THE EFFECTS OF REGULATORY CONSTRAINTS ON THE
DEEP OCEAN MINING INDUSTRY

BY
LANCE ANTRIM

S.B.M.E., Massachusetts Institute of Technology (1971)

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
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Signature of Author

Certified by

Accepted by

Thesis Supervisor

Chairman, Departmental Committee on Graduate Students of
the Department of Ocean Engineering

Chairman, Environmental Engineer Degree Committee

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Chairman, Committee on Ocean Engineering

Chairman, Ocean Engineering Department

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LANCE ANTRIM

Submitted to the Department of Ocean Engineering on August 25, 1976 in partial fulfillment of the requirements for the degree of Environmental Engineer.

ABSTRACT

A model, based on published information pertaining to ocean drilling and mining and to minerals processing, is developed to describe a deep ocean mining system. The costs of the components of the model are estimated and used to determine the attractiveness of deep ocean mining relative to the current investments of the mining companies.

The national and international policies that affect deep ocean mining are reviewed. The model is used to evaluate two proposed regulatory constraints. First, a limit on the production of nickel from nodules, equal to the projected growth of the nickel market, is imposed on the mining industry. Second, the mining operation is prohibited from discharging sediment into the water column. A system to filter the discharge and to return the sediment to the sea floor is developed and incorporated into the model.

It is found that the model deep ocean mining system must recover more than 2.5 million tons of nodules annually to be an attractive investment. The imposition of a production limit is found to affect the industry only in the case of the smallest projected rate of growth of the nickel market. In this case the mining system operates at reduced capacity and efficiency and has a lower net present value. Thus, the minimum projected growth rate reduces the revenues that could result from taxation of the mining operation. The constraint prohibiting sediment discharge is found to cause a negligible reduction in the net present value of the mining operation and so it can be applied without discouraging investment in deep ocean mining.

Thesis Supervisor: J. D. Nyhart
Title: Associate Professor of Ocean Engineering and Management
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CHAPTER 1
Policy Considerations of Deep Ocean Mining

The sea has always been important to the United States as a source of food and as a means of transportation, but since World War II it has also become a vital source of minerals to supplement land-based reserves. Improvements in oil drilling technology have made possible the production of oil and gas from below the continental shelf. The seaward march for oil was begun in 1945 when, in order to obtain secure and private access to offshore oil deposits, President Truman proclaimed that the resources on and below the continental shelf belonged solely and entirely to the United States.\(^1\)

The wording of President Truman's proclamation was carefully phrased to avoid interference with fishing rights and the right of free transit, but the precedent of unilateral extension of national jurisdiction was sufficient to permit other nations to extend their claims over not only the continental shelf, but over the high seas to a distance of as much as 200 miles.\(^2\) The differing claims over the extent of national jurisdiction led to the 1958 Geneva Conventions which covered the topics of territorial seas, the continental shelf, the high seas, and living resources.\(^3\) The conventions served as a temporary solution to the problem of codifying the law of the sea, but they are subject to several limitations. The conventions are not universally accepted; the Convention on the Continental Shelf was ratified by only 50 nations, and some of these nations have
found it in their interest to call for a new treaty. The conventions have been made obsolete by advances in the technology for mineral exploration, as well as advances in fishing methods and the increasing impact of pollution on the marine and coastal environments. The recovery of minerals from the sea in 1958 was possible only in the relatively shallow area of the continental shelf, but advances in deep water drilling have led to a technology for recovering the hard minerals from the deep seabed, and this topic has not been covered in previous discussions on the law of the sea.

In 1969, after two years of study, the Commission on Marine Science, Engineering and Resources (the Stratton Commission) submitted its report to the President and the Congress. Policy recommendations were made for a wide range of ocean related issues and, with respect to deep ocean mining, it was recommended that the United States propose in the United Nations the formation of an International Registry Authority that would file the claims to ocean minesites made by member nations. In addition, the commission recommended that an international fund be created to compensate the nations of the world, who are the "common owners of the mineral resources of the deep seas." The payments to the fund would come from the proceeds of the mining operations.

The policy of the United States toward deep ocean mining, as established in 1970, was developed as part of the U.S. position at the 3rd United Nations Conference on the Law of the Sea. The United States proposed a Draft "United Nations Convention on the International
Seabed Area. The draft convention was the result of the combination of the policy objectives proposed by the Stratton Commission in 1969, the objectives of the Mining and Minerals Policy Act of 1970, and national defense policy. Thus the goal of the United States was to obtain a broad agreement that would cover all aspects of the use of the seas, and the requirement that the United States "foster and encourage sound and stable domestic mining, minerals, metal and reclamation industries" was postponed in hope of obtaining a comprehensive treaty on the law of the sea. In an effort to obtain wide approval of a satisfactory treaty the U.S. proposed a regime for the seabed that was more restrictive of the domestic mining industry than the system proposed by the Stratton Commission. In the U.S. Draft the Seabed Authority would have the power to control the exploitation of the sea floor instead of being limited to a registry function. The power of the Authority would be restricted by the terms of the treaty. The United States hoped to obtain satisfactory restrictions on the Authority that would provide a stable regime for the seabed while encouraging industry to exploit its resources.

Developing states did not accept the restrictions on the Authority that were proposed by the United States. Instead, the developing states, represented by the Group of 77 and led by states with land based reserves of nickel and copper such as Zaire and Chile, used the U.S. draft as a basis for their own proposed regime. Under this regime the Authority, which would be controlled by a majority vote of its members, would be the only institution allowed to exploit the sea
private industry would be allowed to participate, but only under contract to the Authority. This proposal has been unsatisfactory to the United States because the supply of ore from nodules would be under foreign control.

Concurrent with the negotiations in the U.N. Conference on the Law of the Sea the mining industry has been lobbying the congress for domestic action to protect and encourage ocean miners. In 1971 the American Mining Congress prepared a bill that was submitted by Senator Metcalf to the Senate for discussion. The bill has been modified and resubmitted several times. In 1974 S1134 was approved by the Senate Committee on the Interior and Insular Affairs, but it failed to be passed by the entire senate. Several concepts are found in common to all the congressional bills. First, the bills have been drafted with the recognition that it is the policy of the United States to encourage an international regime for the seabed, and that such a regime will supercede the domestic legislation. Second, in recognition of the fact that the United States does not claim ownership of the seabed minerals, there is no provision for the collection of royalties or for bidding on minesites. Third, the domestic legislation provides the mining companies with the assurance that the value of their investments will not be decreased by changes in the legal status of their claims that might result from the acceptance by the United States of a treaty on the seabed. In the event that a treaty would lower the value of the investment the United States would be required to compensate the companies for their loss. This provision has been
viewed as essential by the mining industry because it provides assurance to lending institutions that loans to the industry will not be jeopardized by the uncertain legal status of the seabed at the present time.27 C. Thomas Houseman, Vice President and Technical Director Mining of the Chase Manhattan Bank, stated before the Senate Subcommittee on Mines, Minerals and Fuels that without such assurance he felt that ocean mining is an unacceptable risk for financial institutions.28

Both the Nixon and Ford administrations have discouraged unilateral action on the ocean mining issue to avoid the appearance of bypassing the LOS conference in order to obtain national objectives,29 but some consideration has been given to the form domestic legislation might take in the event that an international treaty is not reached. In 1975 the Interior Department prepared a draft ocean mining bill and submitted it to other departments for comment.30 The bill represents the view of the Interior Department in the event that the conference is unsuccessful. It was not disclosed to the public for fear that the developing states would claim that the United States was not committed to the goal of an international treaty on ocean usage. The draft bill, while differing from congressional bills in administrative details, contains the three considerations discussed above.31 This suggests that if a treaty is not reached in the United Nations then domestic legislation can be formulated that will satisfy both the congress and the administration in a short time.

As the LOS conference has continued the mining industry has deve-
loped the recovery and processing technology for ocean mining and is technically ready to make the huge capital investment that is required for further progress. In order to protect the technical advantage that the industry presently enjoys over foreign firms the mining companies have been lobbying for domestic action. The National Advisory Committee on Oceans and Atmosphere, which is composed of leaders of industry and academia, recommended to the President and the Congress in 1975 that "legislation be enacted to encourage and regulate deep seabed mining by United States private industry to the end that the minerals of the deep seabed will be available to decrease United States dependence on foreign sources and to increase world supply."

The importance that the United States places on deep seabed mining was emphasized to the international community by Secretary of State Kissinger in April, 1976, when he stated that if an international agreement satisfactory to U.S. interests was not quickly forthcoming, then the United States would act unilaterally to protect the technical advantage enjoyed by the U.S. industries. He also suggested that the U.S. might agree to a temporary limitation on the production rate of the mining operations in order to reduce the economic impact of ocean mining on the developing states that produce the metals that will be obtained from nodules. The results of this new approach will be seen in future discussion in the LOS conference, but it is apparent that some form of seabed regime, either domestic or international, will soon be supervising the exploitation of the deep sea floor.

Discussion in public forums on the subject of deep ocean mining
has dealt with economic and resource policy in detail, but environ-
mental policy aspects have been relegated to a lesser role. This has
occurred because environmental protection is not the primary concern of
either the mining industries or of the developing states in the Group
of 77. Private corporations are concerned with maximizing the return
on their investment and the developing states want to maximize their
share of the profits resulting from exploitation of the sea floor.
The developing states consider environmental protection to be a respon-
sibility of the developed states. The problem is compounded by a
lack of information about the ocean environment in the area of the po-
tential minesites. Without detailed knowledge of the mining environ-
ment it is not possible to accurately predict the consequences of deep
ocean mining, so the problem cannot be dealt with in detail at the
present time.

Although the environmental consequences of deep ocean mining af-
fect the entire world they are presently dealt with on a national
level. In the United States the environmental policy is set by the
National Environmental Policy Act of 1969 (NEPA). NEPA requires
that the government agencies that are concerned with any federal ac-
tion to study the environmental consequences of the action and to
report the results in an environmental impact statement. The pro-
posed federal actions must minimize the adverse impact to the environ-
ment in a manner consistent with "other essential considerations of
national policy."

The deficiency in scientific research into the effects of ocean
mining was illustrated in a 1974 draft environmental impact statement prepared by the Department of the Interior. In 1975 the National Oceanic and Atmospheric Administration began its Deep Ocean Mining Environmental Study (DOMES I) which gathered data to establish baseline conditions at several potential minesites. To date the only environmental monitoring of a mining operation using equipment similar to systems proposed by U.S. industries has been a test of the Deepsea Ventures airlift system in the summer of 1970. The test was performed in the Atlantic Ocean on the Blake Plateau and was monitored by scientists from the Lamont-Doherty Geophysical Observatory. The scientists also monitored tests of a continuous line bucket system in the Pacific. The results of these tests indicate that the disturbance to the ocean bottom will be limited to the area swept by the dredge. Bottom water from the lift that mixes with the surface water will cause only a slight change in water properties. These effects are projected to have minor impact in the near future, but changes in mining techniques or large increases in the area under exploitation may result in a need for regulation. The tests were too short to provide information about the effects of the discharge of sediment into the water column. The sediment in the area of potential minesites may take as long as 5 years to settle through the upper 100 yards of the ocean. If eight units are in operation in 1990 several hundred thousand square miles of the ocean may contain sediment from mining operations in the euphotic zone. This is the upper layer of the ocean in which photosynthesis takes place. There is concern that
the suspended sediment may disturb the ecology by altering the light transmission characteristics of the water.\textsuperscript{51} As the sediment settles it may also interfere with the "deep scattering layers",\textsuperscript{52} which consist of small marine animals that live several thousand feet deep and travel to the surface at night to feed.

Because of the uncertainty surrounding the environmental consequences of the mining of deep ocean nodules it is desirable to minimize the discharge of sediment into the water column. The effect of the environmental constraint will be felt by the ocean mining industry in terms of the cost of meeting the constraint. If the cost of compliance is too high then the seabed resources will not be exploited by domestic companies. NEPA stipulates that other national policy objectives must be accommodated in establishing environmental policy.\textsuperscript{53} For this reason it may be necessary to allow some degradation of the environment in order to provide a regime that will encourage domestic companies to invest in ocean mining.

Domestic ocean mining operations will be conducted by private industry. The decision of a company to invest in ocean mining, and the scale of investment, is determined by the projected rate of return on the investment and the degree of risk involved. The attractiveness of nodule mining relative to other operations can be determined by calculating the net present value (NPV) of the operation using a discount rate that represents the internal rate of return that the company expects from an alternative operation with a similar degree of technical risk. This method is used below to determine the
effect of two potential constraints on the ocean mining industry. An engineering cost model of an ocean mining operation is developed in chapter two to serve as the basis for the analysis. The financial analysis of the basic system is described in chapter three. The effects of two regulatory constraints are examined in chapter four. First, the production limit suggested by Secretary of State Kissinger is imposed on the ocean mining industry and its effect on the mining operation is determined. Second, a system to remove sediment from the lift discharge is developed and the effect of the increased capital and operating costs of the operation is determined. The chapter concludes with a discussion about the effectiveness of the policy restraints on the ocean mining industry in obtaining national objectives.
CHAPTER 2
The Deep Ocean Mining System Model

The model of the deep ocean mining system is developed in three parts: the recovery system, the transportation system, and the processing system. The development of each system is based on the properties of the nodules and of the site in which they are deposited. The first part of this chapter examines the qualities of the nodules as they relate to system design. The remaining three sections examine the individual systems of the mining operation and estimate their costs as a function of the annual recovery rate of the operation, measured in tons of dry nodules recovered from the sea floor.

Characteristics of the Ore Body:

Nodules are widely distributed around the world and are found in both fresh and salt water. Their composition varies greatly, as is shown in table 2-1. Nodules have elicited the interest of minerals

Table 2-1
Chemical Composition of Nodules

<table>
<thead>
<tr>
<th></th>
<th>Pacific</th>
<th></th>
<th>Atlantic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>max</td>
<td>min</td>
<td>avg</td>
<td>max</td>
</tr>
<tr>
<td>Mn</td>
<td>41.1%</td>
<td>8.2%</td>
<td>24.2%</td>
<td>21.5%</td>
</tr>
<tr>
<td>Fe</td>
<td>26.6%</td>
<td>2.4%</td>
<td>14.0%</td>
<td>25.9%</td>
</tr>
<tr>
<td>Co</td>
<td>2.3%</td>
<td>.014%</td>
<td>.35%</td>
<td>.68%</td>
</tr>
<tr>
<td>Ni</td>
<td>2.0%</td>
<td>.16%</td>
<td>.99%</td>
<td>.54%</td>
</tr>
<tr>
<td>Cu</td>
<td>1.6%</td>
<td>.028%</td>
<td>.53%</td>
<td>.41%</td>
</tr>
</tbody>
</table>
companies for their content of nickel, copper, and cobalt. Because of their low content of nickel, copper, and cobalt, many of the nodule deposits, and all of the easily accessible ones, are of little interest for commercial development. The richest of the explored nodule deposits are found in the Pacific Ocean about 1000 miles east-southeast of Hawaii. These nodules provide a rich ore of nickel and copper, with traces of cobalt. They are easily crushed and are amenable to several forms of hydrometallurgical processing. The depth of the region is approximately 4750 meters. The seabed consists of gently rolling abyssal hills of 180 to 600 foot relief, which are covered by pelagic sediment that forms a silicious ooze. Bottom life in the region is sparse, with the biomass measured in the range of .01 to .05 grams per square meter.

Table 2-2
Model Mine Site Characteristics

| Location | Depth | Surface Density | Soil Type               | Nodule Specific Gravity | Manganese Content | Nickel Content | Copper Content | Cobalt Content |
|----------|-------|-----------------|-------------------------|-------------------------|-------------------|----------------|----------------|----------------|----------------|
| 140 W, 10 N | 4750 meters | 6 pounds/(foot)^2 | Radiolarian Ooze         | 2.0                     | 26%               | 1.6%           | 1.3%           | 0.24%           |

(Specific Gravity = 1.14)
For the purposes of this work a hypothetical minesite has been specified. Its characteristics are based on actual qualities of the region and represent the characteristics that may be expected in a commercial minesite in the near future. These characteristics are summarized in table 2-2.

**Nodule Recovery System:**

Deep ocean mining has become technically possible with the development of methods of moving large quantities of nodules from the sea floor to the surface.\(^{12}\) Commercial interests plan to move the nodules by mixing them with water and pumping them upward. Two pumping systems have been proposed. One system injects air into the nodule and water mixture to reduce its density so it is forced to the surface.\(^{13}\) A second system uses a conventional multi-stage slurry pump to propel the mixture.\(^{14}\) On board the mine ship the nodules are collected and the water is pumped over the side.\(^{15}\)

Nodule recovery systems are still in the development stage. Since there are no operational systems it is difficult to forecast the cost of the recovery system. The proposed recovery systems utilize technology developed for the offshore oil industry and for other oceanic operations.\(^{16}\) Costs for the recovery system model are estimated from these applications.

The recovery system is divided into three components: the bottom unit, the hydraulic lift, and the mine ship. The bottom unit is a device that separates the nodules from the seabed and feeds them into
the hydraulic lift. A drag net design is used in this model. In this design the nodules and the upper layer of sediment are scraped into the net, where the nodules move to the rear and center of the net while the sediment is washed off by the ocean water. The rear of the net feeds the nodules into the hydraulic lift to be sent to the surface. The construction of the dredge net is not complicated and does not represent the bulk of the cost of the unit. The bottom unit carries extensive instrumentation to monitor its operation. A television camera observes the flow of nodules into the lift. A forward looking sonar scans for obstacles, and a side-scan sonar surveys the minesite to the sides of the dredge. The signals from the equipment are sent to the surface by two armored cables attached to the lift. The cost of the side scan sonar and the two cables are approximately half a million dollars. The total cost of the bottom unit, with its instrumentation and cables, is estimated to be $1.5 million. Two bottom units are used in the model system so operations can continue in the event one unit malfunctions or is lost. The monitoring equipment is the same regardless of the scale of production so the cost of the bottom unit is constant for the three scales of production considered in this study.

Hydraulic systems have been used for the horizontal transfer of slurries and for dredging in depths of over 100 feet, but deep ocean mining is the first application of vertical slurry transport from great depths. The lift used in the model system is similar to one analyzed by International Nickel for their deep ocean mining system.
The lift consists of a pipe string extending from the surface vessel to the bottom unit and a seven-stage centrifugal pump. In order to achieve its maximum suction head the pump is submerged to a depth of 3000 feet. The pipe string supports its own weight so it is constructed of a high strength steel such as HY-80 or Grade E drill pipe. The characteristics of the hydraulic lift are examined in Appendix A and the results are shown in table 2-3.

Table 2-3
Summary of Hydraulic Lift Characteristics

<table>
<thead>
<tr>
<th></th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine Rate ($10^6$ dry tons per year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe Diameter (inches)</td>
<td>12</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Ratio of nodule volume to total pipe volume</td>
<td>.17</td>
<td>.17</td>
<td>.17</td>
</tr>
<tr>
<td>Suction Pressure (PSI)</td>
<td>1251</td>
<td>1275</td>
<td>1277</td>
</tr>
<tr>
<td>Power Required (HP)</td>
<td>3078</td>
<td>7048</td>
<td>10923</td>
</tr>
<tr>
<td>Cost ($ x 10^6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe and Couplings</td>
<td>1.7</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Pump and Housing</td>
<td>0.4</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The Mine Ship:

The mine ship serves as the operating platform for the nodule mining system. The essential qualities of the ship are:

--ability to handle pipe sections for the hydraulic lift;
--precise navigation;
--power supply for propulsion and lift;
<table>
<thead>
<tr>
<th>Production Rate (10^6 tons per year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital Costs:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mine Ship</td>
<td>35.0</td>
<td>50.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Hydraulic Lift</td>
<td>2.0</td>
<td>2.7</td>
<td>3.3</td>
</tr>
<tr>
<td>Bottom Unit</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Total Capital Cost</strong></td>
<td>40.0</td>
<td>55.7</td>
<td>66.3</td>
</tr>
<tr>
<td><strong>Operating Costs:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel ($0.03/HP-HR):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift</td>
<td>0.6</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Propulsion</td>
<td>0.3</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Pipe Replacement (50% per year)</td>
<td>0.8</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Labor:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ship Crew (45 men)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Pipe Handlers (30 men)</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Operators (15 men)</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Maintenance:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ship (10% of Ship Cost)</td>
<td>3.5</td>
<td>5.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Pump (20% of Pump Cost)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Bottom Unit (20% of Unit Cost)</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Insurance (5.5% of Ship Cost)</td>
<td>1.9</td>
<td>2.8</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Total Annual Operating Cost</strong></td>
<td>9.8</td>
<td>14.2</td>
<td>17.7</td>
</tr>
</tbody>
</table>
--living quarters for the crew.

In addition, the ship may be required to provide treatment facilities for the water expelled from the lift to prevent the discharge of sediment into the surface water. In this model the treatment of water is omitted, but it will be considered in chapter 4.

The mine ship may be built from the keel up for the task of deep ocean mining or it may be converted from another task. In either case the mine ship will be similar in construction to present deep ocean drill ships. For a small mining operation capital investment can be minimized by converting a bulk carrier into a mine ship. Such a ship, converted to a dynamically positioned drill ship, costs $35 million. A large operation can justify the expense of constructing a new ship, and costs are in the range of $50 to $65 million.

The major operating costs of the mine ship are the cost of fuel and labor and costs of maintainence and insurance which are proportional to capital investment. These costs are included in table 2-4, which summarizes the costs of the entire recovery operation.

The Transportation System:

Nodules that are recovered by the mine ship can be transported to shore by a barge and tug system or by a conventional bulk carrier. For this model a barge and tug combination is used. The advantage of this system is that barges can be left at the mine ship and the processing plant as temporary storage facilities while the tugs and their crews are all in transit between the ship and the plant.
Table 2-5

Module Transportation Costs
(Costs in Units of $10^6$)

<table>
<thead>
<tr>
<th>Production Rate ($10^6$ tons per year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of barges</td>
<td>5</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Number of tugs</td>
<td>3</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Cost of barges ($8.98 \times 10^6$ apiece)</td>
<td>44.88</td>
<td>71.81</td>
<td>107.70</td>
</tr>
<tr>
<td>Cost of tugs ($2.14 \times 10^6$ apiece)</td>
<td>6.41</td>
<td>12.82</td>
<td>21.40</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>51.29</td>
<td>84.63</td>
<td>129.10</td>
</tr>
</tbody>
</table>

Operating Costs:

**Tugs:**

- Labor ($0.369 \times 10^6$/tug-year) | 1.11 | 2.22 | 3.69 |
- Fuel and oil ($0.69 \times 10^6$/tug-year) | 2.07 | 4.14 | 6.90 |
- Maintenance (4% of tug cost) | 0.26 | 0.51 | 0.86 |
- Insurance (2% of tug cost) | 0.13 | 0.26 | 0.43 |
- Duties and fees (.3% of tug cost) | 0.02 | 0.04 | 0.06 |
- **Sub-total:** | 3.59 | 7.17 | 11.94 |

**Barges:**

- Labor ($0.032 \times 10^6$/barge-year) | 0.16 | 0.26 | 0.39 |
- Maintenance (2% of barge cost) | 0.90 | 1.43 | 2.15 |
- Insurance (2% of barge cost) | 0.90 | 1.43 | 2.15 |
- Duties and fees (.3% of barge cost) | 0.13 | 0.22 | 0.32 |
- **Sub-total:** | 2.09 | 3.34 | 5.01 |

**Administration costs:**

(6.4% of tug and barge costs) | 0.36 | 0.67 | 0.76 |

**Total Operating Cost** | 6.04 | 11.18 | 18.03 |
The barge and tug maintain a speed of ten knots, and travel a one way distance of 2200 nautical miles to the processing plant. Nineteen days are allowed for round-trip sea time and one day is allowed at the ship and at the plant to change barges and crew and to refuel.

The barges are of 40,000 ton capacity and are propelled by ocean going tugs with 6000 SHP. The capital and operating costs of this system are based on a study by E. G. Frankel, and are updated to 1976 prices. The costs are listed in table 2-5.

The Processing Plant:

Because the valuable metals are finely dispersed throughout the nodule structure, pyrometallurgical techniques are not an effective method of processing nodules. Several hydrometallurgical methods have been developed and have been shown to be successful in recovering the metal values. The most promising system utilizes an ammonia-ammonium carbonate leach that recovers the nickel, copper, and cobalt while leaving the iron and manganese in the tailings. The technology for such a system is well documented in its application to nickel and copper oxide ores.

The ammonia leaching system used in this model is based, in part, on a system described by engineers at Kennecott Copper's Ledgemont Laboratory. In this system, the nodules are first crushed to a diameter of 3/8 inch and dried in a fluid bed dryer. They are then ground to a diameter of 50 microns and heated in a fluid bed furnace to reduce the metal oxides to pure metal. The reduced ore is then fed into a series of mixing vessels and thickeners that run counter to
the flow of the leaching solution. Air is injected into the mixing vessels to oxidize the metals into soluble ammonium complexes. The pregnant leach liquor is then passed through a series of liquid ion exchange columns to separate the nickel, copper, and cobalt and send them to electrowinning tanks where the pure metals are recovered. The leach solution, stripped of metal values, is recycled and the tailings from the final thickener are sent to a steam stripping tower to recover ammonia and carbon dioxide.

The capital and operating costs of the processing system are examined in Appendix B and are summarized in table 2-6.

Table 2-6
Summary of Processing Plant Costs

<table>
<thead>
<tr>
<th>Ore Processing Rate ($10^6$ tons/year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installed Process Equipment............</td>
<td>61.44</td>
<td>118.20</td>
<td>166.17</td>
</tr>
<tr>
<td>Offsite Facilities......................</td>
<td>61.44</td>
<td>118.20</td>
<td>166.17</td>
</tr>
<tr>
<td>Utilities...............................</td>
<td>35.02</td>
<td>67.37</td>
<td>94.72</td>
</tr>
<tr>
<td>Buildings...............................</td>
<td>17.82</td>
<td>34.28</td>
<td>48.19</td>
</tr>
<tr>
<td>Total Capital Cost.....................</td>
<td>175.72</td>
<td>339.27</td>
<td>475.25</td>
</tr>
<tr>
<td>Operating Cost:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct.................................</td>
<td>22.10</td>
<td>48.76</td>
<td>74.47</td>
</tr>
<tr>
<td>Indirect...............................</td>
<td>0.92</td>
<td>1.31</td>
<td>1.61</td>
</tr>
<tr>
<td>Fixed..................................</td>
<td>3.51</td>
<td>6.79</td>
<td>9.51</td>
</tr>
<tr>
<td>Total Operating Cost...................</td>
<td>26.53</td>
<td>56.86</td>
<td>85.59</td>
</tr>
</tbody>
</table>
Summary:

The capital and operating costs of the three systems in the deep ocean mining operation are summarized in table 2-7. These results are used in the following chapter to determine the financial feasibility of the model operation.

Table 2-7
Summary of Deep Ocean Mining Costs

(Costs in Units of $10^6$)

<table>
<thead>
<tr>
<th>Production Rate ($10^6$ tons per year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovery System</td>
<td>40.1</td>
<td>55.7</td>
<td>66.3</td>
</tr>
<tr>
<td>Transportation System</td>
<td>51.3</td>
<td>84.6</td>
<td>129.1</td>
</tr>
<tr>
<td>Processing System</td>
<td>175.7</td>
<td>339.3</td>
<td>475.3</td>
</tr>
<tr>
<td>Total Capital Cost:</td>
<td>267.1</td>
<td>479.6</td>
<td>670.7</td>
</tr>
<tr>
<td>Operating Cost:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovery System</td>
<td>9.8</td>
<td>14.2</td>
<td>17.7</td>
</tr>
<tr>
<td>Transportation System</td>
<td>6.0</td>
<td>11.2</td>
<td>18.0</td>
</tr>
<tr>
<td>Processing System</td>
<td>26.5</td>
<td>56.9</td>
<td>85.6</td>
</tr>
<tr>
<td>Total Annual Operating Cost:</td>
<td>42.3</td>
<td>82.3</td>
<td>121.3</td>
</tr>
</tbody>
</table>
CHAPTER 3

Financial Analysis

In chapter 2 an engineering model of a deep ocean mining system was developed and was used to estimate the capital and operating costs of the operation. This chapter examines the feasibility of deep ocean mining in a financial, rather than a technical, context. This analysis is accomplished in two parts. First, the revenues that will result from the sale of metals from the operation are estimated. Second, the capital and operating costs and the sales revenue are included in a calculation of the net present value of the venture, in order to compare the attractiveness of investment in deep ocean mining with current investments of the mining companies.

Sales Revenue:

Every ton of nodules from the model minesite contains 32 pounds of nickel, 26 pounds of copper, and 4.8 pounds of cobalt. Inefficiency in the processing plant prevents full recovery of the metals. The recovery efficiency of the model processing plant is 95% for nickel and copper and 90% for cobalt. This results in recovery of 30.4 pounds of nickel, 24.7 pounds of copper, and 4.3 pounds of cobalt.

Current metal prices cannot be relied upon to represent metal prices in the future. Some estimate must be made, however, before the profitability of the operation can be determined. Since land-mined sources of nickel and copper will continue to supply most of
these metals in the foreseeable future the price of the land mined metals will establish the value of nickel and copper obtained from nodules. The constantly decreasing grade of continental resources of nickel and copper will result in higher operating costs in recovering the metals and so the prices can be expected to increase. A more conservative estimate is that the prices of nickel and copper will remain constant. The production of cobalt from nodules will significantly increase the world supply and result in a lower market price. Cobalt is a substitute for nickel in plating operations and in high temperature alloys so a lower bound is set on the price of cobalt by the price of nickel. In this model an intermediate price of $3.00 per pound is used as the price of cobalt. This assumption results in a value of $89.90 for the metals recovered from a ton of nodules.

Computation of the Net Present Value:

The net present value (NPV) of the investment in deep ocean mining is used to indicate the attractiveness of the investment relative to current investments of the mining company. The present value of future expenditures accounts for the fact that money earned or spent in the future is of less value than the same amount of money at the present. The present value is determined by discounting all income and expenditures by a discount factor DF:

$$DF = \frac{1}{(1 + i)^n}$$

where $i$ is the discount rate, and $n$ is the number of years in the future that the cash flow occurs. When the NPV is greater than zero the
company will find the operation to be worthwhile.\textsuperscript{6} The computation of the net present value is dependent upon the selection of the appropriate discount rate. The minimum acceptable discount rate can be determined from the company's return on total capital.\textsuperscript{7} The return on total capital (RTC) can be computed from the company balance sheet by the expression:\textsuperscript{8}

\[
\text{RTC} = \frac{\text{Net Earnings plus Interest Payments}}{\text{Total Assets} - \text{Total Liabilities} + \text{Long Term Debt}}
\]

Over the last eight years Kennecott Copper and Tenneco, Inc., the major U.S. companies involved in deep ocean mining, have had average returns on total capital of 9.9\% and 10.0\% respectively.\textsuperscript{9} Because of the risk involved in the development of a new technology the actual discount rate used in the present value computation is higher than the rate indicated by the RTC. The degree of risk involved in deep ocean mining may be described as moderate because a new technology is used to produce a conventional product.\textsuperscript{10} The degree of risk is minimized by preliminary investment in development work. Deepsea Ventures is involved in a development program costing $20 million,\textsuperscript{11} and Kennecott Copper, with its partners, is spending $50 million over five years.\textsuperscript{12} The development programs, through basic research and the testing of pilot operations, reduce the technical risk. The results of current development projects have been reported and indicate that technical problems are being solved before the actual plant investment is begun.\textsuperscript{13} The discount rate used in the calculation of
the NPV is 15%\textsuperscript{14}. This recognizes the moderate degree of technical risk involved in the operation. The discount rate does not consider the risk that results from political uncertainty of the seabed regime.

The present value of the ocean mining operation is calculated as a function of project life for the three scales of the mining operation examined in chapter two. The results are displayed in figure 3-1. The calculations include three forms of cash flow:

1. Exploration and development costs, at $20 million per year for two years. 50\% of the development costs are recovered from reduced income taxes by being expensed against current income from other operations\textsuperscript{15}. The net exploration and development cost is $10 million per year.

2. Capital outlays, which are allocated over a four year period following the development program\textsuperscript{16}. The expenses are staggered with 10\% occurring in year 3, 20\% in year 4, 30\% in year 5, and 40\% in year 6.

3. Net revenues which equal sales revenue minus operating costs and federal income taxes.

The corporate income tax rate is set at 50\%.\textsuperscript{17} Taxes are calculated using straight line depreciation over a ten year period\textsuperscript{18}.

Comment:

The effects of economies of scale are easily apparent in figure 3-1. The small operation, mining one million tons of nodules per
Figure 3-1

Net Present Value of Three Deep Ocean Mining Operations as a Function of Project Lifetime

A: Nodule Recovery Rate of 4.0 million tons per year
B: Nodule Recovery Rate of 2.5 million tons per year
C: Nodule Recovery Rate of 1.0 million tons per year
year, is not an attractive investment, even with an extended project life of 40 years. The medium scale operation, of 2.5 million annual tons, approaches an NPV of zero for a project life of 31 years or longer. The large scale operation, of 4 million annual tons, becomes an acceptable investment by the 17th year, after 11 years of production. If a 25 year production life (31 years of project life) is assumed, then an operation slightly larger than 2.5 million annual tons is marginally acceptable and the large scale operation has an NPV of $62 million. This indicates that deep ocean mining at a rate greater than that of the medium scale operation is an attractive investment for mining companies relative to their current operations.
CHAPTER 4

Issues in Ocean Mining Policy

The variety of issues that affect the U.S. policy on deep ocean mining are discussed in chapter one. This chapter examines two particular cases of deep ocean hard minerals policy in the areas of resource management and environmental protection.

Resource Management:

The United States has failed to achieve a satisfactory agreement on deep ocean mining at the U.N. Conference on the Law of the Sea due to opposition from the developing states. Some of these states have expressed concern that the countries which depend upon the export of nickel, copper, and cobalt will suffer economic loss due to mineral production from the seabed. These states wish to limit competition and minimize the exploitation of ocean nodules. The developing states that do not export minerals have supported the position of the mineral producing states. These states would like to insure that they receive a share of the profits obtained from the exploitation of nodules. In Part 1 of the Single Negotiating Text the desires of both groups of developing states are accommodated. The text states that the development of the international seabed area shall be undertaken to:

avoid or minimize any adverse effects on the revenues and economies of the developing countries, resulting from a substantial decline in their export earnings from minerals and other raw materials originating in their territory which are also derived from the area; and the activities shall be carried out to insure:
equitable sharing in the benefits derived therefrom, taking into particular consideration the interests and needs of the developing countries.\textsuperscript{6}

The provisions of Part I of the Single Negotiating Text are not satisfactory to the United States because it does not provide secure access to the seabed deposits for domestic companies.\textsuperscript{7}

As an alternative the United States has expressed that it is willing to consider a solution that includes a temporary limit on the production of metals from ocean nodules.\textsuperscript{8} The limitation would be tied to the projected growth of the nickel market. In addition, a fund would be established to share the profits of the exploitation of the seabed with developing states.\textsuperscript{9}

Since the profitability of the nodule mining operation is dependent primarily on the revenues from the sale of nickel, a production limit tied to the growth of the nickel market will also limit the production of copper and cobalt.\textsuperscript{10} The production of copper will be slightly less than that of nickel and, since the copper market is over 10 times the volume of the nickel market, the effect on copper prices will be negligible.\textsuperscript{11} The production limit would not protect Zaire, the largest producer of cobalt, from loss of revenue, but since cobalt is a by-product of copper and nickel production it is not as important a source of income.\textsuperscript{12}

The effects of a limit on the production of metals from the seabed will depend on the amount of production allowed. Projected limits on the recovery of nodules are shown in figure 4-1 for three rates of growth of the nickel market. The high rate, 6%, is suggested by the Secretary
A: Annual Growth Rate of Nickel Market = 6%
B: Annual Growth Rate of Nickel Market = 4%
C: Annual Growth Rate of Nickel Market = 2.8%

Figure 4-1

Nodule Recovery Allowed Under a Production Constraint Established by the Projected Growth of the Nickel Market
General of the United Nations. The other two rates, 4% and 2.8%, are the bounds projected by the U.S. Bureau of Mines for the period of 1968 to 2000. A rate of 3% was used by the Department of Interior in its First Annual Report to the Congress under the Mining and Minerals Policy Act of 1970 to predict the growth of U.S. nickel demand by 1985.

In 1985 it is predicted that there will be at least six companies interested in mining the deep ocean floor. Under a limit set by a 6% growth of the nickel market a total amount of 48 million tons of nodules could be mined in 1985. This would supply 12 operations of the large scale described in chapter 2. A 4% growth rate would allow production of 28.5 million tons of nodules, which is equivalent to 7 large scale operations. Under the assumption of the minimum growth rate mining of 18.6 million tons of nodules is allowed. This would limit the six mining companies to a scale of 3 million tons per year. If the production limit is set by a high projected rate of growth of the nickel market, then the nodule industry will not be affected. A low rate of growth will cause the companies to share the limited production and operate at a reduced scale with lower profits. The smaller scale of operation will reduce the NPV of the mining operations and reduce the companies willingness to pay for the right to mine the nodules, thereby lowering the income to developing states.

A temporary limit on the production of metals from the seabed may assure developing states that their economies will be protected but this analysis suggests that such a limit is not needed. The production of metals from nodules will draw capital away from investments in the
development of copper and nickel production operations on land. Recent investments in nickel production have been in nickel laterite deposits. The economics of nickel production from laterites and metal production from nodules are roughly equivalent. New capital will not be attracted to nodule development that would not be available for land-based operations, so the production of metals from nodules will not increase the overall production capacity for nickel beyond that which would result from land-based operations alone.

**Environmental Protection:**

Deep ocean mining will impact on the ocean environment in three areas: the seabed, the water column, and the surface waters. This section is concerned specifically with minimizing the impact in the water column by reducing the amount of sediment discharged from the lift.

There has been only a small amount of research into the effects of discharging large amounts of sediment into the water column. It is feared that the sediment from the discharge will be suspended in the upper layers of the ocean for years and might result in a change in the local ecology. In addition, it is possible that dormant spores may be carried with the sediment, becoming active in the warmer conditions at the surface and becoming a danger to the environment.

The problem of sediment discharge into the water column may be eliminated by pumping the entire lift discharge back to the sea floor. This would require a second pipe and pump system and modification of the mine ship to handle two pipe strings at the same time. A less expensive method is to concentrate the sediment so the denser mixture
can be pumped through a much smaller and less expensive pipe. For the model ocean mining operation sediment is removed from the lift discharge by a filter and centrifuge system. The entire lift discharge is treated with a chemical flocculant, to promote the clumping of sediment grains into larger particles, and pumped through a sand filter. The filtered water, free of sediment, is pumped over the side. Once a day the filter is backwashed to remove the accumulated sediment. This filter concentrates the sediment by a factor of about 70. The backwash is sent through a solid bowl scroll discharge centrifuge and is concentrated by a factor of 10. The overflow of the centrifuge is pumped overboard and the underflow, laden with sediment, is sent to a 2 inch ID plastic pipe that is attached to the hydraulic lift and reaches to the seabed. The underflow contains sufficient sediment to increase its density so that it will flow down the pipe without need of a pump.

The filter capacity is rated at 2 gal/min/ft. The capital and operating costs of the filter, flocculator, and chemical feed system are based on EPA studies and are updated to 1976 costs. The cost of the centrifuge is based on Backhurst and Harker, using a 1970 exchange rate of $2.40 per Pound Sterling and then updated to 1976 prices. The cost of pipe is taken from Mills. The results of capital and operating costs are listed in table 4-1.

The operating costs of the filtering system are less than 2/10's of 1% of the total operating costs of the overall mining operation and will have a negligible effect on the net present value of the operation. The capital costs, however, will have a noticeable effect. If the filter
<table>
<thead>
<tr>
<th>Production Rate ($10^6$ tons/year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift Discharge Rate (gal/min)</td>
<td>2720</td>
<td>6162</td>
<td>9542</td>
</tr>
<tr>
<td>Surface area of filter (square feet)</td>
<td>1360</td>
<td>3081</td>
<td>4771</td>
</tr>
<tr>
<td>Capital Cost:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter</td>
<td>$519000</td>
<td>$887000</td>
<td>$1201000</td>
</tr>
<tr>
<td>Flocculator</td>
<td>34130</td>
<td>54610</td>
<td>72350</td>
</tr>
<tr>
<td>Chemical Feed System</td>
<td>34130</td>
<td>54610</td>
<td>72350</td>
</tr>
<tr>
<td>Centrifuge</td>
<td>8125</td>
<td>12919</td>
<td>16594</td>
</tr>
<tr>
<td>Pipe (plastic)</td>
<td>27000</td>
<td>27000</td>
<td>27000</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>622385</td>
<td>1036139</td>
<td>1389294</td>
</tr>
<tr>
<td>Operating Cost:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter</td>
<td>56360</td>
<td>94380</td>
<td>124530</td>
</tr>
<tr>
<td>Flocculator</td>
<td>771</td>
<td>1395</td>
<td>1831</td>
</tr>
<tr>
<td>Chemical Feed System</td>
<td>27746</td>
<td>36624</td>
<td>40944</td>
</tr>
<tr>
<td>Total Operating Cost</td>
<td>84877</td>
<td>132399</td>
<td>167305</td>
</tr>
</tbody>
</table>
system is purchased in the third year of capital allocation (during year five of the project) the discount factor will be .57. The decrease in NPV of the mining operation is equal to the increased capital expense of the filter system times the discount factor. The decrease in NPV is $.35 million for the small operation (one million tons per year), $.59 million for the medium operation, and $.79 million for the large operation. In the large operation, which has a basic NPV of $62 million, the cost of the filtering system will reduce the NPV by 1.2 per cent, indicating that such a system can be required for mining operations with negligible effect on the attractiveness of the investment.
CHAPTER 5

Summary and Conclusions

United States policy on the exploitation of the hard minerals of the deep seafloor has been a policy of postponement. This is because ocean mining policy is one of several elements of the national oceans policy. The goal of this policy is to achieve a comprehensive treaty on the Law of the Sea which will be recognized by all nations. This treaty has not been reached, in large part, because of disagreements between developed and developing states over the right to mine the resources of the deep seabed. During the 1976 session of the 3rd United Nations Conference on the Law of the Sea the United States suggested that it might accept a compromise that includes a temporary limit on the production of metal from the minerals that are recovered from the deep seabed. If this compromise is not sufficient to produce a treaty that is acceptable to the United States, then the U.S. has stated that it will act unilaterally to protect the technological lead enjoyed by domestic companies by allowing them to proceed with their proposed deep ocean mining operations.

If a satisfactory treaty is not reached and the United States takes unilateral action then a domestic policy toward deep ocean mining must be developed. Such a policy will be based on current United States policies pertaining to the development of mineral resources and to the protection of the environment. The domestic mining and minerals policy requires that the federal government encourage the development
of domestic mining and minerals processing industries. The national environmental policy requires that the government take action to minimize the adverse effects of deep ocean mining operations that are carried out under its jurisdiction. In the event that these policies conflict, the laws and regulations that control domestic deep ocean mining operations must provide a compromise.

The technology to mine the minerals of the deep ocean floor has been developed from existing technology in the areas of minerals processing, deep water oil drilling, and deep sea surveying and observation. Although the mining of manganese nodules is without precedent, research programs conducted by mining companies and by academic institutions have indicated that mining operations are feasible. Since the operations are based on extrapolation of existing technology it is possible to estimate the cost of the mining operation from information about the costs of oil drilling, minerals transport, and minerals processing operations that are in current use.

In chapter 3 it is shown that deep ocean mining, at a nodule recovery rate of greater than 2.5 million tons per year, is an attractive investment for a mining company. At larger recovery rates the operation will generate 'excess profits,' which are the net revenues in excess of those needed to provide the minimum acceptable return on investment to the mining company. The value of the 'excess profits' is equal to the net present value of the mining operation when the costs and revenues are discounted at the minimum acceptable rate of return.
and it represents the maximum amount of money that a mining company would be willing to bid for the opportunity to mine the seabed. If an international authority forces companies to share a limited production of seafloor minerals, then the companies may be forced to operate at a reduced scale and generate less 'excess profits' that could otherwise be shared with the authority. This system of regulation would protect the export markets of the minerals producing developing states, but it would not assure the international community as a whole of a share of the profits of the operations. In order to maximize the revenues to the international community it may be necessary to limit entry into the ocean mining industry so that companies will be able to operate at an efficient scale of production. A method of regulating entry into the ocean mining industry that will satisfy the U.S. government, the mining companies, and the developing states should be developed and approved before a production limit is imposed.

The incorporation of the lift discharge filtering system into the model ocean mining system results in a small decrease in NPV, but the decrease would discourage only those operations that would otherwise mine at the marginal rate of 2.5 million tons per year. Operations larger than the marginal rate would remain as attractive investments when compared to land mining operations. Since the incorporation of the filtering system would not discourage investment in deep ocean mining and it would act to protect the ocean environment from possible degradation, then, in accordance with the National Environmental Policy
Act of 1969, it should be required for all operations that take place under United States jurisdiction.
APPENDIX A

Cost Estimation for the Hydraulic Lift

The hydraulic lift in this model utilizes a seven-stage centrifugal pump. The lift is designed to minimize the power consumption subject to the constraint that the pump is not to exceed its maximum suction head of 3000 feet of water. The power requirement of the lift is expressed in equations 1 through 5. The variables used in the equations are explained in table A-1.

Table A-1
Definition of Variables
Appearing in Hydraulic Lift Power Equations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Inside Diameter of Pipe</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational Constant</td>
</tr>
<tr>
<td>f</td>
<td>Friction Factor</td>
</tr>
<tr>
<td>L</td>
<td>Length of Pipe String</td>
</tr>
<tr>
<td>M</td>
<td>Mass Flow Rate of Nodules</td>
</tr>
<tr>
<td>Pf</td>
<td>Pressure Loss due to Friction</td>
</tr>
<tr>
<td>Ps</td>
<td>Pressure Load due to Suspended Matter</td>
</tr>
<tr>
<td>Q</td>
<td>Volume Flow Rate of Water</td>
</tr>
<tr>
<td>S</td>
<td>Ratio of Nodule Volume to Total Volume in Pipe</td>
</tr>
<tr>
<td>Vr</td>
<td>Velocity of Nodules Relative to Surface</td>
</tr>
<tr>
<td>Vt</td>
<td>Terminal Velocity of Nodules</td>
</tr>
<tr>
<td>Vw</td>
<td>Water Velocity in Pipe</td>
</tr>
<tr>
<td>$\rho_n$</td>
<td>Density of Nodules</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>Density of Water</td>
</tr>
<tr>
<td>$\rho_{ws}$</td>
<td>Density of Water-Sediment Mixture</td>
</tr>
</tbody>
</table>
Power required to operate the lift:

\[ \text{Power} = Q \times (P_f + P_s) \]  

(1)

Pressure loss due to friction:

\[ P_f = fL \frac{V^2}{2D} \]  

(2)

The pressure load due to suspended material:

\[ P_s = Lg[(\rho_n - \rho_w) \times S + (1 - S) \times (\rho_{ws} - \rho_w)] \]  

(3)

The water velocity is:

\[ V_w = V_r + V_t \]  

(4)

The velocity of nodules relative to the surface:

\[ V_r = \frac{(M/\rho_n)}{(S\pi D^2/4)} \]  

(5)

When equation (1) is solved under the conditions set for the model the power requirements for the system can be determined. The assumptions that are made and the results are listed in table A-2.

### Table A-2

<table>
<thead>
<tr>
<th>Assumptions:</th>
<th>Results:</th>
</tr>
</thead>
<tbody>
<tr>
<td>L = 15,000 feet</td>
<td>Mine Rate (dry tons x $10^6$/yr) 1.0 2.5 4.0</td>
</tr>
<tr>
<td>M = 1.35 x mine rate of dry nodules</td>
<td>Pipe Diameter (inches) 12 16 19</td>
</tr>
<tr>
<td>f = .013</td>
<td></td>
</tr>
<tr>
<td>$V_t$ = 3.28 feet/second</td>
<td></td>
</tr>
<tr>
<td>$\rho_n$ = 128 pounds/(foot)$^3$</td>
<td></td>
</tr>
<tr>
<td>$\rho_w$ = 64 pounds/(foot)$^3$</td>
<td></td>
</tr>
<tr>
<td>$P_{max} = (P_f + P_s) = 3000$ feet of water</td>
<td></td>
</tr>
<tr>
<td>No sediment is carried to the surface</td>
<td></td>
</tr>
</tbody>
</table>
Table A-2 (continued)

<table>
<thead>
<tr>
<th>Nodule to Pipe Volume Ratio</th>
<th>0.17</th>
<th>0.17</th>
<th>0.17</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{lift}} ) (PSI)</td>
<td>1251</td>
<td>1275</td>
<td>1277</td>
</tr>
<tr>
<td>Power (HP) - Theoretical</td>
<td>2001</td>
<td>4581</td>
<td>7100</td>
</tr>
<tr>
<td>- Actual</td>
<td>3078</td>
<td>7048</td>
<td>10923</td>
</tr>
</tbody>
</table>

The results shown in table A-2 can be used to estimate the capital and operating costs of the lift.

Capital cost:

The costs of the motor and pump are estimated by power law expressions that are updated to 1976 prices. The cost of the pump is given by the formula:

\[
P_{\text{pump}} = 2771 \times (\text{power})^{0.41}
\]

The motor used to operate the pump has a cost expressed as:

\[
P_{\text{motor}} = 37.5 \times (\text{power}/\text{pump efficiency})^{0.885}
\]

where the pump efficiency is 65\%.

The pump and motor are housed in a steel hull which costs $100,000.

The remainder of the lift consists of the pipe string that reaches to the seafloor, which has a wall thickness of 0.5 inch, and the pipe that reaches 3000 feet up to the mine ship, with a wall thickness of 0.75 inch. The cost of the high strength steel in pipe form is $1.00 per pound. The cost of couplings used to join the pipe total 50\% of the pipe cost.

The costs of the lift sub-sections are listed in table A-3.
Table A-3

Cost of Hydraulic Lift Components

<table>
<thead>
<tr>
<th>Production Rate (10^6 tons per year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($ \times 10^6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe and Couplings</td>
<td>1.7</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Pump and Housing</td>
<td>0.4</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The labor and power requirements of the lift are considered as part of the operating expenses of the overall recovery system. An additional expense of the lift is the replacement of pipe as it ages in the high stress and corrosion of the operating environment. The pipe is estimated to have a two year operating life, so 50% of the pipe is replaced every year.\(^9\)
Appendix B

Cost Estimation of the Processing Plant

Most of the techniques used to recover metal values from nodules have been applied in copper and nickel extractive metallurgy in the past. The experience gained from previous operations is used here to estimate the costs of the processing plant.

Capital Cost:

The capital cost of the processing plant is calculated by the factored estimate method. In this method the total capital cost is set equal to the sum of the installed equipment cost, the buildings cost, the utilities cost, and the cost of off site development. The costs of buildings, utilities, and off site development are assumed to be proportional to the cost of the installed process equipment. The proportionality constants are determined from experience with similar plants. The installed cost of equipment is estimated by a power law expression of the form:

\[
\text{Cost} = \text{constant} \times (\text{Processing Rate})^{\text{exponent}}
\]

The values of the constants and exponents for each item are tabulated in table B-1. All costs are updated to 1976 dollars. The coefficients for the crushing and grinding operations and for the overflow and underflow pumps in the leaching circuit are taken from cost estimates by H.E. Mills and K.M. Guthrie. The costs for the drying and reduction steps are derived from data on the
roasting equipment of the Chambshi RLE plant in Zambia, and from pilot plant operations at the Anaconda plant at Twin Buttes, Arizona. The LIX circuit coefficients are based on a design and

Table B-1

Capital Cost Estimation Factors for Process Plant

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Constant</th>
<th>Exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushers (2 units)</td>
<td>3.17 x 10^{-3}</td>
<td>1.22</td>
</tr>
<tr>
<td>Dryer</td>
<td>335.63</td>
<td>.72</td>
</tr>
<tr>
<td>Grinders (2 units)</td>
<td>27.94</td>
<td>.70</td>
</tr>
<tr>
<td>Reduction Furnace</td>
<td>564.8</td>
<td>.72</td>
</tr>
<tr>
<td>Mixing Vessels with Agitators (7 units)</td>
<td>85.54</td>
<td>.81</td>
</tr>
<tr>
<td>Pumps, Centrifugal (7)</td>
<td>440.58</td>
<td>.34</td>
</tr>
<tr>
<td>Pumps, Diaphram (7)</td>
<td>48.92</td>
<td>.50</td>
</tr>
<tr>
<td>Thickeners (7 units)</td>
<td>715.09</td>
<td>.60</td>
</tr>
<tr>
<td>LIX Circuit</td>
<td>4474.5</td>
<td>.60</td>
</tr>
<tr>
<td>Electrowinning</td>
<td>5.05</td>
<td>1.00</td>
</tr>
<tr>
<td>Stripping Tower</td>
<td>586.41</td>
<td>.71</td>
</tr>
</tbody>
</table>

cost analysis performed by engineers at General Mills. The electrowinning costs are from a study made at the Colorado School of Mines. The cost of the stripping tower is estimated from approximate costs given by Kennecott's Ledgemont Laboratory.
## Table B-2

Schedule of Process Plant Capital Costs

(Costs in $10^6$

<table>
<thead>
<tr>
<th>Ore Processing Rate ($10^6$ tons/year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushers</td>
<td>0.07</td>
<td>0.22</td>
<td>0.38</td>
</tr>
<tr>
<td>Dryer</td>
<td>7.18</td>
<td>13.90</td>
<td>19.53</td>
</tr>
<tr>
<td>Grinders</td>
<td>0.43</td>
<td>0.82</td>
<td>1.13</td>
</tr>
<tr>
<td>Reduction Furnace</td>
<td>11.84</td>
<td>22.89</td>
<td>32.14</td>
</tr>
<tr>
<td>Mixing Vessels with Agitators</td>
<td>5.84</td>
<td>12.20</td>
<td>17.85</td>
</tr>
<tr>
<td>Pumps, Centrifugal</td>
<td>0.05</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>Pumps, Diaphragm</td>
<td>0.05</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>Thickeners</td>
<td>2.93</td>
<td>5.09</td>
<td>6.75</td>
</tr>
<tr>
<td>LIX Separation Circuit</td>
<td>17.72</td>
<td>30.69</td>
<td>40.69</td>
</tr>
<tr>
<td>Electrowinning</td>
<td>4.99</td>
<td>12.46</td>
<td>19.94</td>
</tr>
<tr>
<td>Stripping Tower</td>
<td>10.34</td>
<td>19.78</td>
<td>27.58</td>
</tr>
<tr>
<td><strong>Sub-total (Process Equipment)</strong></td>
<td>61.44</td>
<td>118.20</td>
<td>166.17</td>
</tr>
<tr>
<td><strong>Offsite (100% of Process Equipment)</strong></td>
<td>61.44</td>
<td>118.20</td>
<td>166.17</td>
</tr>
<tr>
<td><strong>Utilities (57% of Process Equipment)</strong></td>
<td>35.02</td>
<td>67.37</td>
<td>94.72</td>
</tr>
<tr>
<td><strong>Buildings (10% of Process Equipment)</strong></td>
<td>17.82</td>
<td>34.28</td>
<td>48.19</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>175.72</td>
<td>339.27</td>
<td>475.25</td>
</tr>
<tr>
<td><strong>Capital cost per ton of ore ($)</strong></td>
<td>175.72</td>
<td>135.71</td>
<td>118.81</td>
</tr>
</tbody>
</table>
The cost of mixing vessels and agitators are based on a 30 minute residence time in stainless steel vessels at each stage of the leach. The costs are obtained from Happel and Jordan. The size of thickeners required in the plant is estimated from the results of the Twin Buttes pilot plant, which required up to 9.2 square feet of settling area for each ton per day of the daily processing rate. The cost of the thickeners is found in the Chemical Engineer's Handbook.

The installed cost of each class of equipment is calculated for three production rates and is shown in table B-2. Building, utilities, and off site development costs are also listed in table B-2. The constants used to compute these costs are developed from the construction costs for refineries.
Table B-3
Operating Costs of the Nodule Processing Plant

<table>
<thead>
<tr>
<th>Production Rate (10^6 tons per year)</th>
<th>1.0</th>
<th>2.5</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Cost:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials and Utilities:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power ($0.3/KW-HR)</td>
<td>3.54</td>
<td>8.70</td>
<td>14.16</td>
</tr>
<tr>
<td>Natural Gas ($1.75/1000 SCF)</td>
<td>7.00</td>
<td>17.50</td>
<td>28.00</td>
</tr>
<tr>
<td>Steam ($1.50/1000 pounds)</td>
<td>1.50</td>
<td>3.80</td>
<td>6.00</td>
</tr>
<tr>
<td>Ammonia</td>
<td>1.00</td>
<td>2.50</td>
<td>4.00</td>
</tr>
<tr>
<td>LIX chemicals</td>
<td>0.40</td>
<td>1.00</td>
<td>1.60</td>
</tr>
<tr>
<td><strong>Direct Labor:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Labor ($4.00/hour)</td>
<td>1.91</td>
<td>2.73</td>
<td>3.36</td>
</tr>
<tr>
<td>Supervision (20% of operating labor)</td>
<td>0.38</td>
<td>0.55</td>
<td>0.67</td>
</tr>
<tr>
<td>Maintenance (6% of equipment investment)</td>
<td>3.69</td>
<td>7.09</td>
<td>9.97</td>
</tr>
<tr>
<td>Payroll Overhead (25% of payroll)</td>
<td>0.57</td>
<td>0.82</td>
<td>1.01</td>
</tr>
<tr>
<td>Operating Supplies (1.2% of investment)</td>
<td>2.11</td>
<td>4.07</td>
<td>5.70</td>
</tr>
<tr>
<td><strong>Sub-total: Direct Cost</strong></td>
<td>22.10</td>
<td>48.76</td>
<td>74.47</td>
</tr>
<tr>
<td><strong>Indirect Cost:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Administration and General Overhead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(40% of direct labor)</td>
<td>0.92</td>
<td>1.31</td>
<td>1.61</td>
</tr>
<tr>
<td><strong>Fixed Cost:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taxes and Insurance (2% of investment)</td>
<td>3.51</td>
<td>6.79</td>
<td>9.51</td>
</tr>
<tr>
<td><strong>Total: Operating Cost</strong></td>
<td>26.53</td>
<td>56.86</td>
<td>85.59</td>
</tr>
<tr>
<td><strong>Cost per Ton ($/ton)</strong></td>
<td>26.53</td>
<td>22.74</td>
<td>21.40</td>
</tr>
</tbody>
</table>
Operating Cost:

The estimated operating cost of the nodule processing plant, shown in table B-3, is based on a 3 shift per day, 300 day per year operation. The expenses include power, fuel, materials, labor and charges proportional to capital and labor such as taxes and general overhead.

Power requirements of each major type of equipment are shown in table B-4. The power consumption of the crushing and grinding operations is calculated by the equation:

\[ \text{Power} = 10 \times B (1/P - 1/F) \]

where \( P \) is the product diameter, \( F \) is the feed diameter and \( B \) is the bond index, which for nodules is 7 KW-HR/ Ton. The power consumed by the fluid bed dryer is estimated at 8.95 KW-HR/ Ton and the roaster, which cycles the ore through its bed a second time, requires twice that amount. The power required by the electrowinning equipment is 1.2 KW-HR per pound of metal recovered. The power consumed in the LIX circuit is derived from the work of Merigold and Sudderth at General Mills. The power requirements of the other equipment is based on the motor size in each application.

The drying and reduction steps consume natural gas at a rate of 4000 SCF per ton of ore.

Material requirements of the operation include ammonia, LIX chemicals, and steam. Ammonia make-up costs about $1.
Table B-4

Schedule of Electric Power Consumption

(Power in $10^6$ KWH)

<table>
<thead>
<tr>
<th>Activity</th>
<th>Power (10^6 kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ore processing rate (10^6 tons/year)</td>
<td>1.0 2.5 4.0</td>
</tr>
<tr>
<td>Crushing and grinding</td>
<td>9.54 23.85 38.16</td>
</tr>
<tr>
<td>Dryer</td>
<td>8.95 22.38 35.80</td>
</tr>
<tr>
<td>Reduction furnace</td>
<td>17.90 44.75 71.61</td>
</tr>
<tr>
<td>Agitators</td>
<td>6.26 15.94 25.04</td>
</tr>
<tr>
<td>Pumps</td>
<td>.47 1.18 1.88</td>
</tr>
<tr>
<td>Thickeners</td>
<td>.19 .47 .75</td>
</tr>
<tr>
<td>LIX circuit</td>
<td>.33 .84 1.34</td>
</tr>
<tr>
<td>Electrowinning</td>
<td>71.30 173.00 285.00</td>
</tr>
<tr>
<td>Total</td>
<td>114.94 282.11 459.58</td>
</tr>
</tbody>
</table>
per ton of ore\textsuperscript{22}. LIX chemicals cost \$0.40 per ton of ore\textsuperscript{23}. Steam is used in the stripping tower at a rate of 1000 pounds per ton of ore\textsuperscript{24}.

Labor costs for the electrowinning section, which is highly labor intensive, are 2.05 \$\text{/pound}, 1.25 \$\text{/pound}, and 1.00 \$\text{/pound} for the small, medium, and large operations respectively. These costs are based on interpolation and extrapolation of the figures reported by Balberyszski and Anderson.\textsuperscript{35} Labor requirements in the crushing and grinding, drying and reduction, leaching, ion exchange, and stripping tower steps are estimated by the formula:

\[
\text{Labor (man-hours/day)} = 48 \times \frac{\text{Production Rate}}{100}
\]

with the production rate expressed in tons per day.\textsuperscript{36}
Footnotes

Chapter 1


8. Ibid., pp. 147-148. 9. Ibid., p. 149.

10. Ibid., pp. 149-150.


14. 30 USC 21a.


20. Ibid., section 5.


25. A fund for developing states, as suggested by the Stratton Commission, was provided in HR 9, 93d Cong., 1st Sess., and in S. 2801. Later versions contain no provisions for collection of royalties or payments to an escrow fund.


27. James G. Wenzel, Statement before Senate Committee on Interior and Insular Affairs, Subcommittee on Minerals, Materials and Fuels (hereinafter Senate Interior Committee), November 7, 1975, pp. 3-4. See also statement of John Flipse before Senate Interior Committee, November 7, 1975, p. 9.


31. Draft Interior Department Bill, Sections 7(d) and 10.

32. Marne A. Dubs, Statement before Senate Interior Committee, November 7, 1975, p. 5.


34. New York Times, April 7, 1976, p. 1. 35. Ibid.


41. Ibid. 42. 42 USC 4331 43. Frank, p. 25-26.


47. Amos, p. 280.


52. Frank, p. 16.

53. 42 USC 4331.

Chapter 2


8. Ibid., p. 77.

9. Roels et al.


14. Ibid.


17. Riedel, pp. 28-29.


21. Personal communication with Ernest Vincent, Klein Associates, August, 1976. Side scan sonars for use at 15,000 feet are constructed by special contract at approximately $250,000. If the units are produced commercially the price may drop as low as $30,000.

22. Armored cable, side scan sonar and other electronics are estimated to cost $750,000. Construction, modification and testing double this figure to give total cost of one bottom unit.


27. Maintainence costs for pump unit and bottom unit are rated at 20% per year to account for the adverse environment.

28. The value of 5.5% reflects the operational safety record of new drillships.

29. Lacourt, passim.


31. Ibid. A new 449 foot dynamically positioned drillship for Odeca cost $48 million.
32. Ibid. The Offshore Company bought a 534 drillship for $61 million.


35. Ibid.


41. The intermediate and final grind sizes are suggested in Frantz and McNulty.

Chapter 3

1. See note 10, Chapter 2.


4. Ibid.

5. Chemical Marketing Reporter, March through April, nickel and copper averages are $2.015 and $0.6375 per pound, respectively.


17. Happel, p. 38.


19. The yield of the operation can be determined by calculating the NPV as a function of the discount rate. By interpolation it is found that for the large operation a discount rate of 18% results in an NPV of zero for a 31 year life. This is significantly above the current return on total capital of the mining companies, and is in the range expected of projects of moderate technical risk.

Chapter 4

1. Marne Dubs, Testimony before Senate Interior Committee, 8 June, 1975.

3. Ibid., p. 5.


6. Ibid.

7. Leigh Ratiner, at MIT Sea Grant Symposium, 16 October 1975, p. 32.


9. Ibid., 1946.


13. Economic Implications, p. 34.


20. Ibid.


23. Bowman, p. 48. Wash water requirement is approximately 1.5% of the total filtered volume.

25. Bowman, p. 48. The backwash, prior to centrifugation, may contain 12 pounds of solids in 200 gallons of water.


30. The actual decrease in NPV will be slightly less than these figures due to the reduction in taxes resulting from the depreciation of the filtering system.

Chapter 5


6. Several processing methods have been shown to apply to manganese nodules by Fuerstenau, et al, at U. of C. (Berkeley). Tests by Deepsea Ventures and International Nickel have shown the feasibility of the hydraulic lift in mining the sea floor.


8. NEPA of 1969, 42 USC 4331.

Appendix A


3. Density of nodules is from Sullivan, p. 1. Terminal velocity is based on a sphere with a diameter of 1.5 inches and a drag coefficient of 0.5.


5. Ibid.

6. The housing cost is based on a hull 26 feet long, 6 feet in diameter, with a wall thickness of 1.5 inches. At $1.00 per pound for HY-80 the hull cost is $35,000. Fabrication and installation costs are estimated at twice the materials cost.

7. Personal communication with James Broda, Woods Hole Oceanographic Institution, April, 1976.


9. Ibid.

Appendix B


2. J.R. Backhurst and J.H. Harker, in *Process Plant Design*, p. 38, suggest that this technique can provide an accuracy of 10% when the factors are carefully selected.


11. Frantz, p. 637, uses a 1 hour residence time and two leaching tanks. The model system has 7 leaching stages so the residence time is reduced.

12. Happel, pp. 229-230


22. Ibid.


26. Ibid.

27. Ibid.

28. Ibid. p. 248.

29. Bennett, p. 146.


31. Bennett, p. 146.

32. Ibid.

33. Ibid.

34. Ibid.

35. Balberyszski, p. 196.

Bibliography


Anderson, Earl V. "Nickel is Key to Ocean Mining Venture." Chemical and Engineering News, August 2, 1976, pp. 10-11.


"Neddrill Will Convert Two Bulk Carriers to Drillships." Ocean Industry, October, 1975, pp. 45-51.


U.S. Government Documents:


United Nations Documents:


Group of 77 Position. c.1/CRP.7 15 August, 1974.

The Impact of Cobalt Production from the Seabed. TD/B(XIII)/Misc.3 GE.73-50049

