursos Naturales - (maps, this department has both the USGS hydrographic mapping office and the Puerto Rican equivalent of this. For the USGS topographic maps see J.V. Trumbull)
USGS
P.O. Box 5917
San Juan, Puerto Rico, 00906

USGS Water Resource Division - (for fresh water maps and information)
Mr. McCoy - chief; Hector Colon and Jim Heisel (for water resource reports)
P.O. Box 34168
Fort Buchanan, Puerto Rico 00934

APPENDIX III

COMPANION DOCUMENTS

In this appendix are presented the citations and abstracts or executive summaries of the other three volumes which have resulted from this project.

1 The Bibliography

The Bibliography constitutes Volume II of this document. It is:

"SELECTED BIBLIOGRAPHY FOR THE EXTRACTION OF URANIUM FROM SEAWATER: EVALUATION OF URANIUM RESOURCES AND PLANT SITING" by Arthur C-T. Chen, Louis I. Gordon, Michael R. Rodman and Stephen E. Binney (Exxon Nuclear Company Publication Number XN-RT-14, Vol. II).

ABSTRACT

This bibliography contains 471 references pertaining to the evaluation of U. S. territorial ocean waters as a potential uranium resource and to the selection of a site for a plant designed for the large scale extraction of uranium from seawater. The work was sponsored by the U. S. Department of Energy.

The bibliography is a companion work to a report on the subject which contains the background discussion and conclusions. That report is: [This report, Volume I]... Both that document and the present bibliography are closely related to two other documents, which were also an important part of the same study: [The two volumes of the companion document. These are cited in the next two sections of this appendix.]...

This bibliography was prepared using machine literature retrieval, bibliographic, and word processing systems at Oregon State University.

The literature cited is listed by author with indexes to the author's countries, geographic areas of study, and to a set of keywords to the subject matter.

2 The Feasibility Study, Volume I

Volume I of the Feasibility Study, the companion document to this report, is the report proper. Its bibliography will be cited in the next section.

"EXTRACTION OF URANIUM FROM SEAWATER: CHEMICAL PROCESS AND PLANT DESIGN FEASIBILITY STUDY" by M. H. Campbell, J. M. Frame, N. D. Dudley, G. R. Kiel, V. Mesec, F. W. Woodfield, S. E. Binney, M. R. Jante, R. C. Anderson, and G. T. Clark. (Exxon Nuclear Company Publication Number XN-RT-15, Volume I, and Oregon State University Department of Nuclear Engineering Report Number OSU-NE-7901, Volume I)

EXECUTIVE SUMMARY

The overall objective for this study is to determine the resource base and the technical, economic, and environmental feasibility of large scale recovery of uranium, as a co-product and a single product, from seawater off the coasts of the United States.

A multidisciplinary work group was assembled under the project management of Exxon Nuclear Company, Inc. (ENC) to fulfill this broad objective. Oregon State University (OSU) provided technical expertise from its Department of Nuclear Engineering, School of Oceanography, as well as the Departments of Chemistry and Chemical Engineering. Vitro Engineering Corporation (VEC) developed engineering flowsheets and provided architectural engineering design. Exxon Nuclear Company utilized its demonstrated ability to transfer technology from development activities to operating systems in coordinating all activities; cost estimating, operating experience, environmental impact and economic modelling were specifically provided by Exxon Nuclear Company.

In an endeavor to assure the technical reliability of this report, a Technical Review Committee composed of experts from the above mentioned fields who were not involved in this study was asked to review and comment on the technical aspects of this study three times during the course of the project. Technical Review Committee comments were taken very seriously and were incorporated into the study.

In that much of the prior work on recovering uranium from seawater was reported by European and Japanese scientists and engineers, trips were taken to these locations to learn of the state-of-the-art (Chapter 15). These visits were most helpful in providing a more substantial basis for the many decisions needed in arriving at acceptable data and facility designs.

The general approach to this work was to consider a number of interrelated parametric studies, details of which have been recorded in two documents each comprised of two volumes. The first document has been devoted to uranium resource evaluation and site selection. The scope was limited to the oceans adjacent to the continental United States and its possession, trust territories, etc., and considered such parameters as uranium concentration, current flow, temperature, turbidity, among others, as they may effect availability, recoverability, and deliverability to an extraction plant. Delivery schemes utilizing (1) current flow, (2) tidal flow, and (3) pumped flow were considered in the site selection for the reference design effort.

> As far as the United States is concerned, the only possible location for a tidal flow plant is along the Alaskan coastline, bordering the Gulf of Alaska. High tides, generally greater than 5 m and sometimes as high as 10 m are found in Cook Inlet. However, the year-around temperature range of the water is from 4 to 11 C which offers poor adsorption kinetics while the biological productivity is high which creates an adsorbent fouling problem. Limited flushing within Cook Inlet and lack of fresh water were also found. For the above reasons, tidal flow was not considered for a delivery scheme.
>
> Current flow delivery was discussed with Japanese and German investigators (Sections 15.1 and 15.2). Within current documentation, the configuration of adsorbent beds or films are still in the developmental stages and not yet sufficiently well defined for conceptual design and cost estimation; hence this delivery scheme was not considered further.
>
> Pumped flow delivery permits siting at a location with optimum uranium recovery conditions. Briefly, these include: high salinity (which also indicates a higher uranium concentration); assurance of seawater feed undepleted in uranium by having an optimum regime; seawater temperature in the 26-30°C range to assure a high extraction efficiency; low water clarification requirements; near sea level elevation for the plant with a minimum offshore-onshore slope; and a large volume supply of fresh water.

A location in southeastern Puerto Rico, Puerto Yubucoa and the Guayanes River valley, was selected as the reference design plant site. This site is very suitable for a pumped flow delivery system because it has the following features:

> The location is less than two kilometers from the continental shelf where strong, warm (28°C) Caribbean currents bring a constant resupply of relatively fresh seawater.

Over six square kilometers of the river flood plain adjacent to the shoreline is less than three meters above mean sea level.

An estimated 180,000 cubic meters of fresh water is available per day for process use, and storage reservoirs could double this supply.

Population density is low.

This document, which includes an extensive bibliography in Volume II, is devoted to chemical process selection, conceptual design and cost estimates, economic analysis, environmental impact considerations, research and development requirements, and feasibility assessment.

The various known methods of extracting uranium from seawater were compared to a set of criteria; the adsorption process appeared to be the most reasonable chemical process. Of the many adsorbent materials which have been investigated, hydrous titanium oxide was chosen as the most promising adsorbent at the present time (Section 5.4).

The chemical process selected (Section 5.4) for separating uranium from seawater requires four operational steps:

Loading the hydrous titanium oxide adsorbent with uranium by direct contact with seawater

Eluting the uranium from the hydrous titanium oxide with ammonium carbonate

Steam stripping the eluant to remove and recover the ammonium carbonate

Preparing a solid uranium product

The following flowsheet criteria are used for process design purposes:

Uranium concentration in seawater is 3.35 parts per billion

Plant capacity is 500 tonnes U_3O_8 per year

On-stream load factor is 90%

Adsorbent is hydrous titanium oxide

Adsorbent bed adsorption efficiency is 97%

Product concentration and recovery efficiency is 91%

Mean flow through the adsorbent bed is 0.4 cm/s

Ammonium carbonate is used to elute uranyl ions from the hydrous titanium oxide

Pumped flow is used to pass seawater through the hydrous titanium oxide

Process design considered four possible configurations for the adsorption beds:

Static downflow bed

Static upflow bed

Continuous slurry bed

Continuous fluidized bed

The continuous fluidized bed was selected for design and cost estimating because it had several advantages over the static beds (Section 7.2). These include: nearly continuous operation; washing and elution in a separate continuous operation; reduced sizes for pumps, piping and storage; elimination of three piping systems and reduction in water requirements.

One hundred sixty vertical turbine pumps are needed for meeting peak flow and spare equipment requirements for a 500 tonne per year plant. The seawater pumps are used to maintain a constant head differential between the forebay and adsorbent bed influent canal system. A 4 m head above sea level is required. Since the seawater of the Caribbean Sea is nearly void of nutrients, and the fluidized bed can pass up to 50 micron sand particles, the seawater can be pretreated by only drawing it through a 278 fabric mesh screen.

The fresh water pumping system is planned to meet a peak flow of 200,000 cubic meters per day with one pump out of service. The system is designed to pump from a stream-fed, wet well to a pressure balancing and storage reservoir. The system includes major water pipes, mechanical filtration equipment, chlorination equipment, and pressure regulation equipment.

The total geographical area requirements are: 8,000 hectares for the basic plant area; 200 hectares for pipelines and roadway rights-of-way; 200 hectares for port and storage facilities; 900 hectares for a fresh water reservoir; and 1,000 hectares of sea floor for the forebay and miscellaneous area.

A labor force of 700 is projected for this facility with an annual labor cost of $12.5 million.

Extensive material takeoff sheets for the reference design were prepared by process and plant designers for pricing and extension to a complete construction estimate by personnel having many years of experience with major industries on large international projects (Chapter 8).

The approximate capital cost for the reference design of the continuous fluidized bed uranium recovery facility, utilizing adsorbent beds with a loading capacity of 210 mg U/kg Ti, is estimated to be $6.2 billion in 1978 dollars (Chapter 10).

Using capital and operating cost breakdowns, sensitivity studies were made using a computer model to vary the parameters in constructing and operating the reference design facility. These sensitivity studies indicated that increasing the flow rate would reduce the overall cost of product uranium. Practically, this can be accomplished by increasing the particle size. At this point, adjusted takeoffs were made and a new, lower capital cost estimate was projected.

It is concluded that the cost of extracting uranium from seawater in 1995 will range from 2000 to 2500 dollars per pound of yellowcake. The production cost is extremely capital intensive and as such, the projected costs are sensitive to the method of financing the project. A private venture, without government support, could not produce uranium for under $2700/lb and the most probable commercial cost will be $3600/lb.

Uranium can be removed from seawater by a process that can be made to be compatible with the environment within which it is located (Chapter 11). The environment of the site will have to be evaluated prior to the start of detail design so that the environmental inputs can be used in the final design. Although there will be a major environmental impact due to the removal of uranium from seawater, these impacts appear to be amenable to mitigation by current technology.

During the course of this project, several key assumptions had to be made in the absence of concrete experimental evidence (e.g., loading capacity, kinetics, loss due to mechanical attrition and solubility, etc.). Thus, many factors need further investigation to provide information needed for a more detailed conceptual design. Chapter 12 discusses some of the key factors that need further study to either improve the present understanding about the process or to reduce the cost of uranium recovery.

Feasibility of uranium recovery has four readily definable sub-divisions: (1) technical feasibility; (2) engineering feasibility; (3) economic feasibility; and (4) social feasibility (Chapter 13). This study finds that it would be technically feasible to recover uranium from seawater, although there are a number of site specific studies that should be conducted prior to site selection. It is not feasible from an engineering viewpoint to go beyond the preliminary conceptual design for a pumped flow system without conducting further studies. It would be socially feasible to recover uranium from the seawater as long as the plant site were in a low population area. Without several major technical breakthroughs leading to significantly lower production costs and/or federal subsidy, a pumped seawater plant to extract uranium from seawater is not economically feasible.

3 Volume II of the Feasibility Study

The citation and abstract of this bibliography are:

"EXTRACTION OF URANIUM FROM SEAWATER: CHEMICAL PROCESS AND PLANT DESIGN FEASIBILITY STUDY" by S. E. Binney, S. Polkinghorne, M. R. Jante, M. R. Rodman, A. C-T. Chen, and L. I. Gordon. (Exxon Nuclear Company Publication Number XN-RT-15, Volume II, and Oregon State University Department of Nuclear Engineering Report Number OSU-NE-7901, Volume II)

ABSTRACT

A selected annotated bibliography of 517 references was prepared as a part of a feasibility study of the extraction of uranium from seawater. For the most part, these references are related to the chemical processes whereby the uranium is removed from the seawater. A companion document contains a similar bibliography of 471 references related to oceanographic and uranium extraction plant siting considerations, although some of the references are in common.

The bibliography was prepared by computer retrieval from Chemical Abstracts, Nuclear Science Abtracts, Energy Data Base, NTIS, and Oceanic Abstracts.

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