The MIT Marine Industry Collegium
Opportunity Brief #12

Deep Ocean Mineral Mining: A Computer Model for Investigating Costs, Rates of Return, and Economic Implications of Some Policy Options

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DEEP OCEAN MINERAL MINING:

A Computer Model for Investigating Costs, Rates of Return, and Economic Implications of Some Policy Options

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PREFACE

This Opportunity Brief and the accompanying Workshop (held on April 6, 1978) were presented as part of the MIT/Marine Industry Collegium program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 90 corporations and government agencies who are members of the Collegium. The underlying studies at MIT were carried out under the leadership of Professor J. D. Nyhart, but the author remains responsible for the assertions and conclusions presented herein.

Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant, at 617-253-4434.

Norman Doelling
1 July, 1978

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1. Business Perspective

Deep-ocean mining has been of interest during the past decade for two main reasons. It appears to have the potential for being profitable and it could serve to reduce U.S. dependence on imports of minerals that have strategic and economic importance.

Professor J. D. Nyhart has led a research group at MIT that developed a deterministic financial simulation model of the deep-ocean mining of manganese nodules. These nodules contain nickel, copper, cobalt, and manganese in commercially valuable quantities. The model incorporates some reasoned assumptions about the technical and financial characteristics of such a project and develops estimates of total capital investment, operating expenses and cash flow for a mining and processing operation handling three million tons of nodules annually over a 25 year period. The cash flow data form the basis for calculating various measures of return on investment, such as net present value, internal rate of return, and the value of annual tax revenues.

The deep-ocean mining model is useful to companies or consortia proposing to engage in deep-ocean mining, to companies interested in providing goods and services to the consortia, and to policy makers concerned with economic consequences of these operations. For consortia, the model permits the exploration of economic consequences of alternative technologies, financing strategies, and regulatory environments. Decision makers can play "what if" games in a simulated environment.

For companies supplying goods and services to the mining consortium, the model indicates the nature of purchases to be made, the approximate dollar amount of each, and when they will be made. As the model reveals, the consortium undertaking exploitation of deep-ocean manganese nodules will make a capital investment of about $500,000,000 and will incur annual operating expenses of roughly $100,000,000 for a single representative mining site.

Finally, subtle differences in national policy options and outcomes of the Law of the Sea negotiations can have profound effects on the cost of the mining operation. The model can be used to make clear to policy makers, legislators, and negotiators the economic consequences of policy proposals, in terms of return both to the consortium and to the net national income.

2. Rationale for Deep-Sea Mining

In 1975, the United States imported 9% of its primary cobalt, 71% of its primary nickel, and 15% of its primary copper. Under certain reasonable assumptions, the United States could, by the year 2000, be totally dependent on imports for all of its nickel and cobalt and a large fraction of its copper. Aggregates of these minerals, called manganese or ferromanganese nodules, are known to exist in substantial quantities over large parts of the deep-ocean floor. If these nodules could be mined profitably in significant quantities, they could reduce dependence on foreign sources.

3. The Deep-Sea Mining Model

3.1 Description of the Model

The deep-sea mining model is a deterministic financial simulation model. Although its focus is monetary, the model elegantly couples considerations of engineering, systems design, and finance in generating cost information. For example, when the user specifies a new depth of the mine site (and some other pertinent variables), the model re-computes the pumping power needed, optimum pipe size, parameters of the mining ship itself, and calculates costs for the required pumps, pipes, etc. Similarly, when distance to port, maximum depth in the port (draught), and other variables are specified, the model computes the optimum number and size of ships needed for transport and calculates the capital costs and operating expenses that are then used by later steps of the program. The inputs to the model are, or are transformed into, capital investments and operational expenses made over certain time periods. The investments and expenses are derived from a carefully reasoned set of assumptions concerning a "baseline" deep-sea mining and refining operation. The outputs include cash flows, taxes and profits (as a function of time), net present value (as a function of discount rate), and internal rate of return, all of which are calculated under certain assumptions about financing and tax environments.

The value of this model is twofold. The first advantage is that the process of building the model requires assembling the requisite input data and making each calculated or assumed variable explicit to both the builder of the model and the user. Almost all the requisite input data can be varied by other users who may make different assumptions about pertinent inputs. Thus, the model is a database that can easily be varied to fit different perceptions of the world.

In addition, the model provides a framework and procedure for computing financial implications of the changes in assumptions about the financial alternatives (e.g., debt-to-equity ratio can be varied) or the tax environment (several depreciation alternatives are permitted, and investment tax credits and depletion allowances can be varied). The model is a tool for investigating the future consequences resulting from alternative views of the political, regulatory, and tax environments.

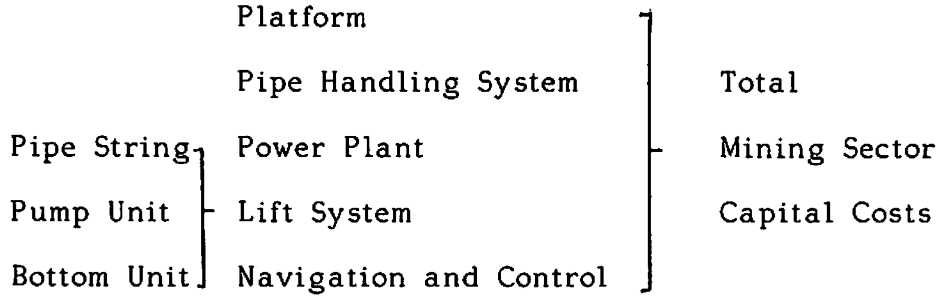
The model divides the deep-sea mining and refining operation into major activities or sectors:

Prospecting and exploration
Mining
Transport
Processing

Each sector is then broken into subsystems to identify capital costs and operating expenses associated with each item. For example, as Figure 1 shows, the mining sector is divided into the following subsystems: platform, pipe handling, power plants, lift system, and navigation and control. These subsystems are further divided where appropriate into smaller components, e.g., the lift system is divided into: pipe string, pump unit, and bottom unit. This breakdown is used for detailing capital costs.

Figure 1

Categories of Capital Costs for Mining Sectors



A similar breakdown identifies detailed operating costs and aggregates them into five classes: energy, labor, materials, fixed, miscellaneous (see Fig. 2).

All of the capital costs and the expenses are assigned a time value or values indicating when they are incurred relative to other activities and costs. Time value assignment permits generation of cash flow schedules. The time values are explicitly given and can be varied so one can see the financial effects of, for example, a two-year political moratorium on mining following prospecting and exploration. The outline of the project time-line is given in Figure 3.

Annual cash flow is then determined as depicted in Figure 4. Total capital costs, net present value, internal rate of return, and payback period are calculated from supplementary subroutines.

Figure 2
Operating Cost Structure
in the Mining Sector

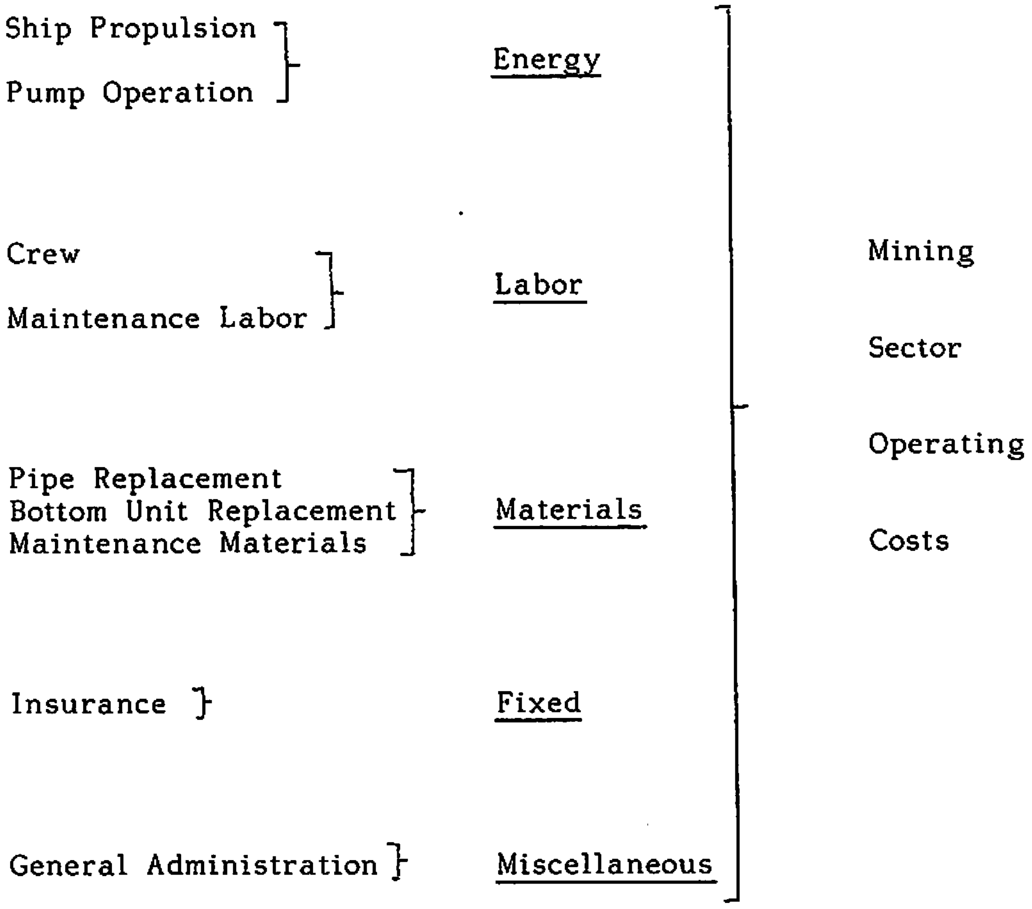
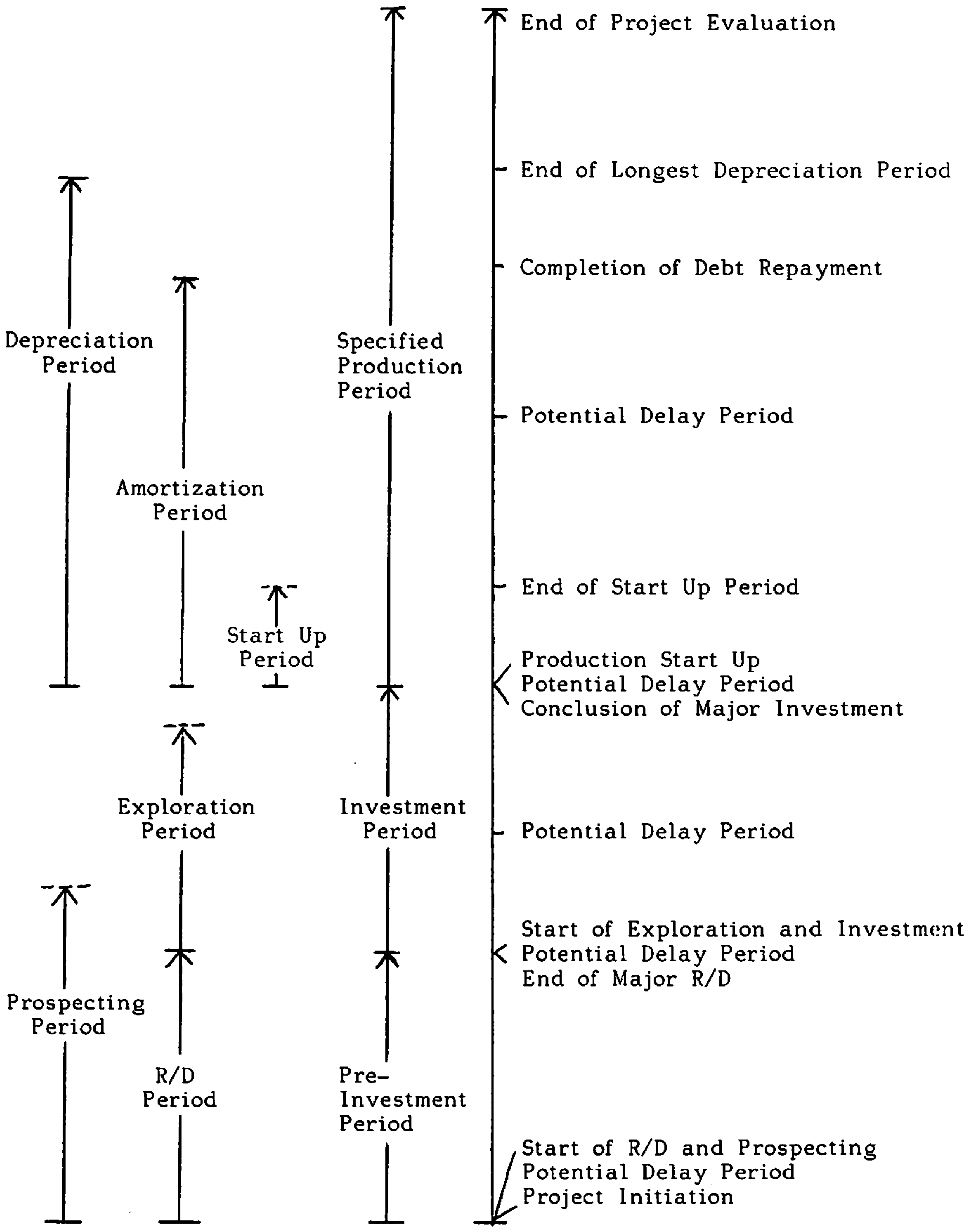


Figure 3
Project Timeline



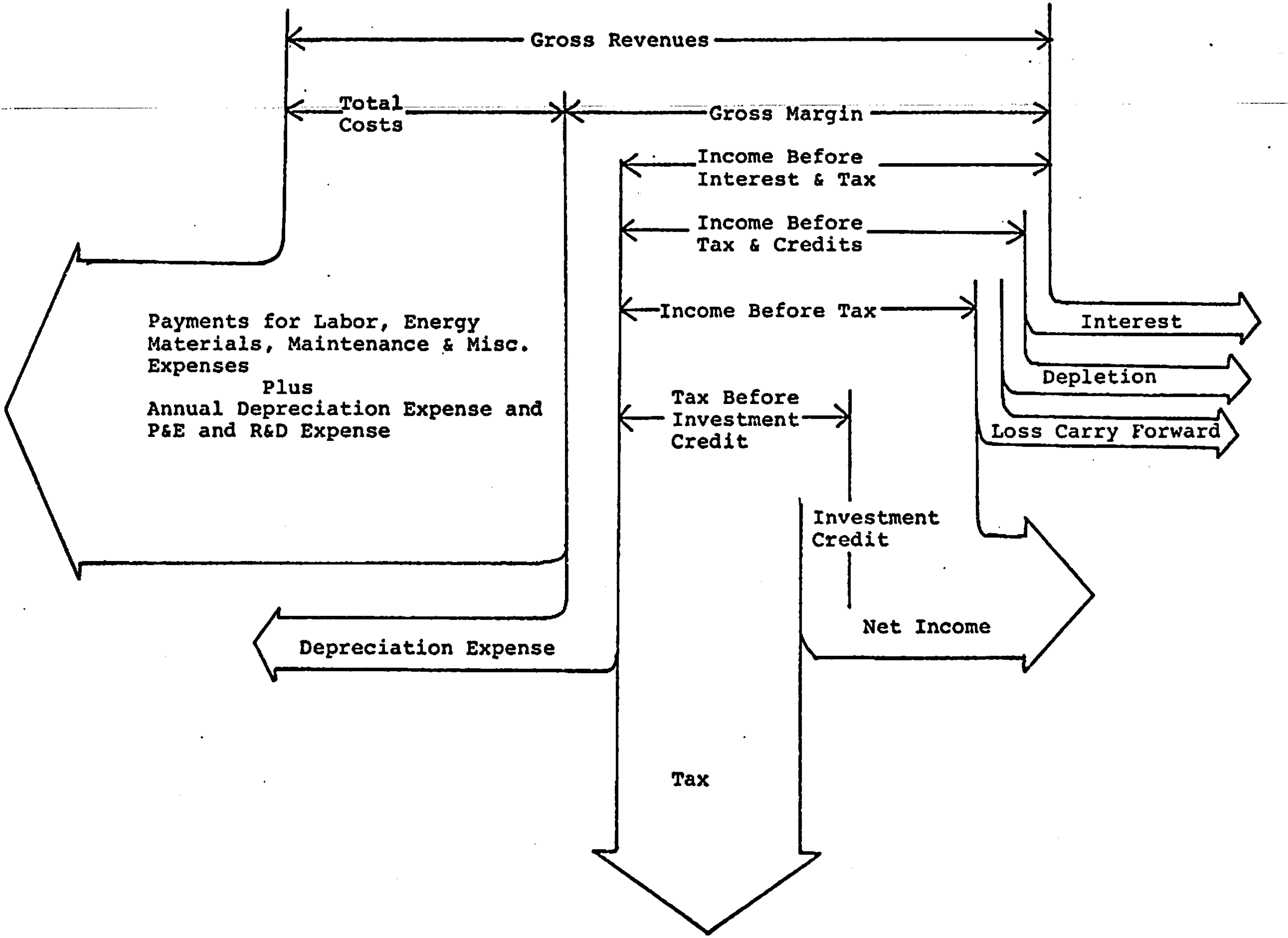


Figure 4

Determination of Annual Tax Liability

3.2. Baseline Model Assumptions

The "Baseline Model" is one run of the model for which the initial values of all the variable parameters represent a reasoned set of assumptions about the activities, equipment, and costs of a "typical" mining operation. Assumptions about costs and the structure of the model represent the efforts of the research team; more than 75% of the costs estimates have been developed independent of the four major industry consortia. However, the authors of the model did benefit from extensive reviews of earlier drafts of Reference 2 by representatives from the consortia, other technical schools, banks, the U.S. Bureau of Mines, and the National Oceanographic and Atmospheric Administration.

The baseline model represents a sensible starting point for looking at the results. The Baseline Model Site Characteristics are:

Water Depth		18,000 feet
Distance to Port		1,750 nautical miles
Surface Abundance		2 pounds/square foot
Nodule Diameter		.125 feet
Drag Coefficient of Nodule		.5
Density of Nodules		128 pounds/cubic foot
Metal Content:	Nickel	1.5%
	Copper	1.3%
	Cobalt	0.24%
	Manganese	26.9%

We have appended Chapter 4 of Reference 2 to this report. It lists the initial baseline values of almost 200 variables used in the baseline model. (Most of the variables will be obvious to the reader, but many are not. We refer the interested reader to Reference 2.)

4. Some Representative Data from the Baseline Model

4.1 Preliminary Investment and Expenses

The first significant result of the model is the total investment prior to receiving income from sale of refined minerals. These expenses total approximately $560 million dollars, broken down as follows:

Research and Development	$ 50.0 (rounded to millions)
Prospecting and Exploration	16.0
Capital Investment	493.0
Total	$560.0

The magnitude of the investment and the many uncertainties associated with the venture suggest why consortia rather than single companies are working on the project.

Capital expenses in more detail are:

Mining Sector (including the mining platform, lift systems, power plant, pipe handling system, navigation systems	$95.8 million
Transport Sector (including transport ships to bring the nodules to shore, slurry system to carry the nodules to a refinery and a slurry system to carry off waste	$55.1 million
Processing Sector, including processing equipment (199.3 million), utilities ($83.6 million), buildings ($19.93 million), site development ($20.2 million), and waste disposal (19.95 million)	$342.2 million

Note that only about a fourth of the total expenses ($150 million) is a direct consequence of mining at sea. The remaining three fourths ($342 million) is related to ore-refining, for which the technology and facilities are presumably similar to land-based mining operations. In other words, the data suggest that the deep-sea mining operation, the part of the operation which is new and therefore most risk-prone, does not excessively dominate the investment costs.

4.2 Operating Expenses

Listed below are annual operating expenses over the production period (assumed to be from the 6th year to the 25th year) following the decision to start:

Mining Sector	$ 21
Transport Sector	15
Processing Sector	65
Total	$100 million

Again, processing expenses are twice the level of the marine-related expenses, further suggesting the marine aspects do not dominate the costs involved.

4.3 Economic Return

Based on the initial values of the model and assumed prices for the refinery output, the annual production and revenue during the 6th through 30th year are:

	Annual Production (lbs. x 10^6)	Revenue (\$ x 10^6)
Nickel	85.5	171.0
Copper	74.1	52.61
Cobalt	8.64	34.56
Manganese	0.0	0.0
Total Annual Revenue		258.17

Three measures of economic return were calculated for the baseline case. These are net present value (NPV), internal rate of return (IROR) (the discount rate for which NPV = 0), and pay-back period.

Representative net present values for several discount rates are:

Discount Rate	8%	12%	16%	20%	24%
NPV (\$ million)	349.07	144.60	36.43	-23.89	-58.73

The IROR for the baseline project is 18.14% and the pay-back period is only 5.4 years from commencement of production. Under the baseline assumptions, the operation becomes profitable during the sixth year, the first year of mining operation.

In summary, although subject to many uncertainties, a deep-sea mining operation as described by the baseline project can be a reasonably profitable endeavor.

5. Some Implications of Variations from Baseline

More than 100 analyses were carried out, using the model to explore different revenues, operating costs, financing options, depletion allowances and other variables. The reader is referred to Reference 2 for details.

Professor Nyhart's group summarized the effects as follows:

1. "The largest impacts on economic return were from changing the level of revenue flowing into the project and from variables which are among the determinants of the level of revenue (market price of nickel, ore grade, production rate).

> Total revenues are the major source of the project's positive cash flows, on which the economic return measures are based. Thus anything that either cuts or adds substantially to revenues will have a heavy direct impact on economic return. A 25% downward shift in the level of revenues itself lowered the internal rate of return measures (IROR) by 8.63% to 9.51%. Conversely, a comparable upward shift added 6.31%. 25% downward and upward shifts in the price of nickel lowered and raised IROR by 5.36% and 4.3%, respectively. Similarly, a drop in combined nickel-copper ore grade from 2.8% to 2% decreased the estimated IROR from 18.14% To 11.16%. Decreasing annual production of .5 million tons (a 16 2/3% change) reduced the IROR by more than two percentage points, while a comparable increase raised it by 1.4%. A slow start-up, with the first two years production at 70% and 85% of projected rate, and higher than expected expenses, indicated a similar reduction in IROR.
>
> These analyses suggest that the relative sensitivity of the economic outlook for deep seabed mining on factors such as market price, or quality of the ore bed, which are at least partially outside the control of the project's managers.

2. "25% shifts in annual operating costs and in capital investment, two other major factors in determining cash flow (when capital investment is allocated on an annual basis) caused smaller changes in indicated economic return which, however, were large when compared to most other changes made.

> Shifting annual operating costs of $100.5 million a year downward and upward by 25% caused the IROR to change from 18.14% to 15.07% and 20.72%, respectively. Similar shifts in total capital investment, for $495 million to $616 and $370 million, changed the indicated IROR to 15.01% and 21.98%.

3. "Delays of two years introduced in the planned project schedule before investment and between investment and comencement of operations also caused decreases in estimated IROR to 17.01% and, more significantly, 12.95% respectively. When these two delays were combined, the IROR decreased further to 12.28%. One year delays caused smaller decreases.

> The analyses point up the impact of delay from any cause from the investor's viewpoint at the time it is considering commitment of funds, and particularly the effect of delay after those funds have been invested.

4. "The one other variable that indicated relatively sizeable resulting shift in IROR is the use of debt funding.

> The baseline model assumed 50% debt funding. Changing that assumption to no debt funding and 66 2/3% debt produced IROR estimates of 15.41% and 19.53% respectively. The slightly more than 4% spread represented in these two assumptions suggests the importance managers may attach to their ability to attract outside capital."

All but two variables investigated had small effects (less than 1.1%). Building the mine ships in United States yards and using United States crews caused a 1.9% decrease in IROR, and varying the capital cost of the processing equipment also strongly affected IROR.

REFERENCES

We present only two references for this brief, since they contain excellent bibliographies for the interested reader. In addition, Reference 1 contains five excellent survey articles. Reference 2 is essential for anyone interested in detailed applications of the model to date or use of the model for further investigations.

1. Marine Mining. Volume 1, Number 1/2, 1977. Crane Russak & Co., Inc. 347 Madison Avenue, New York, NY, 10017

2. Nyhart, J. D., et al. A Cost Model of Deep Ocean Mining and Associated Regulatory Issues. MIT Sea Grant Report Number MITSG-78-4, 1978.

APPENDIX

CHAPTER IV. THE INITIAL VALUE OF THE MODEL'S MAIN PARAMETERS

All input variables to the ocean mining model are assigned initial values that represent the conditions of the baseline model. The baseline conditions are summarized in the following sections of this chapter. The variables can be easily changed by the operator but the initial values have been chosen to represent accurately the current state of the art in mining, transportation, and processing.

The following list of initial values is divided into five groups: Prospecting and Exploration; Mining; Transportation; Processing; and Financial Analysis. The lists include the variable name in capital letters, a description of the variable, and the initial value and units of the variable.

A. Initial Values of Input Variables in the Prospecting and Exploration Section

Variable	Description	Value	Units
AAFM	Area of Site Available for Mining	.8	
ABB	Surface Abundance of Nodules on Seafloor	2	lb/ft^2
ARO	Annual Rate of Recovery of Ore	3000000	Dry Short Tons
COLEFF	Collector Efficienty	.65	
EXPLBR	Cost of Labor in Exploration Program	660000	Dollars
MAPCST	Cost of Continuous Mapping Survey	432	\$/km^2
PROSCS	Cost of Complete Prospecting Program	1600000	Dollars

Variable	Description	Value	Units
SHRENT	Daily Rental Rate of Research Vessel	5000	\$/day
SOILCS	Cost of Discrete Soil Sampling Survey	97	\$/km^2
SWPEFF	Sweep Efficiency	.50	
WNSEF	Water-Nodule Separation Efficiency	1.0	

B. Initial Values of Input Variables in the Mining Sector

Variable	Description	Value	Units
ABB	Surface Abundance of Nodules	2	lb/ft^2
ADMFEE	Administration Expense Fraction	.064	
ARO	Annual Rate of Recovers of Ore	3000000	Dry Short Tons
ASCSTL	Annual Cost of Labor per Mineship	2100000	Dollars
BASMSH	Mineship Cost Equation Multiplier	4550000	Dollars
BUMFAC	Bottom Unit Maintenance Cost Fraction	.05	
BUPY	Number of Bottom Units Replaced per year per ship	2	
CDS	Drag Coefficient of Nodule	.5	
COLEFF	Collector Efficiency	.65	
COLWTH	Collector Width	30	Feet
CPLPR	Price of Single Pipe Coupling	7700	Dollars

Variable	Description	Value	Units
DENS	Density of Pipe Material	485	lb/ft^3
DN	Diameter of Nodule	.125	Feet
DW	Depth of Water at Minesite	18000	Feet
EXPMSH	Mineship Cost Equation Exponent	.39	
FACINS	Pumping Unit Installation Factor	3.4	
FF	Darcy Friction Factor	.013	
NMSH	Number of Mineships in Mining Sector	1	
PEF	Pump Operating Efficiency	.65	
PILF	Pipe String Lifetime	1	Year
PIPTH	Wall Thickness of Lift Pipe	.04	Feet
PMMFAC	Pumping Unit Maintenance Cost Fraction	.05	
PMPDTH	Submergence Depth of Pumping Unit	3000	Feet
PPRICE	Price of Power at Sea	.03	$/HP-HR
RHON	Density of Nodules	128	lb/ft^3
RHOW	Density of Seawater	64	lb/ft^3
SBUCST	Cost of Single Bottom Unit	1500000	Dollars
SEF	Ship Propulsion System Efficiency	.65	
SHMFAC	Ship Maintenance Cost Fraction	.05	
STCST	Cost of Fabricated Pipe	1	$/lb

Variable	Description	Value	Units
WDS	Work Day at Sea	24	Hours
WNSEF	Fraction of Nodules Recovered from Lift	1	
WYS	Work Year at Sea	300	Days

C. Initial Values of Input Variables in the Transportation Section

Variable	Description	Value	Units
BUFCAP	Maximum Mineship Capacity	60	1000 DWT
CREW	Foreign or Domestic Crew Costs	1	Foreign
LIMIT	Limiting Size for Given Port	80	1000 DWT
NMSH	Number of Mineships	1	
OWDIS	One Way Distance to Port	1750	Nautical Miles
SLURRY	Slurry System Cost	1.8	Million Dollars
SPD	Speed	15	Knots
YARD	Foreign or Domestic Ship Yard Costs	1	Foreign

D. Initial Values of Input Variables in the Processing Sector

Variable	Description	Value	Units
ARO	Annual Rate of Recovery of Ore	3000000	Dry Short Tons
ARST	Area of Processing Plant Site	200	Acres
BFAC	Buildings Uost Estimation Factor	.1	
COALPR	Price of Coal Delivered to Plant	15	$/Ton

Variable	Description	Value	Units
COMP	Nodule Composition		
	Nickel	1.5	Percent
	Copper	1.3	Percent
	Cobalt	0.24	Percent
	Manganese	26.9	Percent
CONFEE	Contingency Fee	.15	
DIS1	Distance from Port to Processing Plant	5	Miles
DIS2	Distance from Plant to Waste Disposal Area	25	Miles
DIS3	Distance from Plant to Rail Transportation	5	Miles
ENGFEE	Engineering Fee	.05	
FID	Construction Indirect Cost Factor	1.4	
KOPS	Length of Operating Life of Mining Project	25	Years
LAND1	Price of Land at Waste Disposal Site	2000	$/Acre
LAND2	Price of Land at Plant Site	10000	$/Acre
LAND3	Price of Land at Port Facility	20000	$/Acre
LAND4	Price of Land between Port and Plant	2000	$/Acre
LAND5	Price of Land along Waste Disposal Pipeline	1000	$/Acre
PAYOHD	Overhead on Operating Labor and Supervision	.25	
PINSRT	Insurance Rate on Processing Plant	.01	
PORTAR	Area of Port Facility	10	Acres
POWLIM	Upper Limit on Power Plant Capacity	25100	KW

Variable	Description	Value	Units
PP	Price of Commercial Electric Power	.03	Dollars/KW-HR
PPEFF	Power Plant Energy Conversion Efficiency	.33	
PRLNR	Price of Liner for Waste Tailings Ponds	2	$/Yd^2
PRPCST	Cost of Pre-construction Land Preparation	4.39	$/Yd^2
RE	Metal Recovery Efficiency		
	Nickel	95.	Percent
	Copper	95.	Percent
	Cobalt	60.	Percent
	Manganese	0.	Percent
RLCMP	Cost of Rail Facilities	234000	$/Mile
SCPM	Cost of Slurry Pipeline	250000	$/Mile
SGEXP	Cost Equation Exponent for Syn-Gas Plant	.8	
SHRCST	Cost of Shore-side Facilities at Port	664850	Dollars
SLRYOP	Operating Cost of Slurry Pipeline	.01	$/Ton-Mile
STMEFF	Energy Conversion Efficiency of Steam Plant	.9	
STXRT	State Tax Rate on Processing Sector	.01	
UPKF	Maintenance Cost Estimating Factor	.04	
WAGE	Operating Labor Wage	8	$/Hour
WD	Work Day of Processing Sector	24	Hours
WRFCST	Cost of Wharf Facility	1250000	Dollars

Variable	Description	Value	Units
WY	Work Year of Processing	300	Days
YRDCST	Cost of Yard Improvement at Plant	558600	Dollars

E. Initial Values of Input Variables in the Financial Analysis Section

Variable	Description	Value	Units
AP	'A priori' Probability	5*.1 5*.075 5*.05 35*0.0	
BLDR	Lower Limit on Discount Rate Range	8	Percent
CAPFC	Capital Allocation Factor	3*.3333334 7*0.	
CCSF	Capital Cost Sensitivity Factor	30*1.	
DBTI	Debt Increment	16.7	Percent
DERMAX	Maximum Allowed Debt Equity Ratio	1:1	
DLY	Delay Period Lengths	5*0	Years
DPLA	Ore Depletion Allowance	0	Percent
DRI	Discount Rate Increment	2	Percent
DSCFF	Debt Service Cash Flow Factor	0.67	
IG	Investment Guarantee Selector	0	
KDP	Group Depreciation Period		
	Mining Equipment	10	Years
	Transport Equipment	18	Years
	Process Equipment	14	Years

Variable	Description	Value	Units
KDPMAX	Maximum Depreciation Period	20	Years
KE	Exploration Period Startup	2	Years
KINVST	Investment Period	3	Years
KLN	Amortization Period	10	Years
KPE	Exploration Period	2	Years
KPP	Prospecting Period	2	Years
KOPS	Operating Period	25	Years
KOP1	Initial Operating Period	0	Years
KP1	Preinvestment Period	2	Years
KRD	Research & Development Period	2	Years
KSU	Start Up Period	0	Years
KV1	Initial Investment Period	0	Years
LOAN	Loan Repayment Method	0	
METH	Method of Depreciation	2	
MORTZ	Amortization Selector	0	
MPPD	Depletion Allowance Method Selector	0	
MV	Metal Prices		
	Nickel	2.00	$/lb
	Copper	0.71	$/lb
	Cobalt	4.00	$/lb
N	Number of Sensitivity Analyses	0	
NG	Number of Groups in Each Sector	6	
NGL	Graph Format Control	0	

Variable	Description	Value	Units
NOM	Number of Minerals Recovered	3	
NRUNS	Number of Runs	1	
NS	Number of Sectors in Cost Estimation	5	
NSA	Sensitivity Analysis Selector	0	
NTSA	Sensitivity Analysis Designator	0	
NU	New or Used Assets Designator	19*0,1,10*0	
OCSF	Operating Cost Sensitivity Factor	30*1.	
OOG	Graph Selector	0	
OO1	Output Format Control	1	
PCDPL	Mineral Percentage Depletion		
	Nickel	14	Percent
	Copper	14	Percent
	Cobalt	14	Percent
PSV	Project Salvage Value	0	Percent
RDX	Research & Development Expense	50	Million Dollars
SCEF	Start Up Period Cost Efficiency	5*1.	
SDR	Social Discount Rate	10	Percent
SLDR	Specified Discount Rate for Study	0	Percent
SREF	Start Up Period Recovery Efficiency	5*1.	
STXRT	State Tax Rate	1	Percent

Variable	Description	Value	Units
SVNP	Salvage Value of New Project	50	Percent
SVP	Sector Salvage Value	30*0.	Percent
TLDR	Upper Limit on Discount Rate Range	24	Percent
TR	Tax Rate	48	Percent
USFRAC	Fraction of U.S. Investment	1.	
V	Sensitized Variable Designator	0	
VLO	Value of Landed Ore	0	Dollars
W	Sensitized Variable Descriptor	Blank	
WRD	Recovered Mineral Descriptor	Nickel Copper Cobalt	
WRD2	Recovered Mineral Symbol	Ni Cu Co	
XICDT	Investment Credit, Post 1980	7	Percent
XIF	Escalation Index		
	Revenues	0	Percent
	Investment	0	Percent
	Costs	0	Percent
	Discount Rate	0	Percent
XIR	Term Loan Interest Rate	10	Percent
XTICDT	Temporary Investment Credit	10	Percent
YEAR1	First Year of Project Activity	1976	